# Correction of EPI Nyquist ghosting caused by the non-uniform frequency response of the MRI receiver chain

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## Introduction

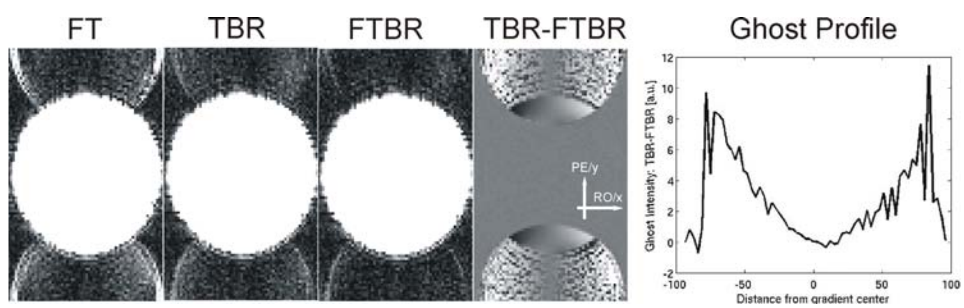
For the majority of rectilinear echo-planar imaging (EPI) sequences, every other phase-encoding (PE) line is acquired with an inverted readout (RO) gradient. Any effect that leads to a signal dependence on the RO direction and thus to a systematic difference between even and odd PE lines results in Nyquist ghosting. Nyquist ghosting appears as a component of image intensity shifted by half the field-of-view in the PE direction. Various causes for ghosting have been studied and techniques for their reduction have been developed. Recently, the magnitude frequency response characteristic of the MRI signal receiver chain has been shown to contribute to the Nyquist ghost [1]. During acquisition of a single PE line, the RO gradient ($G_x$) assigns a different frequency ($\omega$) to each location (x) in space. Since the receiver response depends on $\omega$, the signal originating from a given location x is multiplied by a location dependent weighting factor. Since the distribution of signal frequencies is reversed for every other PE line when inverting the RO gradient, the weighting and signal intensity varies systematically for odd and even PE lines, yielding a Nyquist ghost. Possible solutions are to optimize the coil loading and tuning to even out the frequency response characteristic and to reduce the RO bandwidth to minimize the covered frequency range. However, both methods limit the imaging possibilities and can only be used at the time of data acquisition. Here, we describe and validate a method that corrects for the differential frequency response by rescaling the acquired signal. The rescaling factor is determined from the bi-directional navigator echoes routinely acquired before the EPI readout [2]. Thus, the method needs no modification of the acquisition technique and can be applied post-hoc, provided raw data have been stored.

## Methods

The frequency response of the MRI receiver system is a complex-valued function. Discrepancies in the phase of the two acquisition directions are usually handled by navigator corrections [2]. Here, we correct for differences in the amplitude due to the weighting of the signal with the modulus of the frequency response curve. Since the frequency response depends on the particular configuration, such as the coil and coil loading, the weighting is best re-determined for each scanning session. According to [1] we approximate the frequency response of the receiver system only to first order. Therefore, a signal originating from the location x (measured from the gradient center) is multiplied by the weighting function: $\Phi_{\pm}(x) = \pm(G_x\alpha)x+1 = \pm\gamma x+1$, for a positive/negative RO gradient. In our implementation of EPI, navigator echoes with opposite RO direction are acquired for phase correction [3]. Thus, in image space, we can calculate a point-wise ratio of the magnitude of the navigator echoes ($I_+$, $I_-$) to estimate the differential frequency response: $(I_+-I_-)/(I_++I_-) = \gamma x$. The navigator echoes of all slices can be averaged to increase the signal-to-noise ratio, because the frequency response is determined by the receiver chain configuration. The slope $\gamma$ is estimated by linear regression weighted by the square of the signal intensity to reduce noise introduced from pixels outside the imaged object. The ideal signal intensity can be estimated by $I_0(x) = 1/\Phi_{\pm}(x)I_{\pm}(x)$. We assume that the center of the imaging volume coincides with the center of the RO gradient (as in the present study). If the EPI data are acquired during gradient ramping, $\gamma$ is not only spatially dependent but depends on the present gradient strength $G_x$, because $\gamma(t) = G_x(t)\alpha$. Therefore, we have based the estimation of $\gamma$ only on a subset of k-space data acquired on the flat top of the trapezoidal gradients. In a previously described generalized reconstruction scheme [3], the spatially and temporally dependent rescaling with $1/\Phi_{\pm}(x,t)$ can be readily introduced into the matrix transforming from k-space to image space by rescaling of the respective entries. However, for most objects it may not be necessary to correct for this ramp sampling effect, because low spatial frequency structures dominate. To assess the effectiveness of the presented ghost correction method, EPI images of a uniform spherical gel phantom were acquired on a 1.5 T Sonata scanner (Siemens Medical, Erlangen, Germany) with the parameters: TE = 50 ms, 36 slices, slice thickness/gap = 4/2 mm, matrix 64x96, 50% OS in PE, FOV = 192x192 $mm^2$, BW 2298 Hz/Px. To demonstrate that the variation in signal intensity is caused by the frequency response of the receiver system and therefore depends on the RO gradient strength, EPI images with different RO gradient amplitudes were acquired: $G_x$(flat top) = 64.9, 54.2, 39.5 µT/Px. The images were reconstructed using conventional regridded Fourier transform reconstruction (FT), generalized trajectory based image reconstruction (TBR, [3]), and the TBR with correction for the frequency response (FTBR). The level of ghosting was determined as the mean signal of the ghost minus the mean background signal divided by the mean signal of the phantom (hand drawn regions of interest).

## Results

Fig. 1a shows an imaged slice reconstructed with the FT, TBR, FTBR methods. Fig. 1b shows the difference in intensity between the TBR minus the FTBR image. In line with the theory, the Nyquist ghosting increased going from the gradient center outwards in the RO direction (left and right edge of the phantom). The FTBR reconstruction reduced this ghosting considerably as can be seen in the difference image (Fig. 1b) and the profile through the difference image at the location of the ghost (Fig. 1c). The ghost levels were: FT/TBR/FTBR = 2.4/1.4/0.8 %. As expected, the slope $\gamma$(64.9/54.2/39.5 µT/Px) = 0.101/0.085/0.062%/Px of the correction factor increased proportionally with the gradient strength $G_x$.




a) b) c)

## Discussion

Modulations of the local signal amplitude due to the MRI receiver system magnitude response can be a significant cause of Nyquist ghosting. We have presented a method to correct for this type of Nyquist ghosting, reducing the ghost by more than 40%. Since the correction method estimates the frequency response for each image, it can adapt to the variations in the frequency response due to different coils, coil loading or imaging parameters. The method does not require a special EPI acquisition scheme and is solely based on the navigator echoes acquired prior to the EPI readout. The correction method is fast and has been implemented for real-time image reconstruction at our site.

## References

[1] I. Delakis, K. Petala, and J. P. de Wilde, "MRI receiver frequency response as a contributor to Nyquist ghosting in echo planar imaging," *Journal of Magnetic Resonance Imaging*, vol. 22, pp. 324-328, 2005.

[2] F. Schmitt, M. K. Stehling, and R. Turner, *Echo-planar imaging* Berlin: Springer-Verlag, 1998.

[3] O. Josephs, R. Deichmann, and Turner R. Trajectory measurement and generalised reconstruction in rectilinear EPI. Proceedings of ISMRM 8, Denver, Colorado, p. 1517, 2000.

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