Optimized Combination of Magnetic Resonance Spectroscopy Signal from Multi-Element Coil Arrays

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Target audience: Scientists who involve in the research and application of magnetic resonance spectroscopy (MRS).

Purpose

In recent years, the use of multi-element coil arrays in magnetic resonance spectroscopy (MRS) has become increasingly popular. A few methods have been developed for combining MRS data from multi-element coil array [1-3]. Most of the reported methods are to form a weighted linear combination of the spectral or free induction decay (FID) data that ensure constructive addition of signals with maximized signal-to-noise ratio (SNR). The recently published approach, called "weighting with the ratio of signal to the square of the noise", i.e., S/N^2, represents the theoretical optimal combination if the noise is uncorrelated among different coil elements [1]. However, although a multi-element coil array is designed with minimal mutual coupling, residual noise correlation between coil elements is not uncommonly seen in practice. In this scenario, detrimental effects on the SNR will be observed if the method, weighting with S/N^2, or other existing traditional methods are applied. Therefore, we developed a new method for optimized combination no matter the noise is correlated or uncorrelated among different coil elements and performed validation experiments with different voxel locations/sizes on a 3T MRI scanner with an 8-element head coil. The experiments can be performed at higher field strengths and with larger numbers of coil elements but beyond the scope of this report.

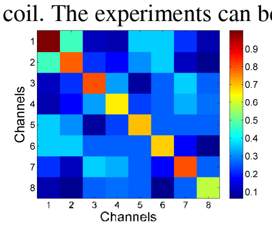

Fig. 1 Noise correlation matrix of the 8-element coil

Methods

Theory. Spectroscopic data received on multi-element coil array can be expressed as $\boldsymbol{Y}=\boldsymbol{bX}+\boldsymbol{N}$, where $\boldsymbol{Y}$ and $\boldsymbol{N}$ are $M\times P$ matrices with M being the total number of coil elements and P being the number of sampled points, $\boldsymbol{N}$ represents the noise contribution and $\boldsymbol{X}$ is a $1\times P$ vector denoting spectral signal from the voxel, $\boldsymbol{b}$ is a $M\times 1$ vector corresponding to the element/channel sensitivity. The combined spectral data can be modeled as $\boldsymbol{Z}=\boldsymbol{w}^{\mathrm{H}}\boldsymbol{Y}$, where $\boldsymbol{w}$ is a $M\times 1$ complex weighting vector, and H denotes conjugate-transpose. Thus, SNR can be calculated with $SNR=\boldsymbol{w}^{\mathrm{H}}\boldsymbol{R}_S\boldsymbol{w}/\boldsymbol{w}^{\mathrm{H}}\boldsymbol{R}_N\boldsymbol{w}$, where $\boldsymbol{R}_S=\left(\boldsymbol{XX}^{\mathrm{H}}\right)\boldsymbol{bb}^{\mathrm{H}}$ is the signal correlation matrix, $\boldsymbol{R}_N=\boldsymbol{NN}^{\mathrm{H}}$ is the noise correlation matrix. To maximize SNR using the weighting vector $\boldsymbol{w}$, the Lagrangian multiplier method is employed, i.e., $L(\boldsymbol{w})=\boldsymbol{w}^{\mathrm{H}}\boldsymbol{R}_S\boldsymbol{w}+\lambda(\boldsymbol{I}-\boldsymbol{w}^{\mathrm{H}}\boldsymbol{R}_N\boldsymbol{w})$, the differential with respect to $\boldsymbol{w}^*$ (* denotes conjugate) is to produce $\partial L(\boldsymbol{w})/\partial\boldsymbol{w}^*=\boldsymbol{R}_S\boldsymbol{w}-\lambda\boldsymbol{R}_N\boldsymbol{w}=\boldsymbol{0}\Rightarrow\boldsymbol{R}_S\boldsymbol{w}=\lambda\boldsymbol{R}_N\boldsymbol{w}$. Substituting $\boldsymbol{R}_S$ gives $\boldsymbol{w}=\alpha\boldsymbol{R}_N^{-1}\boldsymbol{b}$, where α is a scalar defined as $\lambda^{-1}\boldsymbol{b}^{\mathrm{H}}\boldsymbol{w}\left(\boldsymbol{XX}^{\mathrm{H}}\right)$. Because the strongest signal received on each element/channel is nearly proportional to the coil sensitivity of the respective element/channel, the unsuppressed water peak was selected as the reference for computing the coil sensitivity of each element in this report, i.e., $\boldsymbol{b}=\boldsymbol{S}/\beta$, where $\boldsymbol{S}$ is a $M\times 1$ complex vector associated with the unsuppressed water peaks, β is a constant scalar. Ignoring the universal scalar α/β, the final weighting vector is given by $\boldsymbol{w}=\boldsymbol{R}_N^{-1}\boldsymbol{S}$. In the scenario that the noise is uncorrelated, $\boldsymbol{R}_N$ is reduced to a diagonal matrix and the weighting is equivalent to S/N^2, a method as recently reported in NeuroImage [1].

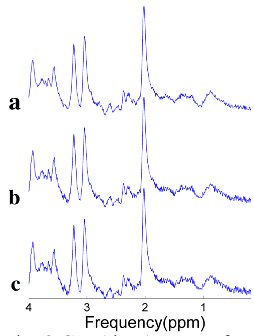

Fig. 2 Combined spectra from ACC with (a) the proposed weighting with $\boldsymbol{R}_N^{-1}\boldsymbol{S}$, (b) weighting with S/N^2, and (c) traditional equal weighting

Data Acquisition. The data acquisition was performed on two volunteers and written informed consent was obtained from each subject in the IRB-approved study. ^{1}H-MRS scans were acquired on a Philips Achieva 3T scanner with an 8-element phased-array head coil. A single-voxel PRESS sequence (TR/TE=3000/35ms) was applied. Each ^{1}H-MRS scan included 128 averages with a 16-step phase cycling. Unsuppressed water signal was acquired at the beginning for eddy current correction and scaling. The MRS voxels were placed in rostral anterior cingulate cortex (ACC) (2×2×2 cm^3), left and right dorsolateral frontal white matter (FWM) (2×1×2 cm^3), and a subcortical region encompassing the head of left caudate nucleus (Caud) (1×2×2 cm^3).

Data Processing. The individual spectroscopic data from each element were first averaged within each phase cycle before the averaged spectra from each phase cycle were aligned in phase and averaged through different phase cycles. And then eddy current correction was applied using unsuppressed water signal. Finally the data on each individual element were combined using three different weighting methods: equal weighing (as used on most of current MRI scanner platforms), weighting with S/N^2, and weighting with $\boldsymbol{R}_N^{-1}\boldsymbol{S}$ as proposed in this study. The SNRs of the resulted spectra were calculated based on the amplitude of the NAA peak divided by the noise level determined from the root mean square (RMS) of the first and last 120 data points in the resulted spectra, which were largely free of any spectral signal.

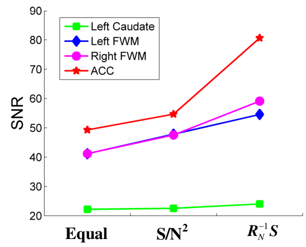

Fig. 3. SNR of spectra using three combination methods

Results

Noise Correlation. Fig.1 shows a noise correlation matrix of the 8-element head coil. Although the largest correlation coefficients are still on the diagonal, some off-diagonal values are nonnegligible, which justifies the need to use the whole noise correlation matrix in the weighting factors rather than the diagonal noise autocorrelation coefficients as used in weighting with S/N^2.

Spectral Quality. Fig. 2 demonstrates the spectra acquired from ACC on one subject using three different combination methods: equal weighting, weighting with S/N^2, and our proposed weighting with $\boldsymbol{R}_N^{-1}\boldsymbol{S}$. It shows that our proposed weighting method yielded a better SNR that would potentially improve the quantification of metabolites, especially those with low concentrations or low MRS sensitivity.

Quantized SNR. Fig. 3 shows SNRs of the spectra obtained using three combination methods from four different voxels. Compared with the other two methods, the proposed new weighting method significantly improved SNR across four voxels with different locations and sizes.

Discussion and Conclusion

The proposed method represents the theoretical optimal combination of spectroscopic signal from multi-element coil arrays, no matter the noise is correlated or uncorrelated among the different coil elements.

References [1]. Hall EL, Stephenson MC, Price D, *et al*. Methodology for improved detection of low concentration metabolites in MRS: optimised combination of signals from multi-element coil arrays. NeuroImage 2014; 86: 35-42. [2]. Martini N, Santarelli MF, Giovannetti G, *et al*. Noise correlations and SNR in phased-array MRS. NMR in Biomedicine 2010; 23(1): 66-73. [3]. Rodgers CT and Robson MD. Receive array magnetic resonance spectroscopy: Whitened singular value decomposition (WSVD) gives optimal Bayesian solution. Magn Reson Med 2010; 63(4): 881-891.