High-Speed Volumetric Proton Echo Planar Spectroscopic Imaging (PEPSI) with RF Sensitivity Encoding Along Two Spatial Dimensions

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INTRODUCTION: Proton Echo Planar Spectroscopic Imaging (PEPSI) [1] provides fast spatial-spectral encoding with a minimum scan time of 64 seconds for a 32x32 spatial matrix at TR: 2 sec. However, 3D is still very time consuming due to phase encoding (PE) in the third dimension. Sensitivity encoding (SENSE) [2-3] has been demonstrated to accelerate the encoding process using multiple RF coils with specific spatial sensitivity functions for parallel acquisition. We have recently introduced the combination of PEPSI with SENSE acceleration in one spatial dimension [4]. SENSE along two spatial dimensions (2D-SENSE) provides more robust reconstruction compared to 1D-SENSE when using the same acceleration factor due to reduced amplification of the g-factor [5], and enables higher overall acceleration factor. In this study we demonstrate feasibility and initial results of very high-speed 3D spectroscopic imaging using a combination of PEPSI and 2D-SENSE.

METHODS: PEPSI data were acquired on healthy volunteers using a 4 Tesla Bruker MedSpec scanner equipped with 8-channel circular surface array coil. Complete 8-slice outer volume suppression (OVS) was applied along the perimeter of the brain. Data acquisition includes water suppressed (WS) and non water suppressed (NWS) scans. A second NWS scan with much shorter readout duration and TR (500 msec) was acquired to estimate coil sensitivity maps. A trapezoidal readout gradient encoded simultaneously one spatial axis and the spectral time domain (t). The first 3D data set (A) was acquired in axial orientation using a 32x32x8 spatial matrix to reconstruct 8 axial slices (FOV: 320x320x80 [mm]). The readout direction was right-left (RL) and PE directions were anterior-posterior (AP) and foot-head (FH). Fully sampled data were acquired in 8.5 min using TR= 2 sec, TE= 15 msec .Acceleration was simulated by decimating the NWS and WS k-space data along the x and y directions. A second 3D data set (B) was acquired with a 32x32x16 spatial matrix in sagittal orientation to reconstruct 32 axial slices (FOV: 220x220x160 [mm]). The readout direction was FH, and PE directions were AP and RL. Fully sampled data were acquired in 17 min with TR= 2 sec, TE= 50 msec .Up to 9-fold acceleration (3-fold in both RL and AP directions) was simulated by decimating both the NWS and the WS k-space data along PE directions. Raw data was filtered in k-space with a 3D Hamming window.

2D-SENSE unfolding [5] was applied to each time point of the accelerated even and odd echo data separately (**Fig. 1**). Coil sensitivity maps ($\mathbf{C}_e(\mathbf{r})$ for even echoes and $\mathbf{C}_o(\mathbf{r})$ for odd echoes) were estimated using spectral water images obtained from the second NWS scan. A 3rd order polynomial fitting was used to refine the sensitivity maps [2]. After SENSE unfolding of the decimated NWS and WS data, coil-by-coil PEPSI reconstruction [6] was performed, where each channel was separately phased and aligned using the corresponding unfolded NWS data set for coherent combination.

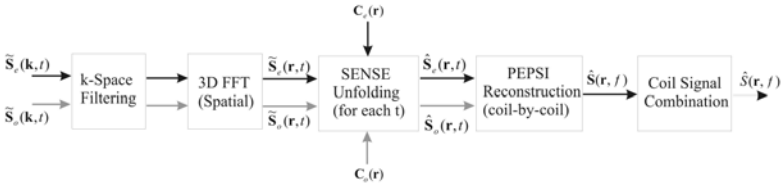

Fig. 1: 3D PEPSI-SENSE reconstruction diagram.

The resulting multi-coil signal $\hat{\mathbf{S}}(\mathbf{r}, f)$ was combined using a weighted-average where the signal from each coil is weighted according to sensitivity of that coil. Metabolite images were obtained from spectral fitting using LCModel [7].

RESULTS: For the simulated acceleration in scan A along two spatial dimensions, 2D-SENSE reconstruction was able to achieve higher accelerations than 1D-SENSE, as expected. Spectral fitting results with 4-fold acceleration were very similar to the weighted average reconstruction of the non-accelerated data. 6-fold acceleration was feasible with only minor reduction in reconstruction performance in peripheral regions. To quantify the error of the reconstruction we used the Cramer-Rao Lower Bound (CRLB) of the concentration estimates averaged over each slice. As expected, the accuracy of the spectral fitting decreased with higher accelerations, due to the decreased SNR [2-3]. The increase in mean CRLB was acceptable until 6-fold acceleration, beyond which reconstruction errors increased substantially. 2D-SENSE reconstruction results in slightly broader spectral lines (Fig. 3). NAA concentrations values averaged across each slice in accelerated data sets were similar to those obtained in fully sampled data sets. Feasibility of even faster acceleration in the axial plane was shown with scan B, using 3-fold acceleration along the AP direction and 2.67-fold acceleration along the RL axis. This 8-fold acceleration corresponds to a scan time reduction from 17 min to approximately 2 minutes. (Fig. 4). However, the limited number of OVS slices required sacrificing extensive peripheral cortical regions to control lipid bleeding.

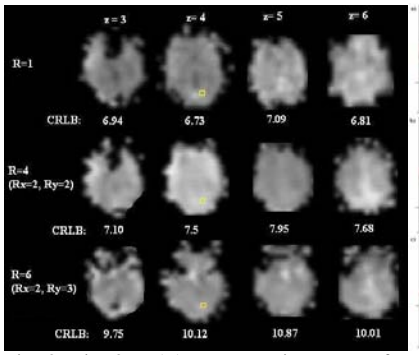

Fig. 2: Fig. 2: NAA concentration maps of the central 4 slices (left-right) from scan A at different accelerations: R=1 (fully sampled), 4 and 6. Threshold: CRLB≤25%.

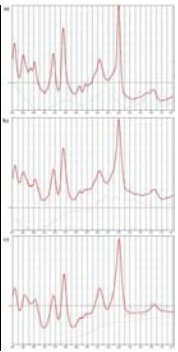

Figure 3: Examples of spectra. The voxel location is indicated in Fig. 2.

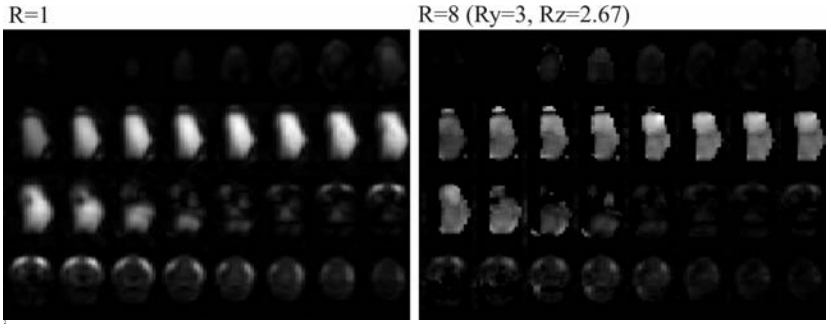

Fig. 4: Spectral water images from scan B corresponding to 32 axial slices with in-plane matrix dimensions 16x32 (FOV: 160x220). Two-dimensional 8-fold acceleration (Ry=3, Rx=2.67) results in similar localization, with slight enhancement of residual signals in peripheral regions. The SNR decreased from 69:1 to 21:1 when comparing un-accelerated and accelerated acquisitions. The corresponding scan time reduces from 17 to 2.125 min .

DISCUSSION: This work demonstrates feasibility of combining PEPSI and SENSE along two dimensions for ultra-fast 3D spectroscopic imaging. The high SNR at high field will enable 3D scanning of major metabolite resonances in just a few minutes [8]. However, in order to take advantage of the high acceleration factor it is necessary to design time-efficient reference scans for coil sensitivity mapping that preserve the contrast and phase characteristics of a fully relaxed NWS scan. Moreover, larger number of OVS slices, automatic positioning of OVS slices and improved shim algorithms are required to achieve adequate volume coverage. The amplification of the g-factor limits the performance of the technique when using a circular 8-channel array coil. In future studies, we are planning to use array coils with much larger number of array elements to achieve even higher accelerations and to obtain more flexibility in choosing the axes for acceleration.

ACKNOWLEDGEMENTS: Supported by NIDA 1 R01 DA14178-0 and the MIND Institute - DOE Grant No. DE-FG02-99ER62764.

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