Investigating the electrode-electrolyte interface modelling in cochlear implants

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Introduction

Proposing a good electrode-electrolyte interface (EEI) model and properly identifying relevant parameters may help designing safer and more optimized auditory nerve fiber stimulation and recording in cochlear implant (CI) devices.

In electrochemistry, EEI is mostly modeled by a Cole or a Basic RC model. The Cole model consists of a constant phase element (CPE) with fractional power $0<\alpha\leq1$ in parallel with a Faradaic resistor R_P. In the Basic model the CPE is substituted with a capacitor C_p where $\alpha=1$.

Temporal and Spectral fitting methods use impulse voltage response (IVR) and electrochemical impedance spectroscopy (EIS) recordings, respectively to fit model parameters.

However, the state-of-the-art and related literature exhibit large variability among EEI model parameter values.

A wide range of parameter values are reported, with variability over three orders of magnitude for C_p and R_p (e.g., R_p is equal to a few kΩ in Tykocinski et al, to a few hundreds of kΩ in Jiang et al, and to $>10^{12}$ kΩ in Mesnildrey et al).

Author/Year/doi	Method	Parameters	
Vanpoucke et al., 2004 10.1109/TBME.2004.836518	Temporal	Rs: 3 kΩ R_p: 7 kΩ	α: 1 Cp: 5 nF
Tykocinski et al., 2005 10.1097/01.mao.0000185056.99888.f3	Temporal	R_S: 4 kΩ R_p: 5 kΩ	α: 1 C_p: 7 nF
Lim et al., 1990 10.1109/IEMBS.1990.692287	Temporal	R_S: 3.5 kΩ R_p: 5 kΩ	α: 1 C_p: 20 nF
Mesnildrey et al., 2019 10.1088/1741-2552/aaecff	Temporal, Spectral	R_S: 4 kΩ R_p: inf	α: 0.64 C_p: 481 nF
Zhou et al., 2018 10.1016/j.conb.2018.01.012	Temporal	R_S: 1.75 kΩ R_p: 38.5 MΩ	α: 1 C_p: 427 nF
Woods et al. , 2011 10.1088/1741-2560/8/4/046032	Spectral	R_S: 190 Ω R_p: 135 Ω	α: 1 C_p: 1021nF
Jiang et al., 2020 10.1063/5.0012514	Spectral	α_1: 0.8 to 1.2 C_{P1}: 2 µF R_{CT1}: 120 kΩ	α_2: 0.8 to 1.2 C_{P2}: 2 nF R_{CT2}: 2 kΩ
Lella et al., 2019 10.1097/mao.0000000000002214	Temporal	R_S: 3 kΩ R_p: 6 kΩ	α: 1 C_p: 6nF
Lella et al. , 2020 10.3389/fbioe.2020.568690	Temporal	R_S: 3-9 kΩ R_p: 500 Ω	α: 1 C_p: 2-50 nF

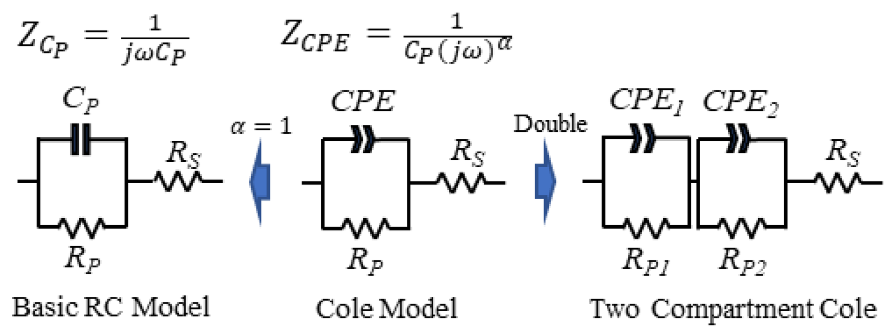
Objective

We aim to explain some root causes of this variability using the Cole model and its simpler form, the Basic RC model.

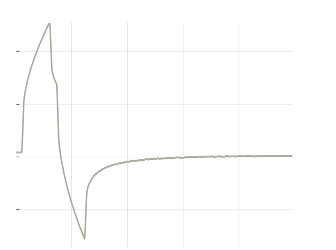
Methodology

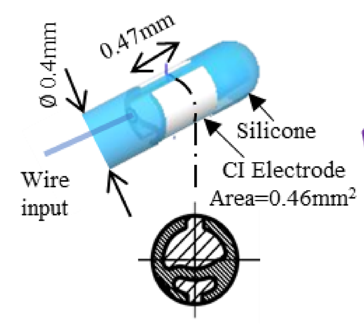
Oticon Medical 10 individual small size EVO CI electrodes were used in this study. For a given electrode inserted in artificial perilymph, electrochemical impedance spectroscopy (EIS) was obtained in the frequency range [0.05Hz - 1MHz]. Chronopotentiometry (IVR) was obtained by short rectangular biphasic current pulses (180µs per phase). Models were fitted Spectral and Temporal model fittings were applied

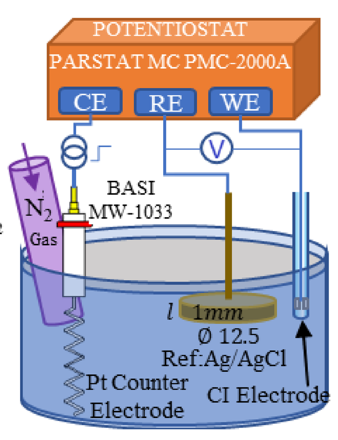
$$Z_{C_P} = \frac{1}{j\omega C_P} \qquad Z_{CPE} = \frac{1}{C_P (j\omega)^{\alpha}}$$



Chronopotentiometry

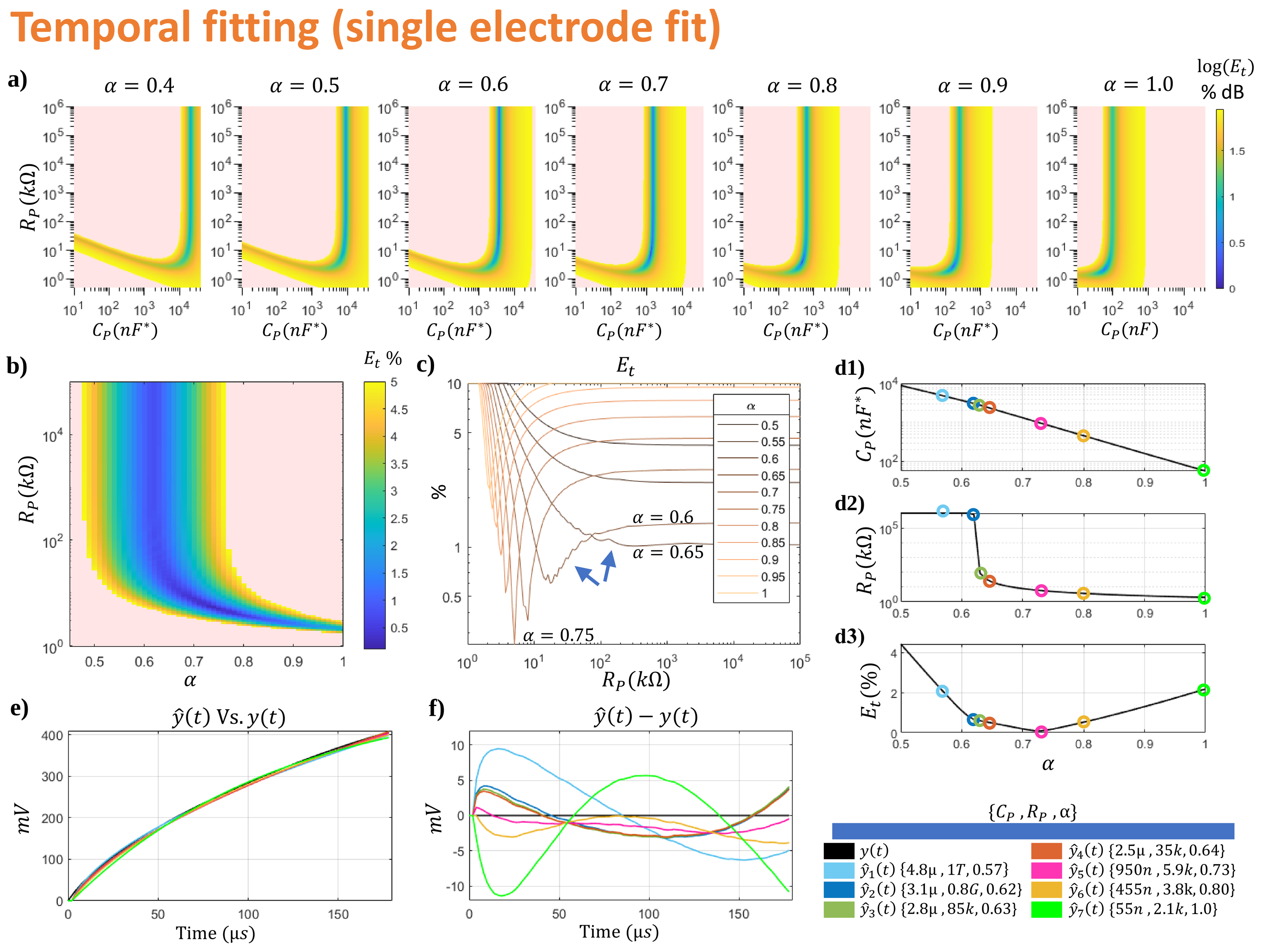






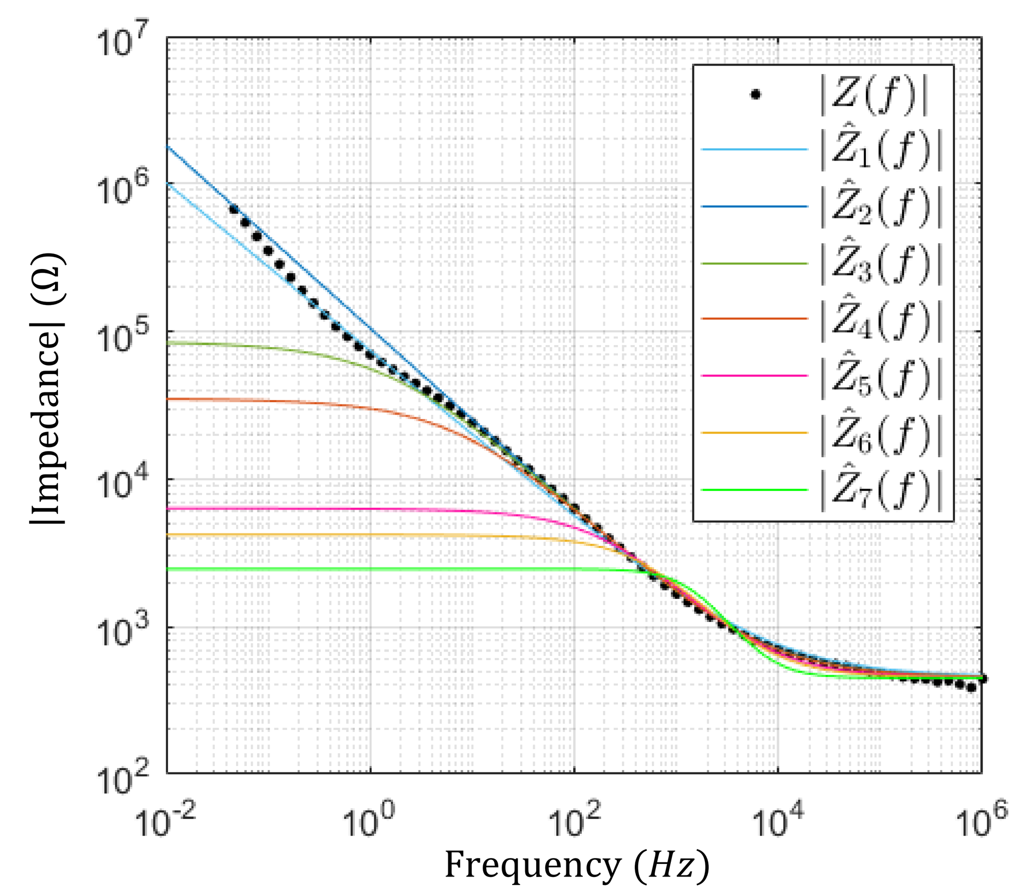
Results

Temporal fitting (single electrode fit)



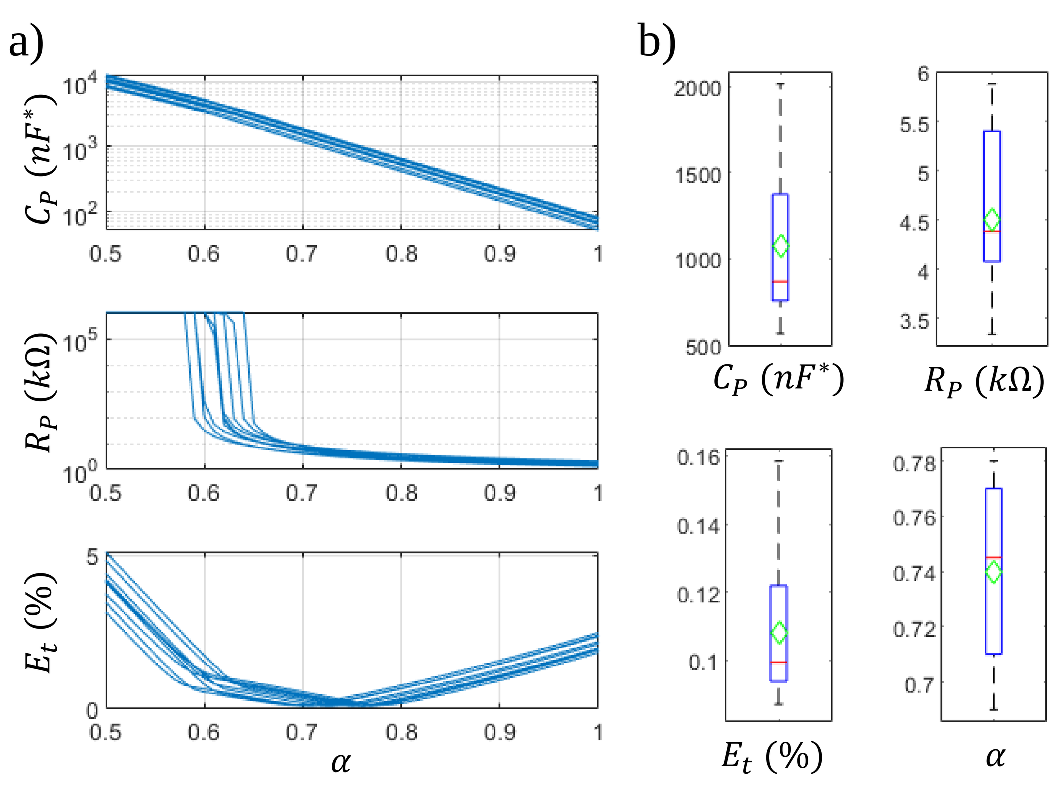
a) nx2D topography maps of the cost function value as a function of C_p, R_p, and α.
b) The nx2D topography maps have been reduced by one dimension (removing the C_p axis) to show the cost function as a function of R_p and α.
c) Cost functions versus R_p for various values of α.
d) Three subplots showing the relation between the model parameters, the cost function, and the α value.
e) IVR of the EEI models (over the double layer) corresponding to the color-coded circles in graph (d) and the measured IVR response to a current pulse of 250 µA.
f) The differences between the modeled and the measured IVR responses.

Linking temporal to spectral (single electrode fit)



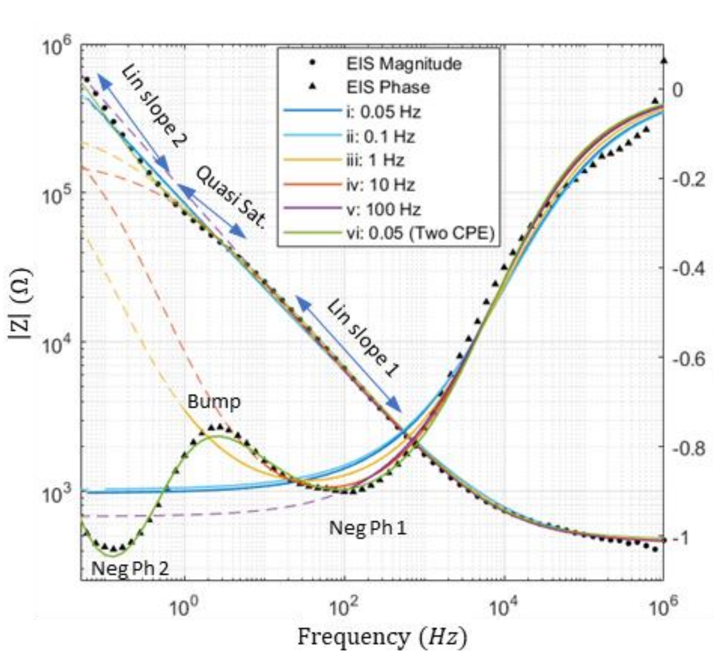
Frequency response of the 7 temporally fit model superimposed on the measured EIS. Models are only different at the low frequency. Indicating that the temporal fit is blind to low frequencies below ~500 Hz.

Temporal fitting (multi electrode fit)

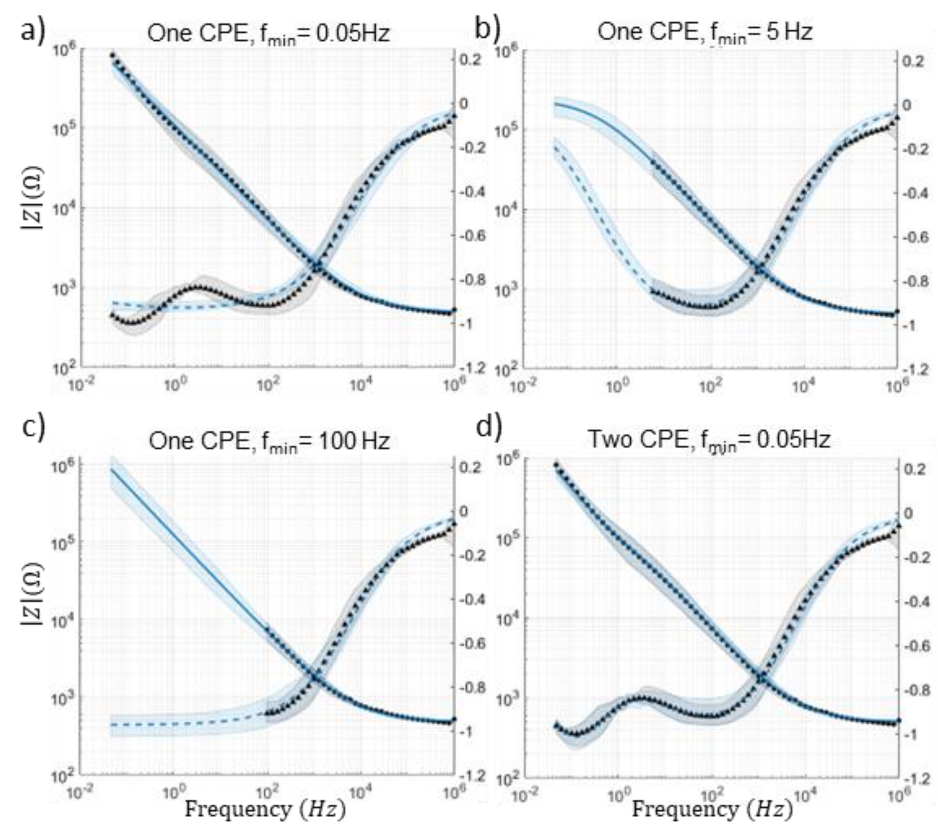


Estimated values of C_p, R_p and cost function for 10 electrodes when α is swept from 0.5 to 1.

Spectral fitting (single and multi electrodes)



Frequency response of Cole model fit changes importantly when the lower frequency of the observed EIS is modified from 0.05 to 100 Hz.



Model	f_{min} (Hz)	R_P (MΩ)	C_P (µF*)	α
a: Cole	0.05	$2.2\ 10^{14} \pm 2.6\ 10^{14}$	3.4 ± 1.1	0.6 ± 0.025
b: Cole	5	0.24 ± 0.01	2.8 ± 1.2	0.63 ± 0.042
c: Cole	100	$8.7\ 10^{11} \pm 7.1\ 10^{11}$	3.2 ± 1.4	0.62 ± 0.042
d: Double Cole	0.05	0.67 ± 0.03 3.0 ± 2.0	3.2 ± 1.0 3.9 ± 1.0	0.63 ± 0.059 0.82 ± 0.09

Single versus double Cole model fitting. Dotted points: Mean EIS values (circles: magnitude; triangles: phase) calculated over 10 electrodes. Solid/Dash Lines: the mean fitted impedance magnitude/phase.

Conclusions

1) The first-order RC model does not match to the temporal IVR data as the Cole model does.

2) A temporal fit is blind to the to frequency component of the EEI → Different model parameters especially R_p but similar IVR response → Literature discrepancies

3) A temporal fit is not so sensitive to the fractional power α

4) The spectral fitting method extends the validity of the fit parameters to very low frequencies.

5) Erroneous predictions may be obtained from a spectral-based fitted model if extrapolation of its results beyond the observed frequencies is used

Because sound matters

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