Recovery of Signal Loss due to In-Plane Susceptibility Gradients in Gradient Echo EPI by Acquiring Extended Phase-Encoding Lines

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Introduction: The local susceptibility induces an inhomogeneous magnetic field, $E(x,y,z)$, which can have gradient in through- and in-plane directions. The in-plane susceptibility gradient causes an echo shift which results in signal loss and a truncation or ripple artifact in gradient echo imaging (1,2). This becomes more severe in the gradient echo EPI due to a low gradient strength applied in the phase-encoding (PE) direction during the long echo train (3-5). An approach of applying the through-plane z-shimming to the PE direction was previously developed (4). However, this method has the same disadvantage of increasing the scan time two or three times as in conventional z-shimming. A new approach is to acquire the echoes that are shifted outside the regular data acquisition time (T_{DAQ}) by extending the PE lines. This will recover the signal loss and remove the ripple artifact without significantly increasing the scan time.

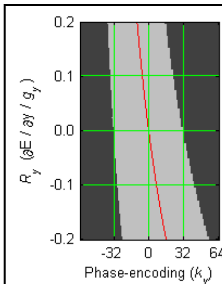

Fig. 1. The echo center (red line) and T_{DAQ} (white strip) as a function of R_y. The boundary of the regular T_{DAQ} is marked by green lines.

Methods: The in-plane susceptibility gradient in the PE direction (y) can be defined as $R_y = \partial E/\partial y/g_y$ relative to the PE gradient amplitude g_y. In EPI, g_y is the average amplitude applied during the echo spacing. R_y will change the effective PE gradient to $g_y(1+ R_y)$. The echo center is shifted by $-N_y\, R_y/(1+R_y)$ from the regular T_{DAQ} center ($k_y = 0$), where N_y is the number of PE steps for the image matrix N_y x N_y (1). An interesting effect of R_y on T_{DAQ} is that T_{DAQ} should change from N_y to $N_y/(1+ R_y)$ to cover $[-\pi:\pi]$ of k_y. The effect of R_y on the echo center and T_{DAQ} are shown in **Fig. 1** as a 2-D map. As R_y increases in the positive or negative direction relative to g_y, the required T_{DAQ} extends in the prior or posterior side of the regular T_{DAQ}, respectively. When the echoes are acquired only during the regular T_{DAQ} as in conventional EPI, the signal outside the regular T_{DAQ} is missed, which results in a signal loss and ripple artifact (5). The lost signal can be recovered by extending the PE lines over the regular T_{DAQ}. The PE lines were extended by adding 16 PE steps before and after the regular T_{DAQ} of 64 steps for the 64x64 imaging matrix (**Fig. 2**). The amplitude of the PE dephasing pulse was increased by 48/32 to keep the echo center at $k_y = 0$. A subject was scanned at 3T with a quadrature birdcage coil (slice thickness and in-plane resolution = 3.5 mm, pixel bandwidth = 3004 Hz, echo spacing = 0.38 ms, T_E = 30 ms, T_R = 5 sec, flip angle = 90°, number of slices = 64, transverse slice orientation, and PE direction = AP). The effect of T_{DAQ} was studied by reconstructing four sets of k_y lines as shown in Fig. 2: Ext (96), Reg (middle 64), Pre (pre 16 + middle 64), and Post (middle 64 + post 16). The k-space data was configured into a 96x96 matrix by padding with zeros for the excluded region in the PE direction. The images were interpolated down to a 64x64 matrix. In addition, a field map was measured at the same slice location by use of the gradient echo sequence with two different echo times of 10 and 12.46 ms.

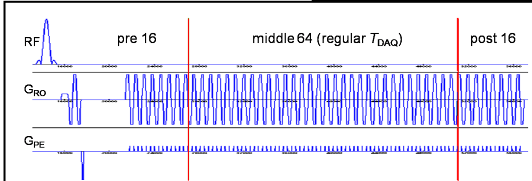

Fig.2. An EPI pulse sequence with extended PE steps.

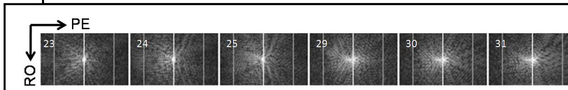

Fig. 3. The k-space maps (log amplitude) from selected slices. In each slice the bright and gray vertical lines denote the center and boundary of the regular T_{DAQ}, respectively.

Results: The k-space maps of selected slices show that the echoes were indeed shifted and extended outside the regular T_{DAQ} (**Fig. 3**), which is better demonstrated in the PE directional profile of the k-space signal averaged in the readout direction as shown in **Fig. 4**. The 1st group of slices (slice number 23, 24, 25) had a higher signal in the prior (left) side, while the 2nd slice group had a higher signal in the posterior (right) side. The signal distribution in the k-space was directly translated into the reconstructed images as expected (**Fig. 5).** The 1st slice group had the signal loss around the ear canal when the prior 16 echoes were excluded. The 2nd slice group had the signal loss around the front sinus when the posterior 16 echoes were excluded. The inclusion of both sides clearly recovered the signal loss from the extended signal over the regular T_{DAQ}. The signal distribution of the k-space was confirmed from the measured susceptibility gradient map of $\partial E/\partial y$ in **Fig. 6**.

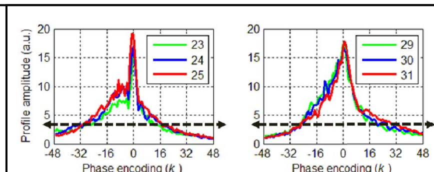

Fig. 4. The k-map profile in the PE direction for the two slice groups. The double-arrow line is to compare the signals outside $k_y = \pm32$.

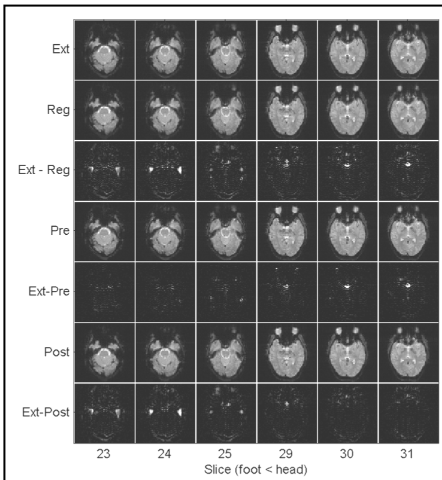

Fig. 5. Reconstructed and subtracted images.

Conclusions: The signal loss due to the in-plane susceptibility gradient can be recovered in the gradient echo EPI at a moderate increase (about 9 %) of the scan time. Therefore, we can focus on the through-plane effect without concern about the in-plane susceptibility gradient, which will simplify the choice of slice orientation to minimize the through-plane susceptibility gradient in particular for fMRI application.

References: 1. Hutchison JM, et al. J Phys [E] 1978;11(3):217-221. 2. Posse S. Magn Reson Med 1992;25(1):12-29. 3. Turner R, et al. IEEE Eng Med Biol Mag 2000;19(5):42-54. 4. Deichmann R, et al. Neuroimage 2002;15(1):120-135. 5. Chen NK, et al. Neuroimage 2006;31(2):609-622.

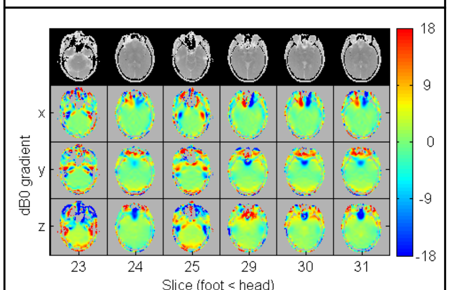

Fig. 6. Susceptibility gradient maps ($\partial E/\partial x$, $\partial E/\partial y$, $\partial E/\partial z$). The 1st row is the inverted-intensity gradient echo images.