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Short communication

Intrinsic functional brain mapping in reconstructed 4D magnetic susceptibility (χ) data space

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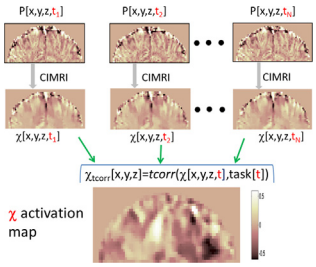
HIGHLIGHTS

- 4D magnetic susceptibility (χ) tomography provides a 4D χ data space.
- A reconstructed χ map represents an intrinsic magnetic state.
- A χ activation map reveals the co-occurrence of bidirectional BOLD responses.
- There are two different approaches to achieve χ-based functional mapping.

GRAPHICAL ABSTRACT



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ABSTRACT

Background: By solving an inverse problem of T2*-weighted magnetic resonance imaging for a dynamic fMRI study, we reconstruct a 4D magnetic susceptibility source (χ) data space for intrinsic functional mapping.
New methods: A 4D phase dataset is calculated from a 4D complex fMRI dataset. The background field and phase wrapping effect are removed by a Laplacian technique. A 3D χ source map is reconstructed from a 3D phase image by a computed inverse MRI (CIMRI) scheme. A 4D χ data space is reconstructed by repeating the 3D χ source reconstruction for each time point. A functional map is calculated by a temporal correlation between voxel signals in the 4D χ space and the timecourse of the task paradigm.
Results: With a finger-tapping experiment, we obtain two 3D functional mappings in the 4D magnitude data space and in the reconstructed 4D χ data space. We find that the χ-based functional mapping reveals co-occurrence of bidirectional responses in a 3D activation map that is different from the conventional magnitude-based mapping.
Comparison with existing methods: The χ-based functional mapping can also be achieved by a 3D deconvolution of a phase activation map. Based on a subject experimental comparison, we show that the 4D χ tomography method could produce a similar χ activation map as obtained by the 3D deconvolution method.
Conclusion: By removing the dipole effect and other fMRI technological contaminations, 4D χ tomography provides a 4D χ data space that allows a more direct and truthful functional mapping of a brain activity.
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Abbreviations: 3D, 3-dimensional; 4D, 4-dimensional; MR, magnetic resonance; fMRI, functional magnetic resonance imaging; BOLD, blood oxygenation level dependent; T2*MRI, T2*-weighted MRI; CIMRI, computed inverse MRI; EPI, echo planar imaging; QSM, quantitative susceptibility mapping; TV, total variation; *tcorr*, temporal correlation.

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1. Introduction

A BOLD fMRI (blood oxygenation level dependent function magnetic resonance imaging) study by T2*-weighted magnetic resonance imaging (T2*MRI, or T2* imaging) produces a 4D complex-valued dataset. Conventionally, only the 4D magnitude component is used for functional brain mapping, and the counterpart of 4D phase component is always discarded for its noisy appearance and encrypted 'artefacts' (the notorious phase wrapping phenomenon). Recent research has shown the phase contains all the information of the inhomogeneous field, which is in turn related to the tissue magnetic susceptibility distribution (denoted by χ) by a 3D convolution (Chen and Calhoun, 2013a,b; Haacke and Ye, 2012). This inspires a great enthusiasm for reconstructing the internal χ source distributions from complex-valued T2* images, essentially solving an inverse problem of T2*MRI. The efforts on reproducing χ source have been described by different terms: quantitative susceptibility mapping (QSM) (Langkammer et al., 2012; Li et al., 2011; Liu et al., 2009, 2012a,b; Schweser et al., 2012b; Shmueli et al., 2009), χ tomography or reconstruction (Chen and Calhoun, 2012; Chen et al., 2013; Sepulveda et al., 1994), and dipole inversion (Schweser et al., 2012a). It is greatly expected that the reconstructed χ distribution can represent the intrinsic magnetic property of brain tissue due to the removal of dipole effect and other T2*MRI technological contaminations (such as phase wrapping artifacts). In past decade, the prevailing research on magnetic susceptibility mapping is for static brain structural imaging. In recent years, the pursuit of χ source has extended to dynamic brain functional imaging and mapping (Balla et al., 2014; Chen et al., 2013), dealing with a 4D BOLD fMRI dataset. We have reported on an approach for obtaining a χ-depicted functional map from a phase activation map (Chen et al., 2013). In this paper, we report on a 4D χ tomography approach (Chen and Calhoun, 2014), that is to reconstruct a 4D χ data space for intrinsic functional mapping.

The underlying source of BOLD fMRI is the neurovascular homodynamic response to a brain activity, which physiologically expresses as a vascular blood χ perturbation that in turn causes an inhomogeneous fieldmap in a main field B_0. The χ-induced fieldmap is then measured by T2*MRI through a gradient-recalled echo sequence. A BOLD fMRI study usually uses a gradient-recalled EPI (echo planar imaging) sequence for fast data acquisition, producing a timeseries of complex T2* images. The MRI physics shows that electromagnetic interaction between tissue and the main field B_0 inevitably imposes a dipole effect on the χ-induced fieldmap, which propagates to the output T2* images during T2*MRI data acquisition. Therefore, the effort on reconstructing the intrinsic χ source from complex T2* images is indeed to solve an inverse problem of T2*MRI, which can be appropriately termed by a canonical imaging nomenclature of χ tomography (Chen and Calhoun, 2014; Sepulveda et al., 1994). We have reported on a computed inverse MRI (CIMRI) scheme (Chen and Calhoun, 2012) for 3D χ tomography that can accomplish the 3D dipole inversion by total-variation (TV) regularized split Bregman iterations. Considering a 4D BOLD fMRI dataset as a timeseries of complex T2* images, it is straightforward to reconstruct a 4D χ dataset by repeating CIMRI for each snapshot volume, an implementation of 4D χ tomography. By removing dipole effect and other T2*MRI technological contaminations, the 4D χ tomography provides a 4D χ data space for intrinsic functional mapping.

2. Theory

2.1. T2*MRI

Let $\chi(\mathbf{r})$ denote the spatial distribution ($\mathbf{r}=(x, y, z)$) of the intrinsic magnetic susceptibility property of a brain state, $b(\mathbf{r})$ the χ-induced fieldmap. Then, the linear constitutive relation of tissue magnetization in B_0 gives rise to (Reitz et al., 1993)

$$b(r) = B_0 \cdot \chi(\mathbf{r}) * h_{dipole}(\mathbf{r}) + \varepsilon(\mathbf{r})$$
$$\text{with } h_{dipole}(\mathbf{r}) = \frac{1}{4\pi}\frac{3z^2 - |\mathbf{r}|^2}{|\mathbf{r}|^5} \quad (1)$$

where * denotes convolution, $h_{dipole}(\mathbf{r})$ the 3D dipole field kernel, $\varepsilon(\mathbf{r})$ the additive noise, and $b(\mathbf{r})$ denotes the z-component of χ-induced fieldmap. It is noted that the dipole kernel is bipolar-valued and non-local ($h_{dipole}(\mathbf{r}) \neq \delta(\mathbf{r})$), which causes a morphological change of $b(\mathbf{r})$ from source $\chi(\mathbf{r})$, in a manifestation of dipole effect. Since $b(\mathbf{r})$ serves as the direct source T2*MRI, the dipole effect is inherent with T2* images. To a great extent, the χ source reconstruction is essentially to solve a dipole inversion problem (Liu et al., 2012a,b; Schweser et al., 2012a).

The data acquisition by T2*MRI is based on an intravoxel spin precession dephasing in the χ-induced inhomogeneous field. Due to spatial partition of a field of view (FOV) by discrete voxels, the output of T2*MRI is a complex-valued multivoxel image (an array of voxel signals). Let $C[\mathbf{r}]$ denote the 3D complex T2* image acquired by T2*MRI with a gradient-recall sequence with an echo time (T_E), it is related to the continuous fieldmap by:

$$C[\mathbf{r}] = \frac{1}{|\Omega|}\sum_{\mathbf{r}'\in\Omega(\mathbf{r})} \exp\{i\gamma b(\mathbf{r}')T_E\} \quad (2)$$

where $\Omega(\mathbf{r})$ denotes a voxel space at $\mathbf{r}$, $|\Omega|$ the number of spin particles in a voxel, and γ the gyromagnetic ratio of proton. It is noted that we denote the continuous spatial variable by $(\mathbf{r})$ and the sampled spatial variable by $[\mathbf{r}]$ in Eq. (2) and henceforth.

The forward data acquisition of T2*MRI can be theoretically expressed by Eqs. (1) and (2), which has been described by a two-step model (Chen and Calhoun, 2012, 2014). The intravoxel dephasing mechanism in Eq. (2) represents a spatially sampled transformation (from a continuous fieldmap $b(\mathbf{r})$ to a discrete image array $C[\mathbf{r}]$) that is a many-to-one spatial mapping for FOV partition into voxels ($(\mathbf{r})\rightarrow[\mathbf{r}]$). It is noted that the voxel complex signal formation from numerous sinusoidal signals in Eq. (2) is a vector sum, that is, the intravoxel average of complex spin signals is a linear operation. However, the calculation of voxel signal magnitude by complex modulus, $|C[\mathbf{r}]|$, is obviously a nonlinear operation. The voxel phase signal calculation by $\angle C[\mathbf{r}]$ takes a different nonlinear operation, $\arctan(\mathrm{Im}C[\mathbf{r}]/\mathrm{Re}C[\mathbf{r}])$ (where Im denotes imaginary and Re real), which may reduce to a linear operation in small phase condition ($\arctan(x)=x$ for $x\rightarrow 0$).

For the convenience of postprocessing, we always normalize the magnitude data in a range of [0, 1] in dimensionless units, and normalize the phase data in a range of $[-\pi, \pi)$ in units of radian. It is noted that the voxel phase angle ($\angle C[\mathbf{r}]$) may suffer phase wrapping phenomenon when the phase accrual during T2*MRI is beyond $[-\pi, \pi)$ (usually observed in air/tissue interfaces). In addition to the source χ values, the phase wrapping artifacts are determined by the scanning parameters (B_0, T_E, T_R, voxel size, etc.), so we consider them as a T2*MRI technological contaminations to the T2* images (not technological defects). One task of CIMRI is to remove the T2*MRI contaminations for intrinsic source reconstruction.

2.2. CIMRI

In principle, from a complex T2* image, we can reconstruct its χ source by solving an inverse problem of T2*MRI by two-step computations of CIMRI. The first computational step of CIMRI