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A New Algorithm for Solving Hemodynamic Models in fMRI under Low Frequency Interference

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Abstract

In order to solve the problem of estimating the model parameters of hemodynamic model under low frequency interference, a new model parameter estimation algorithm (CSCKS) is proposed in this paper for the hemodynamic model with low frequency interference. The algorithm is based on SCKS algorithm to improve, its estimation effect is obviously better than the existing SCKS algorithm and DEM algorithm. We simulate the proposed algorithm and some other traditional algorithms to evaluate the estimation performance of CSCKS proposed in this paper under different Signal to Interference Ratio (SIR) and different integration steps, and through the simulation results, the estimated results of the algorithm were analyzed and compared.

Keywords: fMRI; hemodynamic model; Kalman filter

1. Introduction

The activity of the neurons in the brain is a dynamic process, and we cannot directly observe the interactions that occur in the brain regions by visual means. However, with the continuous development and update of neuroimaging techniques, we have developed new ways to indirectly observe and measure the neuronal activity occurring in the brain and the interaction between brain regions, such as fMRI Technology. By fMRI we can observe the hemodynamic response in the brain region. The hemodynamic response reflects the cerebral blood flow and the concentration of oxygen in the vicinity of the brain, which reflect the state changes of the neurons, because neuronal activity in the brain area will lead to changes in relevant indicators such as cerebral blood flow in the adjacent area.

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If we can clearly understand a series of changes in electrophysiological processes in the brain regions, we can model a series of hemodynamic changes caused by neuronal changes in the brain regions combining this electrophysiological process. Next, we can use the relevant method[1-6]to calculate and inverse the model and then estimate the corresponding model parameters of the model. In fact, the question of the link between neuronal activity and blood vessels/metabolism has been extensively studied. We know that the existing hemodynamic models are almost always based on the Balloon-Windkessel model[6]consisting of the differential equations. The Balloon-Windkessel model is a well-established and highly reliable hemodynamic model used to model the relationship between neurons and hemodynamic responses in brain regions. What we are examining here is the physiological relationship between neurons and hemodynamic responses in a single brain region. Next, we will further study the dynamic model of multiple brain regions. We will use the CSCKS algorithm proposed in this paper as well as the existing traditional algorithms to reverse the hemodynamic model.

The hemodynamic model itself is a nonlinear problem. For the hemodynamic model without low frequency interference, under the condition of known hemodynamic response, some existing traditional methods such as SCKS algorithm and DEM algorithm[7], they can jointly estimate the hidden states, inputs and parameters of the model and can accurately estimate the input, hidden states and identify the parameters. However, the existing SCKS algorithm does not consider low frequency interference factors. For hemodynamic model that includes low frequency interference factors. SCKS algorithm cannot estimate the coefficients of low frequency interference factors.

In the paper, we propose a new CSCKS algorithm on the basis of SCKS algorithm. CSCKS algorithm can accurately estimate the hidden states and the coefficients of low frequency interference factors and recognize the parameters under the condition of known hemodynamic signals and inputs. Then, for the hemodynamic model with low frequency interference factors, we use the proposed CSCKS algorithm and the existing traditional algorithms such as SCKS algorithm, DEM algorithm for inversion and simulation.

2. Model and algorithms

2.1. Model

The process that neuronal state changes over time is a dynamic process[3]. We can describe the dynamic process using the Balloon-Windkessel model.

2.1.1. State equation

The state equation for the hemodynamic model is as follows:

$$\begin{cases} \dot{s} = \dot{z} - \kappa s - \gamma\left(f-1\right) \\ \dot{f} = s \\ \tau\dot{v} = f - v^{\frac{1}{\alpha}} \\ \tau\dot{q} = f\dfrac{E\left(f,\rho\right)}{\rho} - v^{\frac{1}{\alpha}}\dfrac{q}{v} \end{cases} \tag{1}$$

where s is cerebrovascular relaxation signal, $\dot{z}$ is the hidden state, and $\dot{z} = u$, u is an input. τ is the hemodynamic transit time. γ is the rate of flow-dependent elimination. κ is the rate of signal decay. v is the blood volume. q is the deoxyhemoglobin content. α is the Grubb's exponent. $E\left(f,\rho\right) = 1-\left(1-\rho\right)^{1/f}$, where ρ is the constant, representing the resting oxygen extraction fraction.