Increased SNR in Echo Planar Imaging (EPI) using a circular k-space coverage

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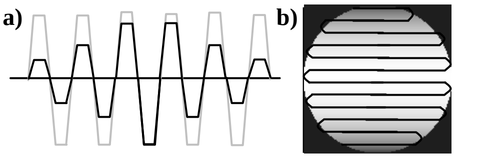
Introduction: Echo Planar Imaging (EPI) is a fast imaging method, which traverses a rectangular *k*-space in one (or more) readout(s) using gradient encoding. To reduce truncation artifacts and increase SNR, EPI reconstruction commonly applies a radial window (e.g. a Fermi filter) to *k*-space (Fig. 1c). With windowing applied, EPI spends unnecessary time acquiring "corner" data that will be excluded (or heavily apodized) during reconstruction. A variant of EPI is circular EPI (cEPI) [1], earlier proposed for real-time imaging [2]. In cEPI, the total readout time is reduced by the use of a readout trajectory that only covers an inscribed circle in *k*-space. This is obtained by modifying the duration of the gradient lobes, which allows for an increased number of slices per TR. However, image distortion in EPI is inversely proportional to the phase encoding *k*-space velocity, therefore the variable *k*-space velocity in cEPI leads to an inconsistent image, where low spatial frequencies are more distorted than the corresponding high spatial frequencies [3]. In this work, we have attempted to increase the SNR – instead of shortening the echo train – by modifying the cEPI acquisition. To distinguish this approach from former work, we denote our method as *constant velocity* cEPI (cv-cEPI).



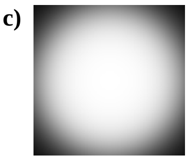


Figure 1. In a) the EPI (gray) and cv-cEPI (black) readout waveforms are shown. b) shows the k-space trajectory on top of the variable rBW-map generated by cv-cEPI. c) is the Fermi window that was used in this study.

Method: A circular *k*-space trajectory was designed to have a constant phase encoding *k*-space velocity by altering the gradient amplitudes, keeping the duration of each gradient lobe constant (Fig. 1a). This lowers the receiver bandwidth (*rBW*) and hence increases the SNR for high spatial frequency k_y lines (Fig. 1b). For simplicity, ramp sampling along k_x was omitted, but will be used in the future. A Fermi filter was used for apodization (Fig. 1c). To make sure potential SNR gains were not an effect of reduced spatial resolution, a 384×384 conventional Spin Echo image was acquired on a resolution phantom, which was used to compare the effective resolution of the full and the circular center of *k*-space. An *in vivo* SNR comparison was performed for a Spin Echo EPI sequence with rectangular and cv-cEPI readouts (TR/TE/Flip/rBW: 4000ms/119ms/90deg/125kHz) and (FOV/Matrix/sl.th: 240mm/128×128/4mm). Images were reconstructed with and without Fermi windowing. EPI was also reconstructed with points acquired outside the circle set to zero. For SNR comparison, EPI and cv-cEPI were scanned 8 consecutive times and for each volume SNR was estimated in two ways:

$$SNR_1 = \frac{\left\langle I_{ROI_{obj}} \right\rangle}{1.526 \cdot \sigma_{I_{ROI_{bg}}}} \text{ and } SNR_2 = \sqrt{2} \cdot \frac{\left\langle I_{i,ROI_{obj}} \right\rangle}{\sigma_{I_{i,ROI_{obj}}}} \text{ where } i=1..8.$$

In the first method (SNR_1), the signal was estimated as the mean signal from all slices within a manually drawn ROI (ROI_{obj}), and the noise as the standard deviation from a background ROI. For the second method (SNR_2), the signal and noise were estimated in each voxel as the mean and standard deviation across 8 consecutive scans. The mean value of the SNR-map inside the ROI_{obj} was then measured to obtain a scalar value. All scans were performed on an Excite 1.5T (G_{max}=40 mT/m, SR=150 T/m/s, GE Healthcare, Waukesha, WI, USA).

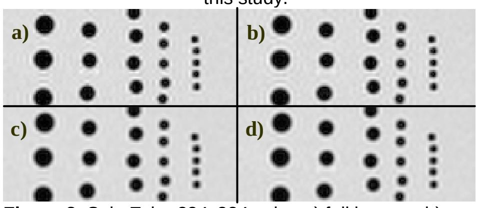


Figure 2. Spin Echo 384x384 using a) full k-space b) inscribed circle c) full k-space w. Fermi window d) inscribed circle w. Fermi window.

Results: Figure 2 shows a close up of the 384×384 Spin Echo scan, reconstructed using all data points vs. only points within an inscribed circle of *k*-space, and with and without Fermi filter. The circular *k*-space images (Fig. 2b and 2d) show a direction independent resolution, while the rectangular *k*-space images (Fig. 2a and 2c) have slightly higher spatial resolution and less truncation artifacts in the diagonal directions (i.e. higher resolution than prescribed). By applying the Fermi filter (Fig. 2c and 2d), most of the truncation artifacts are removed while spatial resolution is close to maintained. Figure 3 shows EPI compared to cv-cEPI, with and without the application of the Fermi filter, and Table 1 shows SNR estimates for EPI and cv-cEPI using the two SNR measures (SNR_1 in parenthesis). For rectangular EPI, an increase of 10% (10.7%) in SNR is seen by just removing data outside the inscribed circle (similar to what the Fermi does but without the smooth transition). This is not done in practice, but indicates that most of the SNR gain induced by the Fermi filter is due to the corner cropping. Adding the Fermi filter on the corner cropped data increases SNR only by another 1.7%. By applying cv-cEPI (having more acquired data points inside the circle) another 6.6% (7.3%) increase in SNR is gained. This increase can be attributed to the decreased *rBW* within the acquired circle compared to EPI.

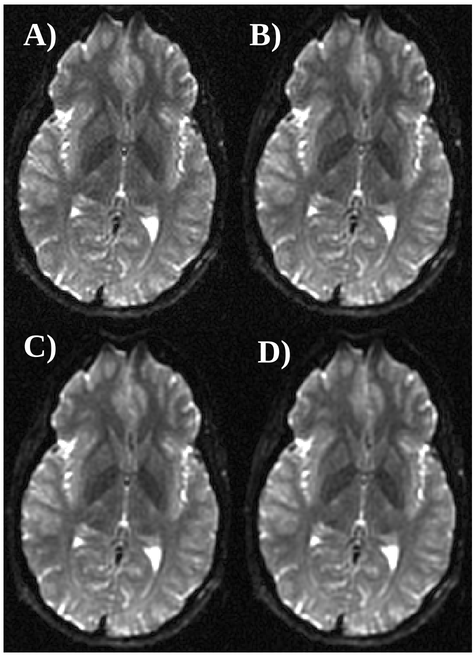


Figure 3. Spin Echo with A) EPI, no window B) cv-cEPI, no window C) EPI, Fermi filter D) cv-cEPI, Fermi filter.

TABLE 1	SNR	relative gain
EPI no window	22.39 (20.78)	100% (100%)
EPI no win. no corners	24.64 (23.00)	110.0% (110.7%)
cv-cEPI no win.	26.10 (24.52)	116.6% (118.0%)
EPI w. Fermi	28.93 (27.00)	100% (100%)
EPI w. Fermi no corners	29.43 (27.55)	101.7% (102.0%)
cv-cEPI w. Fermi	30.68 (28.69)	106.0% (106.3%)

Discussion & Conclusion: We have demonstrated the use of a new circular EPI trajectory, having slightly higher SNR compared to rectangular EPI. With a constant phase encoding velocity, the off-resonance sensitivity becomes homogeneous for all spatial frequencies unlike the previous cEPI method. Compared with the conventional Fermi filtered rectangular EPI, which discards data during reconstruction, the increased SNR in cv-cEPI comes from the lower receiver bandwidth inside the circle. Moreover, windowing techniques such as the above used Fermi filter affect resolution more than reducing the acquisition to a circular *k*-space. Implementation of cv-cEPI in the pulse sequence is quite straightforward. However care must be taken in the reconstruction process w.r.t. Nyquist ghost correction, as well as variable ramp sampling kernel sizes. As we can foresee few other drawbacks than these implementation issues, we believe this SNR increase can have impact on the acquisition strategy in all conventional EPI imaging, with application to fMRI, diffusion and perfusion.

References: 1. Pauly J et al., Proc. Soc. Mag Res., Nice, 1995, p106. 2. Nayak KS et al., Magn Reson Med 2001;46(3):430-435. 3. Skare S. et al., Magn Reson Med, 2007, 57(5): 881-90.