ELSEVIER

NeuroImage

www.elsevier.com/locate/ynimg
NeuroImage 25 (2005) 1310–1324

Modeling both the magnitude and phase of complex-valued fMRI data

Daniel B. Rowe

Department of Biophysics, Medical College of Wisconsin, 8701 Watertown Plank Road, Milwaukee WI 53226-0509, USA

Received 19 November 2004; revised 27 December 2004; accepted 7 January 2005
Available online 19 March 2005

In MRI and fMRI, images or voxel measurement are complex valued or bivariate at each time point. Recently, (Rowe, D.B., Logan, B.R., 2004. A complex way to compute fMRI activation. NeuroImage 23 (3), 1078–1092) introduced an fMRI magnitude activation model that utilized both the real and imaginary data in each voxel. This model, following traditional beliefs, specified that the phase time course were fixed unknown quantities which may be estimated voxel-by-voxel. Subsequently, (Rowe, D.B., Logan, B.R., 2005. Complex fMRI analysis with unrestricted phase is equivalent to a magnitude-only model. NeuroImage 24 (2), 603–606) generalized the model to have no restrictions on the phase time course. They showed that this unrestricted phase model was mathematically equivalent to the usual magnitude-only data model including regression coefficients and voxel activation statistic but philosophically different due to it derivation from complex data. Recent findings by (Hoogenrad, F.G., Reichenbach, J.R., Haacke, E.M., Lai, S., Kuppusamy, K., Sprenger, M., 1998. In vivo measurement of changes in venous blood-oxygenation with high resolution functional MRI at .95 Tesla by measuring changes in susceptibility and velocity. Magn. Reson. Med. 39 (1), 97–107) and (Menon, R.S., 2002. Postacquisition suppression of large-vessel BOLD signals in high-resolution fMRI. Magn. Reson. Med. 47 (1), 1–9) indicate that the voxel phase time course may exhibit task related changes. In this paper, a general complex fMRI activation model is introduced that describes both the magnitude and phase in complex data which can be used to specifically characterize task related change in both. Hypotheses regarding task related magnitude and/or phase changes are evaluated using derived activation statistics. It was found that the Rowe–Logan complex constant phase model strongly biases against voxels with task related phase changes and that the current very general complex linear phase model can be cast to address several different hypotheses sensitive to different magnitude/phase changes.

Keywords: Complex-valued fMRI data; Rowe–Logan complex; Magnitude changes; Phase changes

Introduction

It is well known that in magnetic resonance imaging (MRI) and functional magnetic resonance imaging (fMRI), images or voxel measurements are complex valued or bivariate due to phase imperfections and thus in fMRI, voxel time course measurements appear in both the real and imaginary channels (Bernstein et al., 1989; Haacke et al., 1999; Macovski, 1996). An example of a voxel's complex valued time course with assumed magnitude task related changes and a constant phase is presented in Fig. 1, where the length of the vector from the origin to the point in real-imaginary space is the magnitude and the angle the vector makes with the real axis is the phase. In fMRI, the real and imaginary components are the quantities that are measured with observation error. For example in a block design finger tapping experiment, the vector described by the arrow in Fig. 1 appears to "jitter" around in a lower vector length state during the control task than the length of this vector appears to "jitter" around in a higher vector length state. Any apparent "jitter" in the phase would be purely from measurement error in the real and imaginary components of the vector. In fMRI, complex valued voxel time courses are generally converted to magnitude and phase time courses then task related magnitude-only data activation determined with the phase voxel time course discarded (Bandettini et al., 1993; Cox et al., 1995). The original complex data are unrecoverable after discarding the phase and the magnitude-only operation is nonunique. Other attempts have been made to avoid complex voxel time courses such as phasing them into the real channel (Bernstein et al., 1989).

Rowe and Logan (2004) introduced a general complex fMRI magnitude activation model in which multiple regressors were allowed using the standard general linear statistical model, hypothesis tests were formulated in terms of contrasts, and the phase was directly modeled as a fixed unknown quantity which may be estimated voxel by voxel (Rowe and Logan, 2004). Furthermore, a large sample Chi-square distributed statistic was presented for comparability between the two models. In Rowe and Logan (2005), the complex model was generalized to have an unrestricted phase time course (Rowe and Logan, 2005). They showed that this model was mathematically equivalent to the usual magnitude-only data model in terms of regression coefficients and

E-mail address: dbrowe@mcw.edu.
Available online on ScienceDirect (www.sciencedirect.com).

1053-8119/$ - see front matter © 2005 Elsevier Inc. All rights reserved.
doi:10.1016/j.neuroimage.2005.01.034

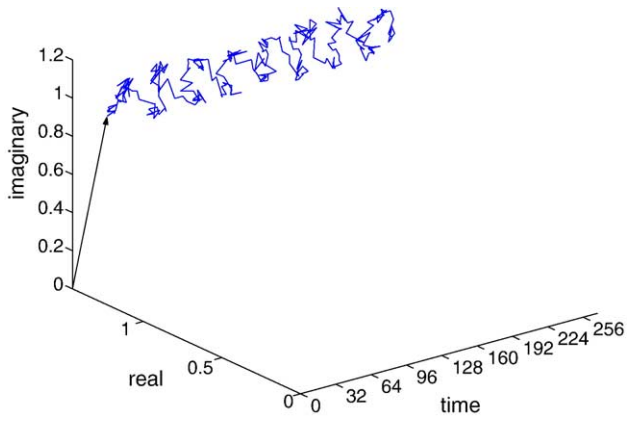

Fig. 1. Complex valued voxel time course.

voxel activation statistic but philosophically different due to its derivation from complex data. The magnitude-only or equivalently complex unrestricted phase data models only utilize information in the magnitude through the exact Ricean distribution or through the large signal-to-noise ratio (SNR) normal distribution approximation (Gudbjartsson and Patz, 1995; Rice, 1944). Parameter estimation in the complex constant phase model and the magnitude-only or equivalently complex unrestricted phase data model were examined in Rowe (2005). Rowe (2005) found that the magnitude-only data model with a normal approximation to a Ricean distribution exhibited decreased activation detection power at lower SNRs when compared to the complex constant phase model but a Taylor series approximation to the Ricean distribution showed modest improvement (Rowe, 2005).

However, Hoogenrad et al. (1998) and Menon (2002) presented evidence to suggest that the voxel phase angle time courses may not be exactly constant over time but may also exhibit task related phase changes in voxels with "large" vessels (Hoogenrad et al., 1998; Menon, 2002). This is the motivation for this work. Specifically, a model is developed to help us characterize voxels in terms of task related magnitude and/or phase changes. Voxels in parenchyma with task related magnitude changes are of primary interest, but voxels with task related phase changes, although not of interest in themselves, their characterization helps us identify voxels that only have task related magnitude changes that are of interest.

In this paper, a general complex fMRI activation model is introduced that describes both the magnitude and phase which can be used to specifically model and test for task related changes in the magnitude, the phase, or both the magnitude and phase. Thus, in principle, activation can be determined from voxels with "small" vessels such as those in the capillary bed of parenchymal tissue having solely magnitude changes and not voxels with "large" vessels having task related changes in both the magnitude and phase. This implies that the phase may contain information about the brain that is not present in the magnitude of the response. The situation of the vector valued voxel observation residing in the two magnitude length states is depicted in Fig. 2a while the situation of the two vector states that involve a lengthening and rotation is depicted in Fig. 2b. Where for example, the magnitude and phase are described by linear models with x_t' being the t^{th} row of a design matrix $\mathbf{X}$ having, for example, a column of ones, a column of counting numbers, and a square wave reference function with corresponding coefficients (β_0, β_1, β_2) and (γ_0, γ_1, γ_2). The activation model from magnitude-only data is sensitive to voxels that have task related changes in the magnitude regardless of whether there are changes of any kind in the phase, while magnitude activation from complex data specifically describes and dictates whether or not we wish to include voxels that have task related phase changes. Menon sought to account for changes in the observed magnitude that could be accounted for by changes in the phase by including voxel phase values as a random independent regressor variable in a least squares model (Menon, 2002).

In fMRI, we seek voxels with small vessels in parenchymal tissue having random orientations whose phase contributions are small in aggregate. Thus, in principle, the phase angle

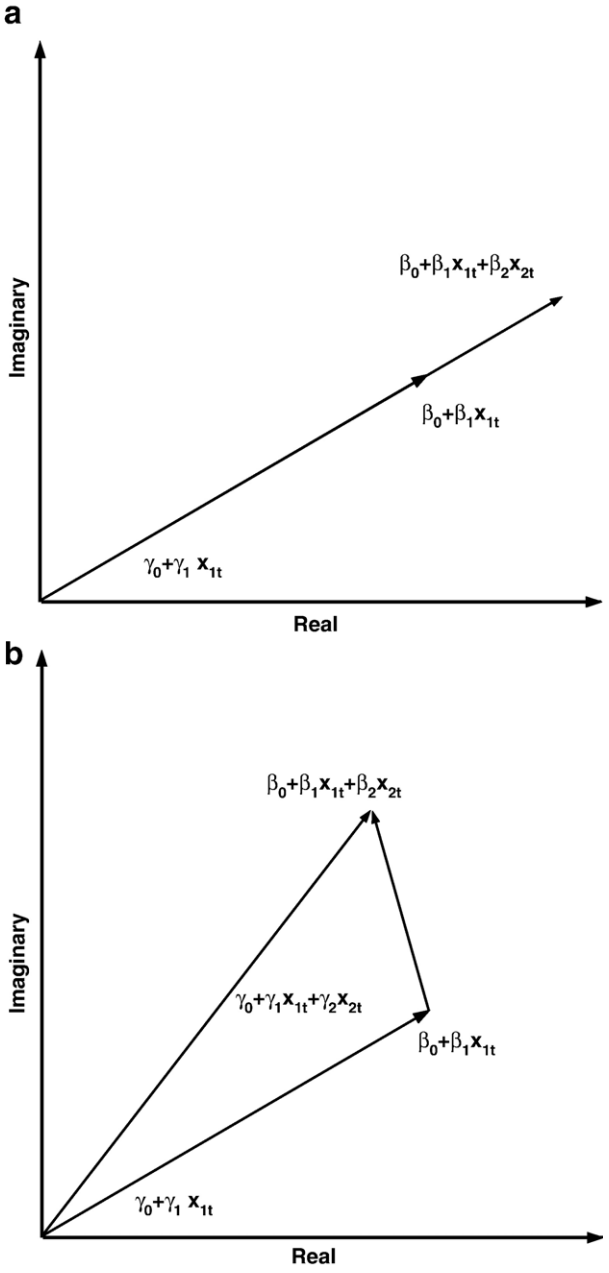

Fig. 2. Task related magnitude/phase changes. (a) Magnitude-alone change. (b) Magnitude and phase change.