Enhanced contrast of punctuate paramagnetic structures through zero-padding

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Purpose:

Cellular MRI employing gradient recalled echo (GRE) techniques in conjunction with iron-oxide labelled (paramagnetic) cells has proven useful to visualize non-invasively biological processes on the cellular level[1]. Within this study we show that for such punctuate paramagnetic structures the positioning of the perturber relative to the imaging sampling grid has a notable impact on the signal decrease of the acquired voxel. This effect can be employed in order to boost the contrast of labeled cells if zero-padded images are reconstructed and a minimum intensity projection is calculated. Simulations and in-vitro cell phantom experiments are used to confirm our theory. The results show a remarkable gain in negative contrast for iron-oxide labelled cells.

Theory:

As an effect of the convolution with the imaging point-spread function, the magnitude of a single point like object varies depending on the relative position between the object and the discrete image sample point (max. 36% employing a 1D-sinc-PSF[2] and 74% for a 3D experiment if the point is placed half a voxel away from the voxel center in all 3 dimensions). Given a phase dispersion across the voxel caused by an punctuate magnetic dipole moment, simulations reveal that the magnitude after convolution with the corresponding imaging PSF results in an intra-voxel course comparable with a point like object. Therefore, a maximum contrast loss is observed if the perturber is displaced by half the voxel dimensions. By zero-padding, we gain a finer sampling grid in order to approach the sampling point of our signal minimum as discussed by Haake et al.[2] for the point like object.

Methods:

SIMULATIONS: Intra-voxel grid simulations are carried out as described by Lebel[3] for GRE acquisitions. A 7x7x7 voxel-volume is calculated with a discretization of 351³ sub-voxels. The resulting intra-voxel phase dispersion is convolved with the PSF corresponding to the sampling window given for the 310µm³ acquisition including off-resonant RO-displacement of the sub-voxel magnetization. MEASUREMENTS: Cells loaded with an average of 80pg Fe (SPIO: Resovist) were diluted within 0.5% agar to reach a final concentration of 10 cells/µl. Isotropic 3D GRE datasets were acquired on a 3T clinical system using a volume coil for mice. A low-res 310µm³ scan (TA~5min) with TR=11ms, α=8, TE=4.76ms, matrix=160³, 320Hz/pixel and a high-res 148µm³ scan (TA~48min) with TR= 22ms, α=12, TE=9.06ms, matrix=256³, 320Hz/pixel are performed. RECONSTRUCTION: Through zero-padding, a 4-times finer imaging grid is calculated and a minimum intensity projection of the 4x4x4 sample points corresponding to the native resolution of 310µm³ was calculated to gain the high-CNR images of the cells.

Results & Discussion:

The image magnitude (Fig. 1a) caused by the convolution of the phase dispersion with the imaging PSF show that the contrast is maximized if the imaging grid position is centered with the perturber and follows a PSF caused contrast loss if the perturber is positioned between two sample points (Fig. 1b). Simulations reveal that the gain in contrast for a perturber centered to the image-grid compared to the worst displaced case is best for small iron concentrations (Fig. 2a). This observation is of major importance since for in-vivo applications the displacement might reduce the signal decrease of small particles below the noise-dictated detection threshold. A minimum intensity projection over 4x4x4 sample points of the 4-times refined sampling grid enhances the contrast for the labeled cells remarkably (Fig. 2b). In Figure 2c a comparison between the image gained through zero-padding and a high-resolution 150µm³ GRE image is shown. Cellular contrast (yellow arrow) not visible within the original 310µm³ reconstruction but within the MIP of the 4-times zero-filled dataset is clearly depicted within the high-res scan indicating that the perturber is far displaced from the original 310µm³ grid.

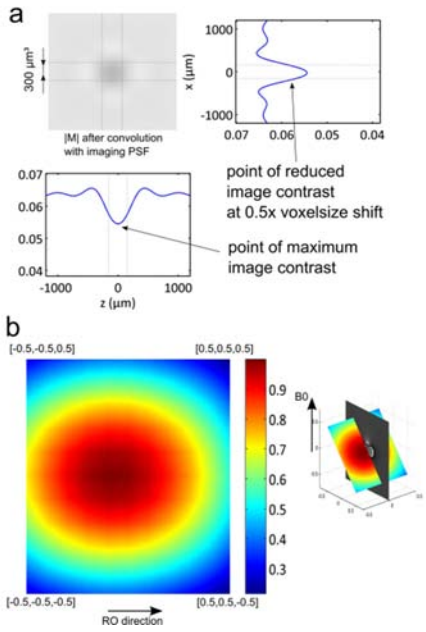

Fig.1: Signal evolution after convolution with the imaging PSF (a) shows a maximum signal decrease for a voxel centered with the perturber (50pgFe, PSF corresponding to 300µm³ sampling). (b) Shows the change in contrast for a displaced imaging grid. The plot was made diagonal through the voxel in order to catch the points of maximum contrast loss for a displacement within all 3 directions of 0.5 times the voxel dimension (blue areas).

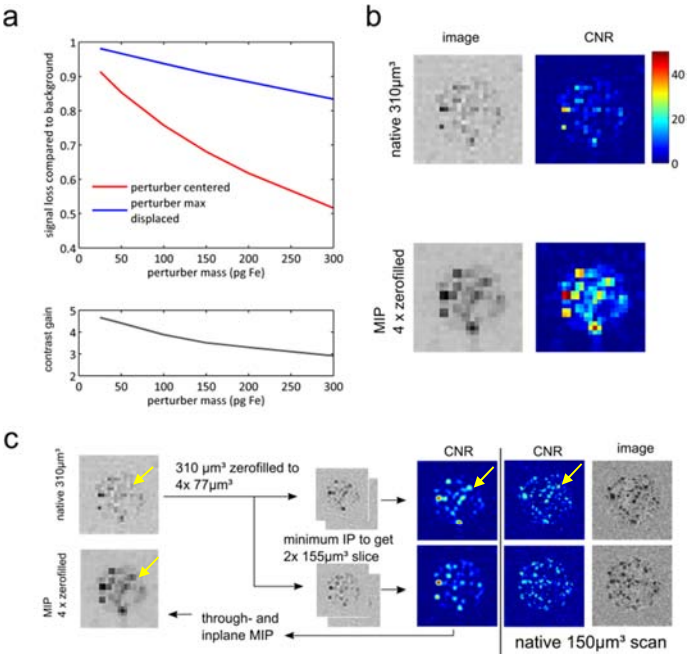

Fig.2: (a) top: original 310µm³ GRE image and CNR plot; bottom: image + CNR values after minimum intensity projection of the zero-filled refined grid showing enhanced perturber contrast. (b) Expexted simulated signal values and contrast enhancement between max. displaced and centered perturber over different perturber masses. (c) Comparison between the zero-filled MIP and a native 150µm³ scan confirms the origin of the contrast enhancement from punctuate perturbers which had not been visible with the standard 310µm³ reconstruction before (arrow).

Conclusion:

Although no further gain in image information is produced by zero-filling, additional sample points allow for the detection of the voxel signal minimum caused by paramagnetic structures. Since the proposed method is able to recover contrast of displaced punctuate perturbers not visible within the native scan before, it is an excellent tool for MRI based cell tracking.

References:

[1] Bulte J., Kraitchman D., NMR Biomed. 2004; 17:484-499; [2] Haake et al., Wiley-Liss: Magnetic Resonance Imaging (1999); [3] Lebel at al. MRM 55: 583-591 (2006);