Probing epilepsy in human cortex with delay differential equations

Claudia Lainscsek[1], Sydney Cash[2], and Terry Sejnowski[1]

[1] The Salk Institute; 10010 North Torrey Pines Road; La Jolla, CA 92037; USA
[2] Department of Neurology, Epilepsy Service, Harvard Medical School, ACC 835, Massachusetts General Hospital, 55 Fruit Street, Boston, Massachusetts 02114; USA

Abstract

Time series analysis with nonlinear delay differential equations (DDEs) is a very powerful tool since it reveals spectral as well as topological properties of the underlying dynamical system. Here DDEs are used to identify different regimes in ECoG (Electrocorticography) data. Electrocorticography is the practice of using electrodes placed directly on the exposed surface of the brain to record electrical activity from the cerebral cortex. ECoG is currently considered to be the "gold standard" for defining epileptogenic zones in clinical practice. A general form for the DDEs used here is $\dot{x} = f(x_{\tau_1}, x_{\tau_2}, \dots)$, where $x_{\tau_j} = x(x - \tau_j)$ and $\tau \in \mathbb{N}_0$ that relates the derivative at a data point to previous data points of the signal. The linear terms of such a DDE correspond to the main frequencies in the signal. For n independent frequencies in the signal $2n - 1$ linear terms are needed. The nonlinear terms in the DDE are related to nonlinear couplings between the harmonic signal parts. DDEs can also be re-written as functions of dynamical higher order data correlations. These dynamical higher order data correlations can be seen as generalizations of Nth order data moment functions such as e.g. the auto-correlation (2nd order moment) and the bi-correlation (3rd order moment). Comparing both versions of higher order data correlations can reveal useful information when analyzing non-linear data. The DDE framework therefore can be seen as a time-domain analysis tool akin to Fourier analysis that is highly robust against noise contamination and computationally fast.

In multichannel epilepsy ECoG data the nonlinear parts of the signal are of special interrest. A simple nonlinear two-term DDE can be used to reliably identify artifacts as well as seizures by a large model error and be clearly distinguished by applying ICA to the DDE outputs. Such an analysis can also reveal the seizure onset channels of each seizure. The DDE ouputs further show the three different stages present while a seizure is happening, and post-seizure states.