Sensitivity and Localization Reliability Analysis for Spectral Localization by Multichannel Coils

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Introduction: A spectral localization technique for in vivo magnetic resonance spectroscopy using a multichannel receiver coil has been previously reported (1). Similar to SLIM (2), structural information extracted from anatomical imaging is utilized by the proposed technique to define compartments which provide the basis for spectral localization. Different from SLIM, inherent spatial heterogeneity of multiple receiver coil elements is used to resolve signals from different compartments. Optional phase encoding gradients can be added to enhance localization. The proposed technique allows a few compartmental spectra to be reconstructed from multichannel data acquired with no or very few phase encoding steps. In this work, a sensitivity parameter, a spatial response function (SRF), and a localization parameter are defined to compare the sensitivity and localization reliability between the proposed technique and SLIM.

Theory: Based on anatomical images and other *a priori* knowledge, the subject can be divided into N compartments, each of which is assumed to have a spatially uniform magnetization vector $C_n(t)$ (n = 1, 2,…, N). The FID with P data points detected by each coil m (m = 1, 2, …, M) at each phase encoding step h (h = 1, 2, …, H) is the sum of signal contributions from the N compartments according to $\boldsymbol{D} = \tilde{\boldsymbol{S}}\boldsymbol{C}$, where $\boldsymbol{D}$, $\tilde{\boldsymbol{S}}$, and $\boldsymbol{C}$ are matrices for the detected FIDs ($MH \times P$), integrated sensitivity matrix ($MH \times N$), and compartmental FIDs ($N \times P$), respectively. The elements of $\tilde{\boldsymbol{S}}$ are given by $\tilde{S}_{(m,h),n} = \int_{\text{compartment } n} s_m(\boldsymbol{r})\exp(-i2\pi\boldsymbol{k}_h\bullet\boldsymbol{r})\, d^3\boldsymbol{r}$, with $s_m(\boldsymbol{r})$ being the sensitivity of the mth coil element at location $\boldsymbol{r}$ and $\boldsymbol{k}_h$ the k-vector due to the hth phase encoding gradient. Matrix $\boldsymbol{C}$ can be resolved using weighted least square according to $\boldsymbol{C} = \tilde{\boldsymbol{F}}\boldsymbol{D}$, where the unfolding matrix $\tilde{\boldsymbol{F}}$ is given by $\tilde{\boldsymbol{F}} = (\tilde{\boldsymbol{S}}^\dagger\tilde{\boldsymbol{\Psi}}^{-1}\tilde{\boldsymbol{S}})^{-1}\tilde{\boldsymbol{S}}^\dagger\tilde{\boldsymbol{\Psi}}^{-1}$. The operator '$\dagger$' denotes conjugate transpose and $\tilde{\boldsymbol{\Psi}}$ is defined as $\tilde{\boldsymbol{\Psi}} = \boldsymbol{I_H} \otimes \boldsymbol{\Psi}$, where $\boldsymbol{I_H}$ is an $H \times H$ identity matrix, '$\otimes$' denotes tensor product, and $\boldsymbol{\Psi}$ is the noise covariance matrix of the coil elements.

In order to evaluate signal-to-noise (SNR) performance, a sensitivity parameter "efficiency $\mathcal{E}_n$" (3) is defined as $\mathcal{E}_n = SNR_n^{\text{actual}} / SNR_n^{\text{ideal}}$, where SNR_n^{actual} is the SNR of the nth compartment when the compartmental spectra are reconstructed using the proposed method; SNR_n^{ideal} is the best-possible SNR of the nth compartment, which is computed as if the nth compartment was isolated from the rest of the sample and its entire magnetization was detected by the multi-element coil in H acquisitions without any phase encoding. Similar to the derivation of the SNR ratio in SENSE (4), efficiency $\mathcal{E}_n$ is found to be $\mathcal{E}_n = 1/\sqrt{[(\tilde{\boldsymbol{S}}^\dagger\tilde{\boldsymbol{\Psi}}^{-1}\tilde{\boldsymbol{S}})^{-1}]_{n,n}(\boldsymbol{S}^\dagger\boldsymbol{\Psi}^{-1}\boldsymbol{S})_{n,n}H}$, where $[(\tilde{\boldsymbol{S}}^\dagger\tilde{\boldsymbol{\Psi}}^{-1}\tilde{\boldsymbol{S}})^{-1}]_{n,n}$ is the actual noise variance and $(\boldsymbol{S}^\dagger\boldsymbol{\Psi}^{-1}\boldsymbol{S})_{n,n}$ is the inverse of the ideal noise variance with H = 1. Matrix $\boldsymbol{S}$ is the integrated sensitivity matrix without phase encoding gradients, whose elements are given by $S_{mn} = \int_{\text{compartment n}} s_m(\boldsymbol{r})\, d^3\boldsymbol{r}$. As described in Refs (3) and (5), a "spatial response function (SRF)" can be used to better understand the mechanism of localization. The SRF for each compartment describes how each point in space contributes in magnitude and phase to the reconstructed compartmental spectrum. The SRF for the nth compartment is defined as $SRF_n(\boldsymbol{r}) = \sum_{m=1}^{M}\sum_{h=1}^{H}\tilde{F}_{n,(m,h)}\, s_m(\boldsymbol{r})\exp(-i2\pi\boldsymbol{k}_h\bullet\boldsymbol{r})$. The signal contribution of compartment j to the spectrum of compartment n is computed as the integral of $SRF_n(\boldsymbol{r})$ inside compartment j, which can be proved to be $\delta_{n,j}$ with δ denoting the Kronecker delta function. This means that contamination-free localization is achieved under the assumption of uniform compartments. In practice, however, this assumption is often violated to some degree. As a result, a localization that heavily depends on SRF signal cancellation outside the compartment of interest could be unreliable. A more robust localization will be achieved if the SRF has a low intensity outside the compartment of interest. A parameter for gauging the reliability of localization is defined as (3) $\mathcal{O}_n = \int_{\text{outside compartment } n} |SRF_n(\boldsymbol{r})|\, d^3\boldsymbol{r}$.

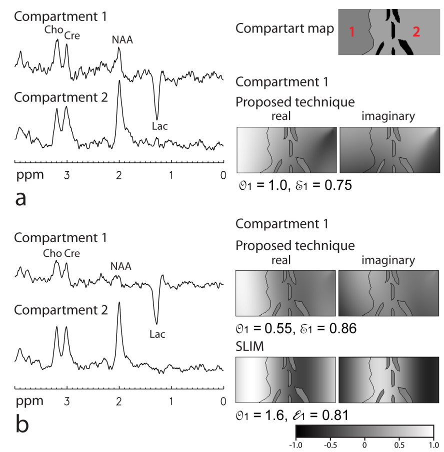

Fig. 1. a: Compartmental spectra and SRF maps reconstructed from single-shot data using the proposed technique. Scan time = 2 s. **b:** Compartmental spectra reconstructed from 2×1 k-space data using the proposed technique, as well as SRF maps of compartment 1 computed using both the proposed technique and SLIM. Scan time = 4 s.

Method and Results: The compartmental map shown in Fig. 1 was obtained using a region growing process based on a diffusion weighted image (1). Compartment 1 and 2 contain ischemic brain tissue and normal brain tissue, respectively. The PRESS CSI (TR = 2 s, TE = 144 ms, VOI = 11 x 5 x 1.4 cm^3, phase encoding matrix = 11 x 5) data (1) were reprocessed in this work, taking into account the actual noise covariance matrix. The compartmental spectra and SRF maps shown in Fig. 1a were computed using only the dc-component of the CSI data, which were equivalent to those of a 2 s single-shot PRESS spectroscopic scan. The localization parameter and efficiency for compartment 1 were found to be $\mathcal{O}_1$ = 1.0 and $\mathcal{E}_1$ = 0.75. SLIM did not work using this single-shot data because two unknown spectra could not be resolved from only one equation. The same compartment boundary definition was used in computing compartmental spectra and SRF maps shown in Fig. 1b. Two k-space data points (k_x = 0, 1/11 cm^{-1}, k_y = 0) were used in the reconstruction and the equivalent scan time was 4 s. The localization parameter and efficiency for compartment 1 were found to be $\mathcal{O}_1$ = 0.55 and $\mathcal{E}_1$ = 0.86. SLIM would also work for this phase encoding scheme. The SLIM SRF maps were computed according to Ref. (3). The localization parameter and efficiency for compartment 1 using SLIM were found to be $\mathcal{O}_1$ = 1.6 and $\mathcal{E}_1$ = 0.81. Although the efficiency of the proposed technique is only slightly higher than that of SLIM, the actual SNR performance of the proposed technique can be several times higher than that of SLIM. For the proposed technique, $\mathcal{E}$ is defined to be 1 when the compartment of interest is isolated from the rest of the sample and its entire magnetization is detected by a multi-element receiver coil. For SLIM, $\mathcal{E}$ is defined to be 1 when the compartment of interest is isolated from the rest of the sample and its entire magnetization is detected by a single-element coil. Because the spatially averaged SNR performance of a well-designed multi-element coil can be several times higher than that of a single-element coil (6), $\mathcal{E}$ = 1 for the proposed technique represents a much higher spatially averaged SNR performance than $\mathcal{E}$ = 1 for SLIM. In terms of localization reliability, the proposed technique ($\mathcal{O}_1$ = 0.55) is more reliable than SLIM ($\mathcal{O}_1$ = 1.6).

Discussion and Conclusions: The proposed technique is designed to be used with a multi-element receiver coil, which makes it possible to reconstruct compartmental spectra from a single-shot scan or a scan with reduced phase encoding steps. Because the spatially averaged sensitivity of a multi-element receiver coil can be much higher that of a single-element coil, the actual SNR performance of the proposed technique can be much higher than that of SLIM when similar phase encoding schemes are used. Localization reliability can also be improved using the proposed technique when the compartment sizes are relatively large compared to the size of the coils.

References: 1. An L, *et al.*, Proc ISMRM 2010;18:25. 2. Hu XP, *et al.*, MRM 1988;8(3):314-322. 3. Vonkienlin M, *et al.*, JMR 1991:94(2):268-287. 4. Pruessmann KP, *et al.*, MRM 1999;42: 952-962. 5. Dydak U, *et al.*, MRM 2001;46(4):713-722. 6. de Zwart JA, *et al.*, MRM 2002;47(6):1218-1227.