Regularized Channel-Dependent Kernel Deconvolution for Resolution Enhancement in SEA Imaging

J. X. Ji[1], J. Son[1], M. P. McDougall[1], S. M. Wright[1]

[1]Electrical and Computer Engineering, Texas A&M University, College Station, Texas, United States

INTRODUCTION

Single Echo Acquisition (SEA) is a totally parallel imaging method that can obtain a 256x64 2-D image using only a single echo [1-3]. In doing so, it utilizes a bank of 64 or more mm-size linear phased-array elements with highly localized sensitivity. As a result, the conventional phase encoding steps are completely eliminated and the spatial localization along the phase encoding direction is achieved solely by the coil localization. Nevertheless, the spatial resolution of the SEA images is still limited by the coil sensitivity profiles, which are not completely localized to the desirable voxel size. An averaged time window method has been proposed to enhance the SEA image resolution [4]. In this work, we developed a deconvolution method for resolution enhancement in SEA imaging. To address the highly ill-conditioning problem, Tikhonov's regularization is adopted to constrain the deconvolution process. Preliminary computer simulation results using data collected from a 4.7 Tesla scanner show that the new method can achieve super resolution when appropriate channel sensitivity is available.

METHODS

The SEA image is formed by stacking a sequence of 1-D images together, each from one channel by inverse Fourier transform of a single k-space line acquired. Since the localization along the frequency encoding direction can be solved by the 1-D Fourier transform, deconvolution is applied along the phase encoding direction, *y*, only. Denote $d(m), m = 1,2,...,M$ as the image point from the M channels at a particular x coordinate. According to the MR physics,

$$d(m) = \int_{object} I(y) S_m(y) e^{j\theta(y)} e^{j\phi_m(y)} dy \tag{1}$$

where $I(y)$ is the image object, $S_m(y)$ is the spatial sensitivity function of the *m*-th coil, $\theta(y)$ is the phase induced by the gradient, and $\phi_m(y)$ is a coil-dependent phase term due to the wavelength effect and electronics delay. Since the coil sensitivity functions vary from channel to channel (see Fig. 2), conventional deconvolution technique using a space-invariant kernel is not effective. In this work, we discretize Eq. (1) with a step size equal to the distance between adjacent coils, which results in a linear approximation, i.e., $d(m) \approx \Delta \sum_{m=1}^{M} E_m(m\Delta) I(m\Delta)$ where E_m incorporates both the coil sensitivity and other phase factors. Note that this is a forward discrete convolution with a channel-dependent kernel function. Utilizing this approximation formula from all channels, a linear model similar to SENSE equation can be formed as $\mathbf{d} = \mathbf{EI}$, from which the image function can be obtained in principle by simple matrix inversion. Note that the convolution matrix $\mathbf{E}$ is usually very ill-conditioned and deconvolution by direct matrix inversion or pseudo inversion amplifies the data noise making the final image not useful. In this work, we adopt a Tikhonov regularization scheme to address this problem. With this scheme, the deconvolution solution becomes

$$\hat{\mathbf{I}} = \mathbf{P} + (\mathbf{E}^H \mathbf{R}^{-1} \mathbf{E})^{-1} \mathbf{E}^H \mathbf{R}^{-1} (\mathbf{d} - \mathbf{EP})$$

where $\mathbf{P}$ is a regularization image and $\mathbf{R}$ is the channel correlation matrix. The matrix inversion $(\mathbf{E}^H \mathbf{R}^{-1} \mathbf{E})^{-1}$ here is performed by singular value decomposition truncation where the eigen values smaller than 5% of the maximal eigen value of the matrix are eliminated.

RESULTS AND DISCUSSION

A phantom was scanned using a 33cm-bore 4.7 Tesla Bruker scanner using a 64-channel SEA imaging system and a spin-echo sequence. The acquisition parameters are: TR = 500 ms, TE = 20 ms, bandwidth = 50 kHz, slice thickness = 2 mm, and matrix size = 256 x 256. A high-resolution sums-of-square image is shown in Fig. 1(a). The 141-th k-space line was used to simulate a SEA image shown in Fig. 1(b). The deconvolution was applied to improve the resolution. To do so, the central 256x64 data were extracted and complex Gaussian noise were added to make average SNR=10 dB. This data was Fourier transformed to estimate the $\mathbf{E}$ matrix. The kernel matrix $\mathbf{E}$ is partially shown in Fig. (2) (magnitude only). Then the root-mean-sum-of-squares image of the low resolution images is used to make the regularization image. Deconvolution results from direct matrix inversion in Fig. 3(a) shows significant artifact due to ill condition and noise. The enhanced image using the regularized deconvolution is shown in Fig. 3(b), which has better SNR and improved resolution. These preliminary results show it is feasible to use regularized deconvolution to improve the SEA image resolution given the prior information of the channel sensitivity. Further development of the algorithm has the potential to improve the resolution and utility of the SEA imaging method for practical applications.

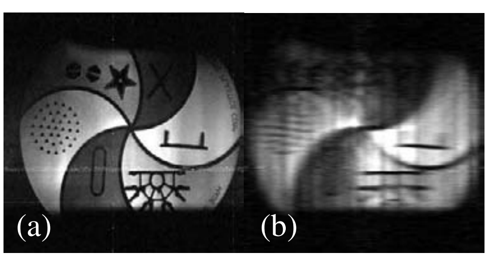

Figure 1. (a) Sum-of-squares image from 256 echoes; (b) SEA image from a single echo.

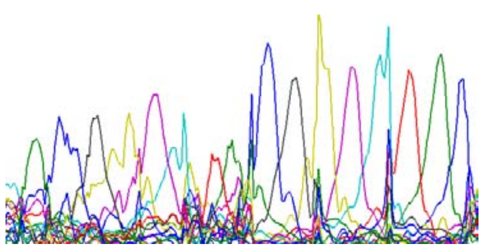

Figure 2. Sixteen of the 64 channel-dependent convolution kernels (shown magnitude only).

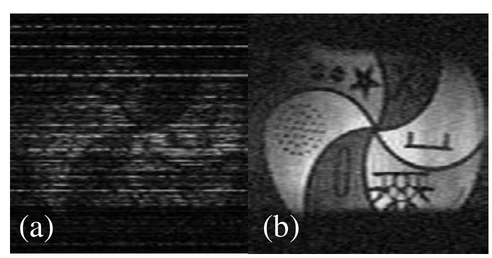

Figure 3. (a) Deconvolution using direct matrix inversion; (b) Enhanced image using the propsed method.

ACKNOWLEDGEMENTS: Support from the National Institutes of Health (1R21EB003296-01A1) is gratefully acknowledged.

REFERENCES

[1] Wright SM, et. al. EMBS 2002:23-26. [2] McDougall MP, et. al. MRM 2005; 54:386–392. [4] Wright SM, et.al. ISMRM 2003;2493. [5] Pruessmann KP, et. al. MRM 1999; 42: 952-962.