Diffusion Tensor Imaging with View Angle Tilting Technique for Distortion Correction

S. Ahn[1], K. Choi[1], and X. Hu[1]

[1]Biomedical Engineering, Georgia Institute of Technology and Emory University, Atlanta, GA, United States

INTRODUCTION

Image distortion caused by field inhomogeneity along the phase-encode (PE) direction is manifested in diffusion echo planar imaging (EPI) due to the long echo spacing and signal acquisition. Distortion typically causes inter-subject variance and intensity modulation, which hinders an accurate analysis of diffusion characteristics. View angle tilting (VAT) technique [1] has been used for many applications to correct distortion in the readout (RO) direction in spin echo (SE) imaging. This work describes a method for correcting in-plane image distortion along the PE direction using the VAT technique in twice-refocused [2] diffusion tensor imaging (DTI). As opposed to SE VAT imaging, the VAT gradient is applied concurrently with the PE gradient blips along the slice-select (SS) direction. Phase generated by the VAT gradient offsets an unwanted phase accumulation by field inhomogeneity which leads to the correction of image distortion.

METHODS AND MATERIALS

The EPI signal in the presence of field inhomogeneity along the PE direction can be expressed as $s(t_m,t_n)=\int_x\int_y\int_{\Delta s+\Delta z(x,y)}\rho(x,y,z)\exp(-j\gamma\Delta B(x,y)nT_{esp})\exp[-j\gamma(mG_x\Delta t_x x+nG_y t_b y)]\,dxdydz$ where, $\rho(x,y,z)$ is spin density, γ is the gyromagnetic ratio, T_{esp} is the echo spacing, t_b is the PE gradient blip duration, $\Delta z(x,y)$ is the position displacement along the SS direction given by $\Delta z(x,y)=-\Delta B(x,y)/G_z$, G_z is the SS gradient, Δs is a slice thickness, and *m* and *n* are k-space indices along RO and PE directions, respectively. By reformulating using $z=z'-B(x,y)/G_z$ and by adding the VAT gradient ($G_{vat}=G_zT_{esp}/t_b$) concurrently with the PE gradient (Fig. 1), the above equation can be rewritten as

$$s(t_m,t_n)=\int_x\int_y\int_{\Delta s}\rho(x,y,z'-\frac{\Delta B(x,y)}{G_z})\exp(-j\gamma nG_zT_{esp}z')\exp(j\gamma\frac{\Delta B(x,y)T_{esp}}{G_zt_b}nG_zt_b)]\exp\{-j\gamma[mG_x\Delta t_x x+(y+\frac{\Delta B(x,y)T_{esp}}{G_yt_b})nG_yt_b]\}\,dxdydz'$$

$$=\int_x\int_y\rho(x,y,z_0'-\frac{\Delta B(x,y)}{G_z})\exp\{-j\gamma[mG_x\Delta t_x x+nG_yt_by]\}\,dxdy\cdot\int_{\Delta s}\exp(-j\gamma nG_zT_{esp}z')\,dz'=\int_x\int_y\rho(x,y,z_0'-\frac{\Delta B(x,y)}{G_z})\exp\{-j\gamma[mG_x\Delta t_x x+nG_yt_by]\}\,dxdy\cdot\Delta s\cdot\mathrm{sinc}(\gamma n\Delta sG_zT_{esp})$$

, where an optimal tilting angle is found to be $\tan(\theta_{opt})=G_{vat}/G_y=G_zT_{esp}/(G_yt_b)$. Spin density was assumed only dependent on a position (x,y) with z_0' being a constant value at each coordinate (x,y) in deriving the above equation. Rectangle slice profile was assumed when calculating the integral of phase over the slice which produced a sinc function. The signal equation dictates that distortion is corrected at the expense of image sharpness by applying the VAT gradient. Since tilting angle in EPI is usually high enough to cause severe image blurring, VAT was performed in combination with parallel imaging. Following relationship of distortion with sequence parameters and field inhomogeneity (Fig. 2) can be inferred from the above equation.

$D_0(x,y)=\Delta y(x,y)=\frac{\gamma}{2\pi}\times T_{esp}\times FOV_y\times\Delta B(x,y)$ [3], $D_r(x,y)=\frac{D_0(x,y)}{R}[1-\frac{\tan(\theta)}{\tan(\theta_{opt})}]$, where R means an acceleration factor in parallel imaging,

D_0 is an inherent distortion, D_r is a reduced distortion by using parallel imaging and the VAT technique. Parallel imaging alone reduces distortion. However, it is unable to remove image distortion (Fig. 2). In this study, VAT of the optimal tilting angle with R=4 was investigated, which would render virtually distortion-free images. All experiments were performed on a 3 T scanner (TRIO, Siemens Medical Solution, Malvern, PA) using a 12-channel head coil. DTI with VAT was performed on a human head with 2.5x2.5x2.5 mm resolution, 2488 Hz/pixel receiver bandwidth, 2 averages, GRAPPA (R=1 and 4), VAT with R=4 ($\theta=\theta_{opt}=69.3^0$), and b= 1000 s/mm^2. Diffusion weighting was isotropically distributed in 30 directions. Diffusion data underwent brain extraction and eddy current correction using FSL (http://www.fmrib.ox.ac.uk/fsl) toolbox. To evaluate the performance of DTI with VAT, deterministic fiber tractography (TrackVis, FACT algorithm, http://trackvis.org) was calculated for three acquisitions (R=1, 4, and VAT with R=4).

RESULTS AND DISCUSSIONS

Figure 3a-c show b_0 images from three acquisitions overlaid onto an undistorted T_1 contour image. Fig 3a shows a significant image distortion as usually observed in DTI studies. Fig. 3b shows the reduction of distortion due to the shortening of the effective echo spacing of parallel imaging. When VAT was applied, distortion was effectively corrected (the regions of anterior corona radiata and optic tract indicated by yellow arrows). In addition to the comparison of b_0 images, deterministic tractography calculated from VAT imaging shows the improvement of track reconstruction in terms of track length and strength (bottom images of Fig. 3) which may be attributed to the correction of image distortion by VAT. Tilting angle used in this study was somewhat high (69.3^0) which caused image blurring. Blurring is trade-off with distortion correction as shown in Fig. 2. Distortion correction using the VAT technique is based on the assumption of homogeneous field across the slice which is not always the case in vivo. Therefore, in vivo DTI VAT imaging may not always provide the optimal correction of distortion, which depends on anatomical regions and slice orientation. However, the application of VAT to diffusion EPI is expected to benefit the correction of distortion and consequently, more accurate diffusion analysis since diffusion EPI typically suffers significant image distortion.

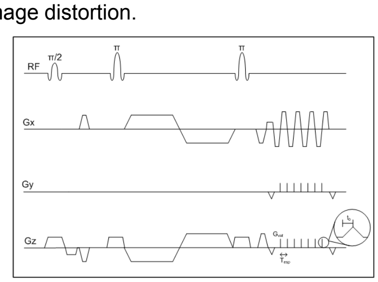

Figure 1. Sequence diagram of twice-refocused DTI with VAT

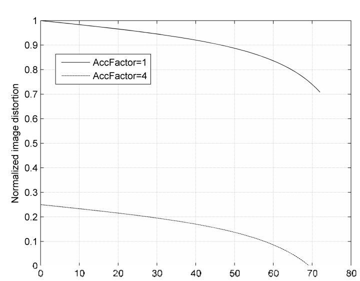

Figure 2. Relationship of distortion with sequence parameters in EPI

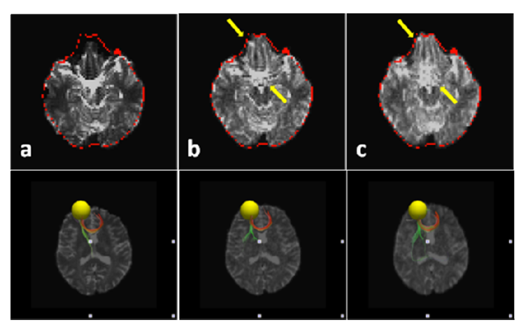

Figure 3. Top: b_0 images overlaid onto a T_1 image (red contour). (a) R=1 (b) R=4 (c) VAT with R=4. Bottom: deterministic fiber tractography. From left to right, R=1, R=4, and VAT with R=4.

REFERENCES

[1] Med Phys 1988:15(1):7-11. [2] MRM 2003:49:177-182.
[3] X. Liu 2009 Dissertation, U. Rochester, p33