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Journal Title: Magnetic Resonance in Medicine
Volume: Volume 68, Number 4
Publisher: Wiley | 2012-10-01, Pages 1211-1219
Type of Work: Article | Post-print: After Peer Review
Publisher DOI: 10.1002/mrm.23320
Permanent URL: https://pid.emory.edu/ark:/25593/trhn9

Final published version: http://dx.doi.org/10.1002/mrm.23320

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Accessed January 11, 2021 6:49 AM EST
View Angle Tilting Echo Planar Imaging for Distortion Correction

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Abstract

Geometric distortion caused by field inhomogeneity along the phase-encode (PE) direction is one of the most prominent artifacts due to a relatively low effective bandwidth along that direction in magnetic resonance echo planar imaging (EPI). This work describes a method for correcting in-plane image distortion along the PE direction using a view angle tilting (VAT) imaging technique in spin-echo EPI (SE-EPI). SE-EPI with VAT (SE-EPI-VAT) utilizes the addition of gradient blips along the slice-select (SS) direction, concurrently applied with the PE gradient blips, producing an additional phase. This phase effectively offsets an unwanted phase accumulation caused by field inhomogeneity, resulting in the removal of image distortion along the PE direction. The proposed method is simple and straightforward both in implementation and application with no scan time penalty. Therefore, it is readily applicable on commercial scanners without having any customized post-processing. The efficacy of the SE-EPI-VAT technique in the correction of image distortion is demonstrated in phantom and in vivo brain imaging.

Keywords

- echo planar imaging
- distortion correction
- field inhomogeneity
- view angle tilting

INTRODUCTION

Echo planar imaging (EPI) (1) has been widely used for decades for many magnetic resonance imaging applications due to its fast image acquisition. However, the quality of EPI is typically degraded by artifacts caused by off-resonance effects including static field inhomogeneity, susceptibility-induced field inhomogeneity, chemical shift, and eddy currents. In EPI, distortion caused by field inhomogeneity and chemical shift occurs predominantly along the phase-encode (PE) direction due to its low effective bandwidth and long data acquisition window (2,3).

Distortion correction in EPI has been an active research area due to its importance in improving image quality over the years and many useful schemes have been proposed. One well-known approach is to measure a field map and correct an image according to the map. This method relies on the accuracy of the measured field map that usually requires additional computational steps such as phase unwrapping (2,3). Various schemes involving reference scans or pre-scans have been proposed to either estimate phase and amplitude errors at each k-space data point (4), to field-map through multi-channel modulation utilizing k-space and the image domain (5), to obtain a point-spread-function (PSF) (6,7), or to obtain a displacement map by additional phase labeling (8). In addition, a direct distortion

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correction in the image domain, which requires an accurate image processing procedure to locate a half way of two distorted boundaries (9), was also introduced.

Most of existing methods utilize either substantial post-processing or lengthy pre-scans that may be susceptible to motion artifacts. In this work, we describe a direct method for the correction of image distortion in EPI by using a view angle tilting (VAT) technique in combination with parallel imaging. The VAT technique was initially introduced to correct image distortion caused by field inhomogeneity and chemical shift along the readout (RO) direction (10) and has been employed in several conventional SE imaging applications (11–14). The VAT gradient whose amplitude is the same as the slice-select (SS) gradient is applied along the SS direction concurrently with the RO gradient. Recently, the possibility of applying VAT to EPI along the PE direction, with the tilting angle given by the ratio of the SS gradient to the PE gradient, was briefly discussed (15). However, the tilting angle for such a direct implementation of VAT would be close to 90° due to the very small effective PE gradient relative to the SS gradient. No practical implementation with experimental data was reported. In the present study, we introduce the concept of combining VAT with parallel imaging to make VAT feasible for single-shot EPI and provide the first experimental implementation. Similar to VAT in SE imaging in principle, the VAT gradient pulse blip is applied along the SS direction at the same time when the PE gradient pulse blip is applied, producing an additional phase. This additional phase effectively offsets phase errors introduced by field inhomogeneity and chemical shift, providing the removal of image distortion along the PE direction with no additional scan time. The proposed technique does not involve the use of additional post-processing steps and is relatively easy to implement, making it easy to use in practice. In the following subsections, a theoretical description is provided and the efficacy of the proposed technique is demonstrated by experimental studies.

THEORY

The original VAT technique was proposed to correct image distortion along the RO direction since field inhomogeneity primarily causes distortion in the RO direction in conventional spin-warp imaging (10). In contrast, image distortion occurs predominantly along the PE direction in a single-shot EPI acquisition. Hence, the VAT technique is applied here to address image distortion along the PE direction in a single-shot EPI acquisition. Ignoring spin relaxation effects, the EPI signal in the presence of field inhomogeneity, $\Delta B(x, y)$ with the VAT gradient, $G_{vat}$ applied along the SS direction concurrently with the PE gradient can be expressed as

$$s(t_m, t_b) = \int \int_{\Delta s + \Delta z(x, y)} \rho(x, y, z) \exp(-j\gamma nG_{vat} t_b z) \exp(-j\gamma \Delta B(x, y) n T_{esp} ) \exp[-j\gamma(mG_z \Delta \alpha + n G_x \Delta \alpha)] dz dy dz$$

where, $\rho(x, y, z)$ is spin density, $\gamma$ is the gyromagnetic ratio in radian sec$^{-1}$Tesla$^{-1}$, $\Delta \alpha$ is the sampling rate, $T_{esp}$ is the echo spacing, $t_b$ is the duration of the PE gradient blip, $\Delta \alpha$ is the position displacement due to field inhomogeneity along the SS direction given by $\Delta \alpha(x, y) = -\Delta B(x, y)/G_z$, $G_z$ is the SS gradient, $\Delta s$ is a slice thickness, and $m$ and $n$ are k-space indices along the RO and PE direction, respectively.

By reformulating the integral over the slice thickness using $z = z' - \Delta B(x, y)/G_z$ and by letting $G_{vat} = G_z T_{esp}/t_b$, Eq. [1] is rewritten as follows
Eq. [2] shows distortion correction with the additional phase term, \(\exp(-j\gamma nG_z T_{esp}z')\) along the PE direction. The view-tilting angle, \(\theta\) can be found as in the following relation

\[
\tan(\theta) = \frac{G_{val}}{G_y} = \frac{G_z T_{esp}}{G_y t_b}
\]

Assuming that spin density is dependent on a position coordinate \((x,y)\), Eq. [2] can be rewritten as

\[
s(t_m, t_n) = \int_{x} \int_{y} \rho(x,y,z') \cdot \frac{\Delta R(x,y)}{G_z} \exp(-j\gamma nG_z T_{esp}z') \cdot \exp(jy(\frac{\Delta B(x,y)T_{esp}}{G_z t_b} - nG_y t_y)) \cdot \exp[-j(y(mG_z \Delta t_r x + (y+\frac{\Delta R(x,y)T_{esp}}{G_z t_b})nG_y t_y))] \, dx \, dy \, dz'
\]

where, \(z' = 0\) is a constant value at each coordinate \((x,y)\), sinc \((x) = \sin(\pi x)/\pi x\), and \(\gamma\) is the gyromagnetic ratio divided by \(2\pi\). Rectangle RF slice profile is assumed in Eq. [4] when calculating the integral of the additional phase over the slice thickness. Multiplication of a sinc function along k-y direction or its Fourier transform counterpart, convolution with a rectangle function in the image domain, means that the addition of the VAT gradient corrects image distortion at the expense of image sharpness along the PE direction. It can be deduced from Eq. [4] that the Fourier transform of the excitation RF slice profile is multiplied along the k-y direction as a magnitude modulation function which characterizes image blurring caused by factors other than partial volume effects. Image blurring in the image domain can be understood as the low-pass filtering with this magnitude modulation function in k-space. Fig. 2 shows magnitude modulation functions calculated from a RF slice profile used for in-vivo imaging in this study. Modulation function of \(\theta = 44.6^\circ\) (solid line) shows less low-pass filtering than the other \((\theta = 63.1^\circ\), dotted line), demonstrating less image blurring. It was reported that specially designed RF pulses can be used to reduce image blurring by generating more uniformly distributed non-zero amplitude modulation function (16).

As seen in Eq. [3] in EPI, the required VAT gradient amplitude along the SS direction is \(G_x T_{esp} t_b\). For standard single-shot EPI, this value is much larger than that of the PE gradient blip due to the ratio of \(T_{esp}\) to \(t_b\). The view-tilting angle can be reduced by reducing FOV\(_{PE}\), RF bandwidth, and/or increasing the slice thickness. Even with these measures, the amplitude of the VAT gradient could be more than three times greater than the PE gradient with typical EPI parameters, leading to significant blurring and making it impossible to produce quality images. Parallel imaging acquires k-space with reduced FOV\(_{PE}\) by the factor of acceleration, \(R\). Hence, the ratio of the VAT gradient to the PE gradient can be reduced by using parallel imaging in the VAT technique. Parallel imaging alone reduces image distortion due to shortened data acquisition time and increased effective bandwidth along the PE direction (17). However, when the VAT technique is applied, image distortion can be removed.
MATERIALS AND METHODS

All experiments were performed on a 3 T scanner (TRIO, Siemens Medical Solutions, Malvern, PA) using a body coil for transmission and a 12-channel head receiver coil. A phantom was constructed to examine the effect of chemical shift and field inhomogeneity in such a way that small air and oil tubes (inner diameter: 28 mm) were submerged in distilled water doped with Gd-DTPA (OMNISCAN, GE Healthcare AS, Oslo, Norway). The concentration of the contrast agent was 0.5 mM (T1 ≅ 500 ms, T2 ≅ 350 ms at 3 T) (18). The phantom was placed in the magnet bore with the axes of small tubes perpendicular to the main magnetic field. Coronal imaging was performed to maximize field inhomogeneity effects, as nonaxial plane imaging shows more field inhomogeneity (19).

VAT with SE imaging along the RO direction has been well documented elsewhere (16). Experimental data were obtained on the fat-air phantom described above and human volunteers to show the performance of VAT with EPI in this study. The fat-air phantom was imaged using 4 different EPI sequences, SE-EPI, SE-EPI with parallel imaging, SE-EPI with VAT (SE-EPI-VAT) and SE-EPI-VAT with parallel imaging. EPI parameters were: TE/TR=43/1000 ms, 170 mm square FOV, 64×64 imaging matrix, 5 mm slice thickness, 2520 Hz/pixel receiver bandwidth, T_C= 0.52 ms, t_s= 60 μsec, G_y= 9.21 mT/m, G_x= 26.99 mT/m and 7.68-ms excitation RF pulse. Generalized auto-calibrating partially parallel acquisition (GRAPPA) (20) was used for parallel imaging (R=4). The view-tilting angle was 41.4° that made the amplitude of the VAT gradient blip 0.9 times that of the PE gradient blip. A 90° Shinar-Le Roux (SLR) (21) slice selective RF pulse was designed with the bandwidth of 200 Hz using MATPULSE software (22) and used for all studies. The relatively low RF bandwidth was employed to make the amplitude of the VAT gradient small.

In the second experiment, a healthy volunteer was imaged with informed consent. Anatomical SE imaging, SE-EPI, SE-EPI with parallel imaging and SE-EPI-VAT with parallel imaging were performed. EPI was used to obtain axial slices that cover brain regions with the following imaging parameters: TE/TR=40/2500 ms, 220 mm square FOV, 64×64 imaging matrix, 30 contiguous 5-mm slices, 2520 Hz/pixel receiver bandwidth. GRAPPA (R=4) was used for parallel imaging. The view-tilting angle was 48.9°. Since SE-EPI-VAT alone corrects chemical shift effects, SE-EPI and SE-EPI with parallel imaging were performed without fat suppression for comparison.

In the third experiment, five healthy subjects were imaged with informed consent to further evaluate the performance of the SE-EPI-VAT sequence. Each subject was scanned with three different slice-tilting angles: axial, −20° from axial plane to coronal plane, and 20° from axial plane to coronal plane which follow the normal range of slice positioning used in clinical applications. The aim of this work is to demonstrate the feasibility of using VAT in EPI for distortion correction in combination with parallel imaging. The performance for more extreme angles and scenarios is beyond the scope of this work. Anatomical SE images were first acquired to compare with EP images using TE/TR= 8.3/3000 ms, 30 contiguous 5-mm slices, 220 mm square FOV, 256×256 imaging matrix, and 271 Hz/pixel receiver bandwidth. SE-EPI was performed with the following parameters: TE/TR= 40/2500 ms, 30 contiguous 5-mm slices, 220 mm square FOV, 64×64 imaging matrix, 3126 Hz/pixel receiver bandwidth, with and without parallel imaging (R=2 and 4), and with and without VAT (θ=63.1° with R=2 and θ=44.6° with R=4). To better visualize distortion and corresponding signal modulation effects, edges of a SE image were overlaid onto each EP image after oversampling an EP image and making the same in-plane resolution between the two. Edges of a SE image were determined by extracting a brain region and then detecting edges using AFNI software (http://afni.nimh.nih.gov/).
For quantitative analysis, EP image volume and high-resolution T1 image volume acquired by using magnetization-prepared rapid 3D gradient-echo imaging (MPRAGE) were registered to a reference space, the MNI space using a linear transformation (http://www.fmrib.ox.ac.uk/fsl/flirt/) as typically practiced in functional studies. Then, binary images of both EP images and T1 images in the common space were generated. The number of non-matching voxels between the two image volumes was calculated in the region of Frontal-pole of FSL’s Harvard-Oxford Cortical Structural Atlas.

All images in this study were generated by the vendor-provided on-line reconstruction without any customized post-processing.

RESULTS

SE-EPI (Fig. 3a) shows significant image distortion, especially near the interface between the water and air (black arrow). It also shows considerable distortion in overall geometry (white arrow). Chemical shift effects are also prominent as the oil tube is shifted significantly to the left from its original location (arrow head). Fig. 3b shows the reduction of distortion from Fig. 3a using parallel imaging. However, there is still significant image distortion (arrow) and chemical shift of the oil tube (arrow head). When the VAT gradient is applied without the parallel acquisition, image becomes heavily blurred due to the large amplitude of the VAT gradient (Fig. 3c) although distortion correction can be appreciated. Fig. 3d shows the SE-EPI-VAT image with GRAPPA (R=4). The geometry of the phantom is restored, chemical shift between the oil and the water is corrected, and severe image distortion is effectively removed (arrows).

Fig. 4 presents images of a slice containing the frontal lobe of a normal volunteer. Fig. 4a shows an anatomical SE image. Edges of the SE image were overlaid onto each EP image for comparison. Fig. 4b is a SE-EP image without fat-suppression. The frontal lobe appears severely distorted in the image and fatty tissue is significantly displaced from its location (indicated by an arrow). Fig. 4c shows a SE-EP image with parallel imaging without fat-suppression. Although parallel imaging reduces the distortion shown in Fig. 4b, there are still visible displacement of fatty tissue and image distortion. With VAT, both image distortion and chemical shift effects are effectively corrected (Fig. 4d). The image from SE-EPI-VAT with parallel imaging better depicts the brain region (rectangle region) than the images from both SE-EPI and SE-EPI with parallel imaging, when compared with the SE image.

Anatomical SE imaging, non-parallel imaging, parallel imaging (R=2), parallel imaging (R=4), and parallel imaging (R=4) with VAT were denoted by SE, R1, R2, R2-VAT, R4, and R4-VAT, respectively in Figs. 5–6. Distortion and/or signal modulation effects were indicated by arrow(s) in R1 of Figs. 5–6. Fig. 5 shows the frontal (a) and deep inferior orbito-frontal (OF) (b) regions of human brain acquired from an axial imaging. R1 shows severe distortion and signal modulation effects in standard EPI without parallel imaging in Fig. 5a. These artifacts were reduced by using parallel imaging (R2 and R4). However, when VAT was applied, both the artifacts were corrected (R2-VAT and R4-VAT). Deep inferior OF region (Fig. 5b) shows both severe distortion and signal modulation effects (R1). Both artifacts were reduced by using parallel imaging (R2 and R4) and further reduced substantially by using VAT (R2-VAT and R4-VAT).

Fig. 6 shows OF (a) and temporal (b) regions of human brain acquired from a tilted-slice imaging (−20° from axial to coronal plane). Orbito-frontal region (Fig. 6a, R1) shows distortion (white arrow) and signal modulation effects (black arrow). These were reduced when parallel imaging was used (R2 and R4). However, VAT corrected distortion and
greatly reduced signal modulation effects (R2-VAT and R4-VAT). Temporal region (Fig. 6b) also shows both distortion and signal modulation effects. Similar to previous results, VAT reduced both the artifacts. However, the right anterior part of cerebellum (see enlarged insets) obtained from R4 is shown to better align with SE than R4-VAT. This implies that VAT may underperform in some regions possibly of high field inhomogeneity across slice thickness. Further investigation may be warranted for the performance with other slice orientations and positions.

Fig. 7b shows the average number of voxels found in the region of Frontal-pole of FSL’s Harvard-Oxford Cortical Structural Atlas (Fig. 7a) calculated from 5 subjects for different EP sequences (R1, R2, R2-VAT, R4, and R4-VAT) and for three slice tilting angles in the reference space. Less distorted image would yield less non-matching voxels (difference of a voxel count) as compared to T1 image volume. As expected from Figs. 5–6, distortion decreased as the acceleration factor in parallel imaging increased and VAT further reduced it. Axial imaging and 20° tilted-slice imaging showed similar results while −20° (same tilting-angle polarity as AC-PC line alignment) tilted-slice imaging provided less distortion for all non-VAT EP images (R1, R2, and R4). The distortion correction by VAT was similar throughout slice-tilting angles and acceleration factors tested although R2-VAT showed slightly higher performance than R4-VAT. This may be due to more blurring effects by a higher view-tilting angle of R2-VAT. Fig. 7c shows the average difference of a voxel count (T1-EPI) normalized by T1 which demonstrates the degree of distortion correction as compared to R1. Difference of distortion between data with and without VAT (R2 vs R2-VAT and R4 vs R4-VAT) was significant (pair-wise t-test, p<0.05 in Table 1).

DISCUSSIONS AND CONCLUSION

The quality of EPI is often degraded by off-resonance effects. Geometric distortion caused by field inhomogeneity along the PE direction is one of the most prominent artifacts due to a relatively low effective bandwidth in the PE direction. In this paper, a straightforward method for correcting image distortion along the PE direction is introduced based on the VAT technique. The key feature is the addition of gradient blips along the SS direction. The VAT gradient causes an additional phase accumulation. This phase offsets an unwanted phase accumulation introduced by field inhomogeneity along the PE direction, leading to the effective removal of image distortion. In the VAT technique, distortion correction comes at the expense of image sharpness. The added image blurring comes from two sources. One is the partial volume effect. Intravoxel contamination occurs near a boundary between two different contrasts due to a tilted imaging plane. The other is the magnitude modulation effect whose function is given by the Fourier transform of the excitation RF slice profile. The latter has been reported as a primary contributor to image blurring (16). VAT may not be appropriate for high-resolution fMRI studies with small smoothing kernel sizes or single-subject studies which do not need to involve smoothing process, especially when the tilting angle is high and a considerable amount of image blurring is produced. It was found from our simulation based on the in-vivo experiments we have performed that the full width at half maximum (FWHM) of the point spread function (Fourier transform of the modulation function) in image domain ranged between 4.68 mm and 9.86 mm (R=2: 9.86 mm, R=3: 6.06 mm, R=4: 4.68 mm). Considering the fact that a 10-mm smoothing kernel may be currently an upper-limit of common practice for group analysis, VAT may be more suitable for low-resolution fMRI studies for group analysis with the benefit of distortion correction. Single-shot sequence alone also causes blurring due to a relatively long acquisition during transverse relaxation. However, parallel imaging combined with VAT may offset the blurring effect of non-parallel EPI due to shortened acquisition period. Distortion correction and image blurring are separate events. Image blurring is shift-invariant in the PE direction so it in principle should not correct distortion per se. However, as R2-VAT shows slightly
higher performance than R4-VAT in the in-vivo imaging (Fig. 7), there is a chance in practice, especially when the view-tilting angle is high, that blurring affects the delineation of an object by the extent of the calculated point spread functions and hence the quantification of image distortion. Distortion correction with VAT worked effectively in all scenarios examined in this study. In the fat-air phantom study, despite the chemical shift between the doped water and the oil (~3.7 ppm) and the susceptibility-induced field shift between the doped water and air (~9.2 ppm) (23), VAT effectively removed the image distortion. With no need of fat suppression, the proposed technique can save scan time, usually more than 10 ms per EPI acquisition, and reduce SAR. Since SAR issue becomes more critical when a high magnetic field strength is involved, the reduction of SAR may be more beneficial for those experimental conditions. The implementation of the EPI-VAT pulse sequence is simple and straightforward. The only modification is the addition of VAT gradient blips. There is no penalty in scan time if the tilting angle is under 45°, as is the case of R=4. Even with the angle greater than 45°, the increase of the blip duration is minimal with a negligible effect on scan time. The VAT approach does not require customized reconstruction algorithm to produce distortion-corrected images. It can be thus readily implemented on commercial scanners as demonstrated here.

There are some limitations with the SE-EPI-VAT technique. As the nature of VAT, SE-EPI-VAT only corrects in-plane image distortion and does not account for the correction of through-plane distortion as has been noted in SE imaging (24,25). This is because the VAT technique is based on the assumption of the homogeneous local field across the slice thickness, which may not be always the case. Therefore, SE-EPI-VAT alone is not capable of effectively correcting image distortion when a local field changes considerably across the slice thickness. It is shown that the degree of distortion correction varies with regions and slice angles. Hence, VAT in EPI should not be applied universally. Rather, caution should be exercised by considering factors such as a targeted brain region, slice-tilting angle, and patient positioning. Quantitative results show that VAT works well in the frontal region. Distortion correction is significant and consistent with different acceleration factors within ±20° slice-tilting angles. Hence, one may benefit from the application of VAT for a substantial distortion correction in studies involving human brain frontal regions.

A high view-tilting angle limits the practice of SE-EPI-VAT. In the present implementation, parallel imaging with a reduction factor of 4 lowered the angle to approximately 45°. Although the view-tilting angles of 45° or higher have been examined in SE-VAT imaging (12,16,26), smaller angles would always benefit the improvement of image quality with less blurring. With more advanced receiver coil design, highly accelerated parallel imaging has been attempted on 3 T in recent years (27,28). Hence, high acceleration may be used to reduce the tilting angle further. The number of readout sampling points was limited to 64 in this study to keep the echo spacing as short as possible. This resulted in a limited spatial resolution and consequently made the spatial resolution a trade-off with image blurring. Receiver bandwidth also needs to be selected carefully so that it provides the short echo spacing. Slice thickness is inversely proportional to the tilting angle because more VAT gradient needs to be applied with a thinner slice acquisition. Hence, VAT may be more useful with 4–5 mm slice thickness than a thin-slice acquisition. Lastly, it is also worth noting the application of VAT to gradient-echo (GE) EPI. As shown in SE-EPI, VAT also has potential of correction of image distortion and chemical shift artifact in GE-EPI. However, signal loss is unavoidable because incoherent spin phases from different spin precessions at the time of echo acquisition lead to signal void.

In summary, this work describes and demonstrates the application of VAT in EPI for eliminating image distortion caused by field inhomogeneity. The technique is simple and straightforward both in its implementation and application, making it readily applicable on
commercial scanners. Due to the simplicity and effectiveness of the proposed method, it is expected to serve as a viable tool for the correction of image distortion in EPI.

Acknowledgments

The authors thank Dr. Govind Bhagavatheeshwaran and Jaemin Shin for helpful discussions and Kisueng Choi for help with data analysis. This work was supported in part by the National Institute of Health (grant RO1EB002009) and Georgia Research Alliance.

References


FIG. 1.
The spin-echo EPI sequence with the VAT technique. The VAT gradient blips are applied along the SS direction at the same time as the PE gradient blips.
FIG. 2.
Magnitude modulation functions for SE-EPI-VAT calculated from a RF slice profile used for in-vivo imaging. (a) $\theta = 44.6^\circ$ (b) $\theta = 63.1^\circ$. 
FIG. 3.
Demonstration of image distortion along the PE direction (row in images) in SE-EPI in relation to parallel imaging and the VAT technique using the fat-air phantom. (a) SE-EP image shows both significant image distortion (black arrow) and chemical shift effects (arrow head). It also shows the considerable distortion of the phantom (white arrow). (b) Image from SE-EPI with GRAPPA (R=4) shows the reduction of distortion. However, it still has quite noticeable distortion (arrow) and chemical shift effects (arrow head) as well. (c) SE-EPI-VAT image shows severe image blurring although distortion correction can be appreciated. (d) Image from SE-EPI-VAT ($\theta=41.4^\circ$) with GRAPPA (R=4) shows distortion correction and the correction of chemical shift effects as well (arrows).
FIG. 4.
Brain images of human frontal lobe. (a) SE image. (b) SE-EP image without fat suppression. The image shows significant image distortion near frontal lobe and the displacement of fatty tissue. (c) Image from SE-EPI with GRAPPA (R=4) without fat suppression. There still remain image distortion and chemical shift effects as well. (d) Image from SE-EPI-VAT (θ =48.9°) with GRAPPA (R=4). Both distortion and chemical shift effects are effectively corrected. Edges of brain region in the SE image were detected and overlaid onto each EP image for comparison.
FIG. 5.
Human brain images of (a) frontal and (b) deep inferior OF region from an axial imaging. Edges of SE images are overlaid onto EP images to examine distortion and signal modulation effects. Regions of distortion and/or signal modulation effects are indicated by arrow(s) in R1 images. Parallel imaging (R2 and R4) has shown to reduce the artifacts due to the reduction of the effective echo spacing. However, when VAT was combined (R2-VAT and R4-VAT), the artifacts were corrected or further reduced significantly.
FIG. 6.
Human brain images of (a) OF and (b) temporal region from a tilted-slice imaging (−20° from axial to coronal plane). Edges of SE images are overlaid onto EP images to examine distortion and signal modulation effects. Severe image distortion and/or signal modulation effects are seen in standard SE-EP images (R1). These artifacts are reduced by applying parallel imaging (R2 and R4) and further reduced or corrected by using VAT (R2-VAT and R4-VAT).
FIG. 7.
(a) Representative sagittal T1 image affine-registered to MNI space with the Frontal-pole region of Harvard-Oxford Cortical Structural Atlas overlaid in red color. (b) Bar graph shows an average number of voxels counted in the region shown in (a) calculated from 5 subjects with a standard deviation value indicated. (c) Difference of a voxel count (T1-EPI) was normalized by T1. From left to right in (b) and (c), results are presented for axial imaging and −20° and 20° (axial to coronal) tilted-slice imaging.
### TABLE 1

Results of pair-wise t-test between data with and without VAT shown in Fig. 7

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