Phase Angle Tilting (PAT) for Distortion Correction Caused by Susceptibility in EPI

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Introduction

Gradient-echo EPI as an ultrafast and T2*-sensitive MRI technique, is most commonly used in functional MRI. However, Gradient-echo EPI is vulnerable to susceptibility-induced local field inhomogeneities, which induces signal loss and distortion mostly in the phase encoding direction. Due to susceptibility artifacts, the brain regions near air-tissue and bone-tissue interface are difficult to image. A number of methods have been introduced for minimizing or reducing susceptibility induced signal loss, such as thin slice, high resolution and z-shimming [1] etc. However most of the existing methods can't effectively deal with the problem of distortion. To date, only a few methods have been proposed to correct the image distortion including large effective bandwidth in phase encoding direction, distortion correction based on inhomogeneity field map [2], positive and negative polar phase encoding gradients [3] etc. Most of these methods are limited by the hardware of MR system, or require additional scanning time and calculation. Here, we propose a simple distortion correction method with a slightly modification in EPI sequence without additional scanning time.

Methods

Our method was similar to the view angle titling technique (VAT) [4-5], which was designed to eliminate magnetic field inhomogeneities in the readout direction. We modified the single-shot EPI sequence with phase angle titling (PAT), considering that the signal distortion mainly present in the phase direction due to the small effective bandwidth. The pulse sequence is illustrated in Fig. 1. Compared to the conventional EPI, a train of gradient, G_c, has been applied in the direction of slice selection simultaneously with the phase gradient (G_y). Fig. 2 illustrates the distortion correction scheme. In generally, the frequency offset does not cause pixel shift in the readout direction due to the high bandwidth of acquisition in the readout direction, instead it will cause large pixel shifts in the phase direction. Therefore we mainly consider the susceptibility effects in the phase encoding direction (y axis). Fig. 2a shows that the frequency offset caused by susceptibility will induce distortion and signal change in the phase direction. Suppose the pixel 1, 2, 3 (the three green rectangles represent the three pixels in Fig. 2) are excited by slice selection pulse at z=0, and there is magnetic filed inhomogeneity $h(y, z)$ in the pixel 2. G_z and G_y are the slice and phase gradient amplitudes, respectively. The position of the pixel 2 is offset by $a = -h(y, z) / G_z$ along the z axis and the pixel 2 is shifted by $b = h(y, z)*ES/(T_y*G_y)$ along the phase (y) axis (the yellow rectangle is shown as the shifted pixel 2), and ES stands for echo spacing, T_y is the duration of G_y. The resulting images are shown with blue standing for the pixel 1 and 3 and red standing for the pixel 2. We can see the overlap between the projection of the pixel 2 and 3 (the purple part in Fig. 2a). When the compensation gradients (G_c) are applied such as in Fig. 1, which make the phase angle tilted to the u axis, $G_u = (G_y^2 + G_c^2)^{1/2}$, as shown in Fig. 2b, the coordinate on the u axis for the pixel 2 is dislocated to $a\sin\theta$ relative to the y axis, and the pixel 2 is shifted by $b = h(y,z)*ES/(G_u*T_y)$ in the tilted phase (u) axis. So the pixel 2 is projected onto the u axis without distortion only when $b = -a\sin\theta$, or $G_c = ES*G_z/T_y$. With this technique, the distortion and signal shift in phase direction in EPI will be corrected, no matter the magnetic filed inhomogeneity $h(y,z)$ is positive (as shown in Fig. 2) or negative.

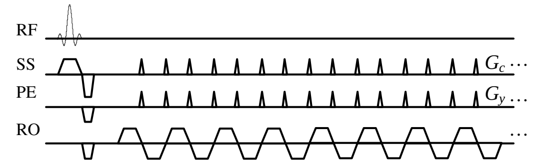

Fig. 1 The gradient-echo EPI sequence with phase angle tilting (PAT)

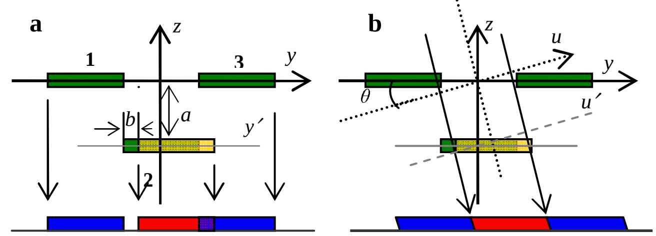

Fig. 2 The schematics of PAT. Three pixels 1, 2,3 (the green rectangles) are selected at the slice selection at z=0, and there is magnetic filed inhomogeneity h(y, z) in the pixel 2. **a** shows no distrotion correction. a is the slice offset of the pixel 2 in the z axis and b is the phase shift in the phase (y) direction (the yellow rectangle is shown as the shifted pixel 2). the purple rectangle represents the overlap between the projection of the pixel 2 (red) and 3 (blue). **b** shows distortion correction using PAT. The phase axis (u) is tiltied by θ from the y axis.

The modified EPI sequence with PAT was implemented on a Siemens Trio Tim 3T MRI scanner, and evaluated on water phantom filled with $NiSO_4$ solution and air as well as on healthy volunteers. The following parameters were applied: FOV=220mm, matrix=256×256 with 6/8 partial k-space, bandwidth = 1446 Hz/pixel, TR/TE=2000/30ms, 20 slices with 5mm thickness and 25% gap were scanned. Additionally, a conventional gradient-echo EPI with same parameters was scanned in comparison, and a GRE images with the same resolution was obtained for reference.

Results

Fig. 3 shows the results from a respective slice of water ($NiSO_4$) phantom, and the phase direction of all sequence is along the A-P direction. There is air above the water in the phantom. Fig. 3a shows the GRE image. We can see the interface of air and water at the top of the phantom clearly, and no distortion in the phase direction. Fig. 3b shows the image obtained by conventional EPI. The significant geometric distortion appeared near the interface of air and water, which was caused by the difference in magnetic susceptibility between air and water. Fig. 3c shows the corrected results by the modified EPI sequence with PAT. The signal shifts were well corrected. Both two EPI images were scaled to the same contrast. Fig. 4 shows the results of a respective slice from a subject. Fig. 4a shows the GRE image. Fig. 4b shows the result from conventional EPI. We can observe the signal shift near the interface between the tissue and air due to the susceptibility effects, which is indicated by the green arrow. Fig. 4c shows the corrected results, and we also found the signal shifts near the interface between air and tissue was well corrected using PAT.

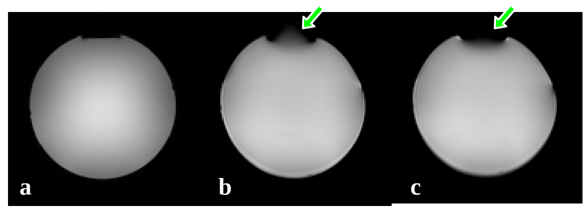

Fig. 3 a: the GRE image; **b:** the conventional EPI; **c:** the EPI with PAT. The phase direction of all the images is along A-P direction. Both the EPI images were scaled to the same contrast.

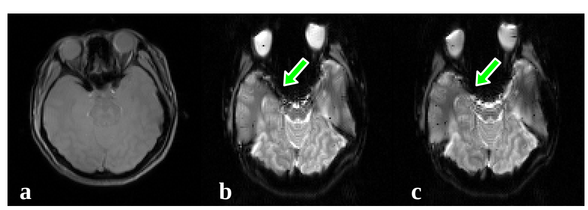

Fig. 4 a: the GRE image; **b:** the conventional EPI; **c:** the EPI with PAT. The phase direction of all the images is along the A-P direction. Both the EPI images were scaled to the same contrast.

Discussion and conclusions

PAT is an effective method for distortion correction in EPI, which was well demonstrated by our experiments on phantom and human. Compared with other correction methods, it does not cost additional scanning time, and is easy to implement in the EPI sequence. This method can also be combined with other techniques, such as z-shim [1], by which we can get better image without image distortion and signal loss. Like the VAT technique, the phase angle titling also introduces some blurring into the image, which can be largely removed using short angle axis readout segmented EPI.

References

[1] Heberlein KA, et al., Magn Reson Med 2004; 51: 212-216. [2] Kadah YM and Hu X., Magn Reson Med 1997; 38: 615-627. [3] Morgan PS, et al., J Magn Reson Imaging 2004, 19: 499-507. [4] Cho ZH, et al., Med Phys 1988; 15(1): 7-11. [5] Jung K-J, et al., ISMRM2007, #1255.