Deblurring in View angle tilting imaging

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Introduction: In MRI, numerous kinds of artifacts exist such as motion-related, metal-induced, field inhomogeneity and chemical shift artifacts. View angle tilting (VAT) technique was proposed[1] to correct chemical shift artifact and in-plane field inhomogeneity artifact. This imaging technique is integrated to EPI and metal artifact correction sequences[2] since VAT is robust against off-resonance related artifact. In spite of this advantage, VAT suffers from blurring artifact (Fig. 1(b)) due to additional G_z gradient called compensation gradient applied during readout time. VAT blurring can be reduced by adjusting imaging parameters, however, it limits the freedom of choosing imaging parameters. In this study, post-processing methods that can alleviate VAT blurring based on VAT signal equation are presented.

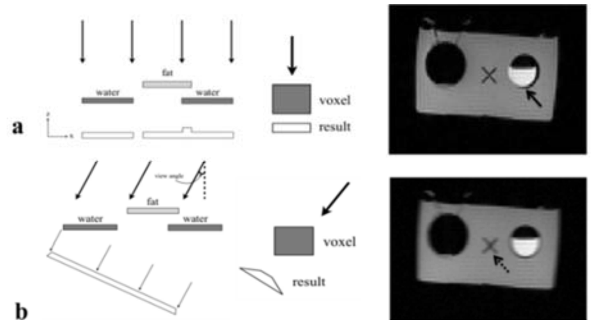

Fig. 1. Illustrations of conventional 2D MR imaging (a) and VAT imaging (b). Phantom images of each technique are shown in right column. Note that the chemical shift artifact (solid arrow) are corrected using VAT. However, the blurring effect (dotted arrow are observed, which degrade the image quality

Methods: Signal equation of VAT can be expressed as

$$S(k_x, k_y, t) = \int_{z_0-\frac{s}{2}}^{z_0+\frac{s}{2}} \iint_{x,y} m(x,y,z) \cdot e^{-j2\pi\left(x\cdot k_x(t)+y\cdot k_y+z\cdot k_z(t)\right)} dxdydz$$

$$= Sinc\left(2\pi k_x(t)\cdot R\cdot \frac{s}{2}\right)\cdot e^{-j2\pi k_x(t)\cdot R\cdot z_0}\cdot \int_{x,y} m(x,y)\cdot e^{-j2\pi\left(x\cdot k_x(t)+y\cdot k_y\right)} dxdy \quad (1)$$

where s is slice thickness, z_o is center of slice and R is G_z/G_x. The integration part along z-direction can be figured out as sinc term and exponential term[1]. Exponential term is related to the off-resonance correction in VAT by shifting off-resonance spins to its original position and sinc term is related to VAT blurring. Intuitively, deblurring of VAT image can be achieved by removing sinc term[3] in acquired VAT data according to Eq. 1.

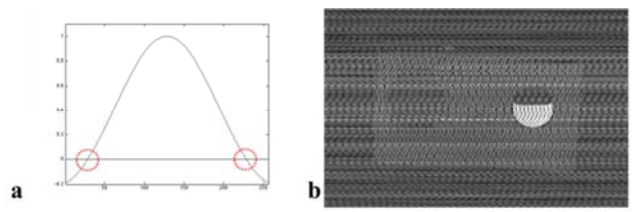

Fig. 2. **a**: VAT blurring kernel presented in Eq. 1. **b**: Deblurred image by direct demodulating of (a) to k-space data of VAT image. Zero-crossing points (dotted circles) cause ill-conditioning in k-space and significant noise amplification

Demodulation of sinc function In k-space perspective, the acquired signal is modulated by sinc function according to applied compensation gradient. Ideally, VAT blurring can be corrected (deblurred) by simply demodulating this sinc function in k-space. However, it may cause 'dividing by zero' problem since the sinc function can have zero-crossing points depending on imaging parameter. Thus, direct sinc demodulation causes noise amplification and degrades image quality significantly as in Fig. 2. To avoid this unwanted noise amplification, the part of singular-point should be modified. As a simple approach, the values near zero-crossing point are theresholded and do nothing on these points (buffered sinc). Deblurring method using buffered sinc can avoid ill-conditioned problem, however, this method does not consider the amplification of high frequency band which dominates overall noise.

Constrained least square (CLS) filter Least square minimization problem $\mathbf{min}_{\mathbf{x_d}}\|\mathbf{A}\mathbf{x}_d - \mathbf{x}_o\|^2 + \lambda\|\mathbf{R}(\mathbf{x}_d)\|^2$ is solved where $\mathbf{x}_d$ is desired deblurred image, $\mathbf{x}_o$ is acquird VAT image, $\mathbf{A}$ is sinc term in Eq. 1 as objective function, λ is a weighting factor on constraint and $\mathbf{R}(\mathbf{x}_d)$ is Laplacian of image to reduce damping noise during deblurring process. This constraint can compensate the zero-dividing problem also. However, missing data points at zero-crossings are not restored perfectly. By adjusting weighting factor λ, deblurring performance and noise amplification can be controlled. Experiments are performed on a 3T scanner (Tim Trio, Siemens Medical Solutions, Erlangen, Germany) using conventional SE and VAT sequences. The imaging parameters are TR/TE = 650.0/12.0ms, resolution = 1.0 x 1.0 mm^2, slice thickness = 2.0 mm and readout bandwidth = 780 Hz/pixel and the view angle is 34.4°.

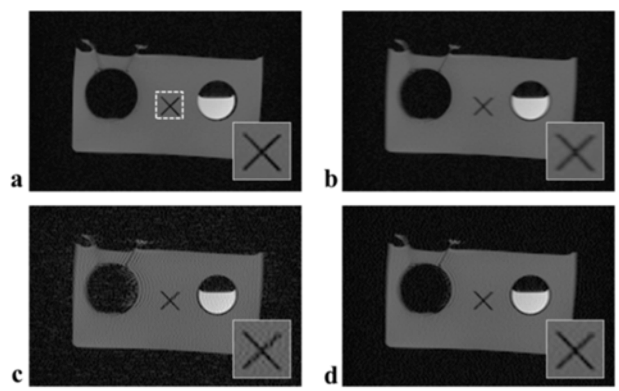

Fig. 3. **a**: Conventional 2D SE image. **b**: VAT image with 34.4° view angle. c: Deblurred image using buffered sinc function. d: Deblurred image using CLS filter. Boxed region in (a) is magnified to show the deblurring performance more effectively

Result: As shown in Fig 3, both buffered sinc and CLS filter can alleviate VAT blurring better than direct demodulation of sinc function. Between the proposed two methods, CLS filter has better performance than dividing buffered sinc function. Image quality is highly improved in the result image using CLS filter especially on the noise components. However, slight ringing artifact is observed due to missing data at sinc zero-crossing points.

Discussion and Conclusion: View angle depends on imaging parameters and zero-crossing points in sinc function is related to view angle. In few zero-crossing condition (small view angle), zero-crossing points are located at high frequency band. Since most energy is concentrated at low frequency components, missing data due to zero-modulation does not cause significant image artifact. However, when large view angle is used, blurring effect gets severe due to more zero-crossing points. Furthermore, it makes hard to remove blurrings in VAT image as well. Relatively low frequency region is vague due to zero-modulation and it considerably affects to the acquired image and deblurring procedure. If missing data is restored appropriately by estimating k-space data using other information, the better deblurring can be achieved.

Acknowledgement: This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (NRF-2012R1A2A2A01009903) **References: 1.** Cho ZH, et al., Total inhomogeneity correction including chemical shifts and susceptibility by view angle tilting. Med. Phys. 1988;15(1):7-11. **2.** Lu W, et al., SEMAC: Slice encoding for metal artifact correction in MRI. MRM 2009;62(1): 66–76, 2009. **3.** Zho S-Y, et al., Time-varying view angle tilting with spiral readout gradients. MRM 2012;68(4):1220–1227.