

Virtually Independent Gaussian Channel Nulling (VIPGen) Image Reconstruction for Functional Magnetic Resonance Inverse Imaging (fMRIInI)

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INTRODUCTION

Single-shot volumetric MR inverse imaging (InI) [1], also known as MR-encephalography (MREG) [2], can achieve 100 ms temporal resolution and 5-10 mm spatial resolution with the whole head coverage. To achieve a high temporal resolution, InI trades off spatial resolution by solving ill-posed inverse problems in image reconstruction. In practice, projection images were acquired during the accelerated InI scan with omitted partition encoding. Different approaches have been proposed to reconstruct InI images, such as techniques based on the L2 norm minimization [3], spatial filtering with a minimized source variance [4], or the L1 norm minimization with respect to the source amplitude [5]. While L2 norm minimization has analytical solution, results are generally blurry. The L1 norm minimization can provide a higher spatial resolution at the cost of a longer computing time. Here we propose a new method called virtually independent parallel Gaussian channel nulling (VIPGen) reconstruction, which is based on nulling virtual Gaussian noisy channels and reconstructs sources directly from scaling the projection measurements by its corresponding sensitivity in the projection reference matrix. The group analysis in our visuomotor experiments shows that VIPGen provides good spatial resolution similar to the sources reconstructed by the eigenspace L1 norm minimization and high statistical values, while the computing time is comparable to the L2 norm minimization.

METHODS

The noise-whitened InI measurements for one pixel in the accelerated projection image within the FOV is denoted as a vector \mathbf{Y}_w , which can be related to the noise-whitened reference scan \mathbf{A}_w and the image to be reconstructed \mathbf{X} : $\mathbf{Y}_w = \mathbf{A}_w \cdot \mathbf{X} + \mathbf{n}_w$, where \mathbf{A}_w was measured from a 3D fully gradient encoded scan, and \mathbf{n}_w is the whitened noise. \mathbf{A}_w can be decomposed by performing singular value decomposition (SVD): $\mathbf{A}_w = \mathbf{U}_A \cdot \mathbf{S}_A \cdot \mathbf{V}_A^T$. The unknown sources, measurements, reference, and noise after projection are then $\mathbf{X}_{proj} = \mathbf{V}_A^T \cdot \mathbf{X}$, $\mathbf{Y}_{proj} = \mathbf{U}_A^T \cdot \mathbf{Y}$, $\mathbf{A}_{proj} = \mathbf{S}_A$, and $\mathbf{n}_{proj} = \mathbf{U}_A^T \cdot \mathbf{n}_w$. $\mathbf{Y}_{proj} = \mathbf{A}_{proj} \cdot \mathbf{X}_{proj} + \mathbf{n}_{proj}$. Since \mathbf{n}_w has been whitened and \mathbf{U}_A^T includes eigenvectors of \mathbf{A}_w , \mathbf{n}_{proj} is still spatially uncorrelated with unit variance. Since \mathbf{A}_{proj} is a diagonal matrix, each element of \mathbf{Y}_{proj} is related to one and only one row in \mathbf{X}_{proj} , meaning that each virtual coil (each row in $\mathbf{Y}_{proj} = \mathbf{A}_{proj} \cdot \mathbf{X}_{proj} + \mathbf{n}_{proj}$) is independent of others. Given the unit-power noise added to each virtual channel, the projection measurements with power larger and smaller than one can be classified as valid sources and noise respectively. Noisy sources then can be nulled. $\mathbf{X}_{proj} \cong \mathbf{A}_{proj}^{-1} \cdot \mathbf{Y}_{proj}$, where $\mathbf{A}_{proj}^{-1} = \mathbf{S}_A(i, i)^{-1}$, if $\|\mathbf{Y}_{proj}(i)\|_2 > 1$ and $\mathbf{A}_{proj}^{-1} = 0$ elsewhere. The actual sources will be $\mathbf{X} = \mathbf{V}_A \cdot \mathbf{X}_{proj}$.

Nine healthy subjects with informed consents were recruited to the fMRI study with a voluntary visuomotor task. This data has been used previously in our eigenspace L1 norm beamformer analysis [5]. The InI was measured with TR=100 ms and TE=30 ms using a flip angle of 30 from a 3T scanner (Tim Trio, Siemens Medical Solutions, Erlangen, Germany) with a 32-channel head coil array. The analysis of the fMRI InI data used the General Linear Model with the finite impulse response (FIR) basis function. The averaged time courses within visual and motor ROIs were normalized between [0 1].

RESULTS

The spatiotemporal VIPGen reconstruction shows that the localization is comparable to the eigenspace L1 norm (Eig L1 in the figure) beamformer. Both VIPGen and the eigenspace L1 norm beamformer methods offer a higher spatial resolution than LCMV beamformer. The figure below right shows the average BOLD responses within visual and motor area ROIs. It clearly demonstrates that VIPGen can also provide correct reconstruction temporally with high statistical values.

DISCUSSION

The source localization reconstructed by VIPGen matched our previous eigenspace L1 norm beamformer analysis [5]. The average BOLD responses across subjects from two cortical areas are consistent with the causal sequence in our visuomotor experimental design. Applying VIPGen to other functional brain imaging such as magnetoencephalography (MEG) may have high spatial resolution and/or reduced computational load. In the future, we will quantify VIPGen spatiotemporal performance by simulations and compare it with other source localization algorithms on both fMRI InI and MEG measurements.

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