AN EFFECTIVE METHOD TO INCREASE TEMPORAL OR SPATIAL RESOLUTION IN INTERLEAVED ECHO PLANAR IMAGING

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INTRODUCTION: Interleaved echo planar imaging (EPI) offers increased SNR over single-shot EPI, but suffers from ghosting in the phase encode (PE) direction due to abrupt phase modulations along the center of *k*-space [1]. A common solution is to employ echo time shifting (ETS) [2-5]. Although ETS corrects for ghosting in a robust, non-iterative, and automatic manner, it does so at the expense of increasing total scan time [5]. There is also a penalty in scan efficiency since the A/D time-to-TR ratio is low. In this work, a simple, yet effective scheme to increase the efficiency of ETS is proposed. Using the proposed technique, shorter scan times are achieved in interleaved EPI acquisitions. Alternatively, the proposed scheme can acquire higher resolution images when total scan time is fixed.

METHODS: In conventional ETS, pre-wait idle time T_{PR} and post-wait idle time T_{PO} are added before and after the echo train, respectively [2]. Time T_{PR} is incremented by some value Δt on each excitation, while T_{PO} is decremented by the same amount [5]. The proposed scheme replaces each of these idle times with an extra readout when either duration is greater than the gradient switching time T_{SWITCH}. When this condition is met, there is sufficient time to switch the gradients and play out an A/D window. The steps of the proposed scheme are summarized in Table I, and illustrated in Fig. 1 for the case of flyback EPI.

The A/D time of the new readout is less than a full echo (Table I, Step 2). This duration changes with each excitation – shrinking by Δt in post-wait replacement, while growing by Δt in pre-wait replacement. Hence, sequence TR is not affected, and a series of partial echoes is acquired at higher k_y spatial frequencies. The linear change in the partial echo A/D time results in a parallelogram coverage of *k*-space (Fig. 1c).

Since more data at higher k_y spatial frequencies are collected within one TR as compared to conventional ETS, fewer excitations are required for a given spatial resolution in the PE direction. Alternately, the total number of excitations can be fixed. In this case, more *k*-space lines that cross the k_y axis are acquired in the same total scan time. The improvement in scan time or PE resolution depends on the interplay between T_{PR}, T_{PO}, and T_{SWITCH}, which in turn relies on echo train length (ETL) and readout bandwidth (BW) [5].

Experiments were performed on a 1.5 T GE Excite scanner (40 mT/m gradient strength with 150 mT/m/ms slew rate) using a 2D gradient recalled echo sequence combined with an interleaved flyback EPI trajectory. A GE resolution phantom was first scanned to demonstrate resolution gain for a fixed scan time. BWs investigated were 15.625, 31.25, 62.5, 83.3, and 125 kHz; while ETL = 2, 4, 8. Two scans were performed for each (BW, ETL) pair: one with conventional ETS, and another using the proposed scheme. Imaging parameters were: TE/TR = 15/37 ms, slice thickness = 3 mm, FOV = 19.2 x 19.2 cm^2, flip angle = 30°, number of excitations = 32 (total scan time 1.2 s). The number of *k*-space lines that crossed the k_y axis was then compared. In vivo images of the brain of a healthy volunteer were acquired with an 8-channel head coil to demonstrate the reduction in total scan time when the target in-plane resolution is fixed. Here, in-plane resolution = 0.75 x 0.75 mm^2, TE/TR = 11/37 ms, and (BW, ETL) = (62.5 kHz, 4). All other imaging parameters were kept constant. Excitations proceeded until the required extent in k_y was covered.

TABLE I: PROPOSED REPLACEMENT SCHEME

POST-WAIT TIME T_{PO}	PRE-WAIT TIME T_{PR}
If $T_{PO} > T_{SWITCH}$, do the following *after* original echo train:	If $T_{PR} > T_{SWITCH}$, do the following *before* original echo train:
1) One full kx retrace	**1)** Place Gx and Gy dephasers before new gradients
2) One partial readout of duration (T_{PO}-T_{SWITCH})	**2)** One partial readout of duration (T_{PR}-T_{SWITCH})
3) One PE blip during extra kx retrace	**3)** One full kx retrace
4) Place Gx and Gy rephasers after new gradients	**4)** One PE blip during extra kx retrace
5) Adjust Gy rephaser amplitude to account for extra PE blip	**5)** Adjust Gy dephaser amplitude to account for extra PE blip
See illustration in Fig. 1a	See illustration in Fig. 1b

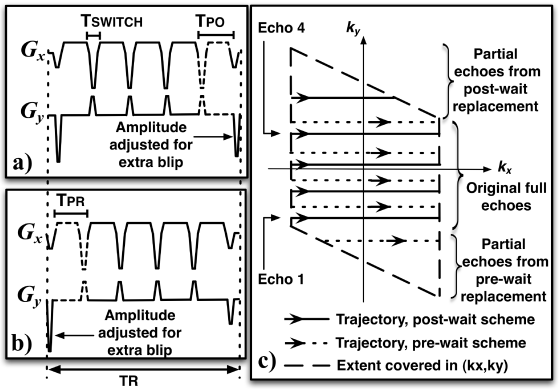

Figure 1: *Illustration of **(a)** post-wait and **(b)** pre-wait replacement schemes, and **(c)** k-space trajectories for flyback EPI with echo train length 4. The proposed gradients are denoted by the dotted trapezoids **(a,b)**.*

RESULTS & DISCUSSION: Figure 2 shows the improvement in resolution expressed as a percentage for various (BW, ETL) pairs. Improvements are significant when shorter ETL and lower BW are used. For the case of ETL = 4 and 8, the gain in PE resolution is approximately linear over a wide range of BWs. At moderate BWs, improvements of between 5% and 25% are possible. For example, when (BW, ETL) = (62.5 kHz, 4), 144 lines cross the k_y axis in the proposed scheme, compared to 128 in conventional ETS. This translates to a fractional resolution gain of 13 %. In Fig. 3, in vivo images from the conventional and proposed schemes are similar, with no noticeable differences. Note the excellent depiction of the cerebellum. Conventional ETS requires 64 excitations for the given resolution and FOV, or total scan time 2.4 s. The proposed scheme, on the other hand, traverses the same extent in k_y in 52 excitations, or 1.9 s. This is a scan time reduction of 20 %. The proposed technique can also be applied to partial *k*-space acquisitions to obtain even larger temporal or spatial resolution gains. Further, any interleaved EPI trajectory that employs ETS may be used with the proposed method.

CONCLUSION: This work demonstrates the possibility of shortening scan times, or improving spatial resolution in interleaved EPI acquisitions. The proposed method shows great promise in rapid imaging schemes such as functional and cardiac imaging where temporal and spatial resolution are important.

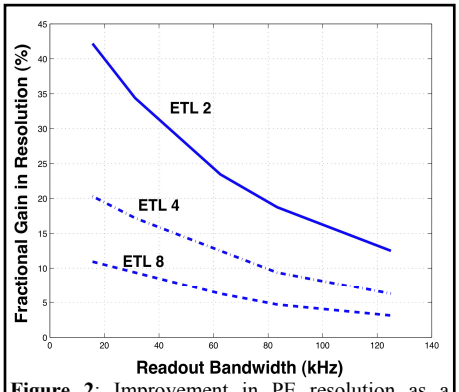

Figure 2: Improvement in PE resolution as a function of ETL and BW. Scan time was 1.2 s.

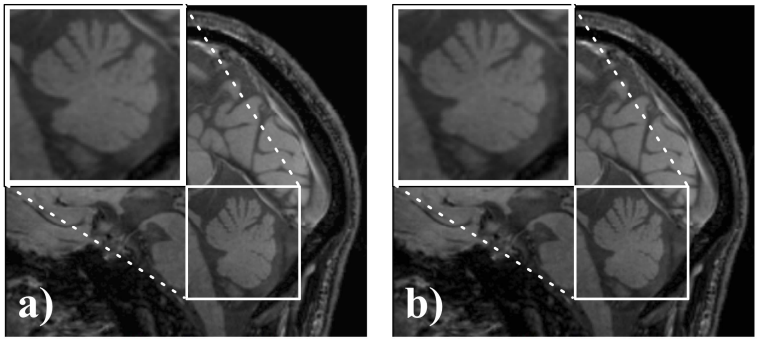

Figure 3: *In vivo images. **(a)** was acquired using flyback EPI with conventional ETS, and **(b)** shows the result of using the proposed scheme. Image **(a)** required 2.4 sec, while **(b)** was acquired in 1.9 sec. Temporal resolution improved by 20 %.*

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[**Acknowledgement:** NIH RO1 EB006471.]