Potential impact of time-varying gradient delays in the EPI train on Nyquist ghost correction

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Introduction: EPI acquisitions are prone to ghosting artifacts due to gradient delays during its long readout. It is often assumed that such delays are constant over time and across the whole EPI echo train, which facilitates correction of the delays by inserting multiple phase navigators (i.e. ky=0 lines) into the EPI pulse sequence [1].Previous works [2,3] however have demonstrated that gradient system responses differ depending on operating frequencies. In this work, we show that the gradient delays vary across the echo train, and the degree and character of the variation depends on the echo-spacing frequency of the imaging sequence and may change in the course of a long acquisition (several minutes). Appropriate timing of the gradient delay calibration is crucial to control the ghost level to the minimum, ideally using echoes acquired at the nominal echo time for phase navigation.

Methods: Multiple time series of single-shot gradient echo EPI fMRI scans were acquired on a 3T Achieva-TX MR scanner (Philips Healthcare, Best) using a spherical phantom. The read-out bandwidth was modified to assess possible variations of gradient delays across the echo train. Values were chosen to gradually approach the mechanical resonance. A single non-phase encoded calibration acquisition is used to calculate the gradient delays for each individual gradient echo. Furthermore, for two echo-spacing frequencies the dynamic behavior of the gradient delays during the fMRI scan was studied by determining the gradient delays every 100 dynamics.

Results: Figure 1 a) visualizes the dependency of the gradient delay of each EPI echo on different echo-spacing frequencies. For echo-spacing frequencies (815 Hz – 929 Hz) far away from mechanical resonance frequencies of the gradient coil, the measure phase delays show a damped oscillation with periods of 8 to 16 echoes and maximal amplitudes of 2-5 mrad/pixel. For echo-spacing frequencies (1025Hz and 1043 Hz) close to a mechanical resonance frequency, however, the variations across the echo train increase considerably with amplitudes up to 20 mrad/pixel. Stabilization is not achieved until the end of the echo train, if at all. Depending on which echo is used to calculate the gradient delay, residual ghost levels can vary from 1%-2% to 9%. Figure 1 b) visualizes the temporal changes (i.e. over the time series of dynamic scans) of the gradient delays for each echo with various echo-spacing frequencies. For a chosen frequency (815 Hz, blue graphs) far away from the resonance of the system, only a slight offset is visible between consecutive scans while the variations show a similar pattern. This drift can be tracked and compensated to maintain constant ghost levels. The red graphs, however, show the temporal variation of the echo dependency for the 1025 Hz echo-spacing frequency close to the system resonance frequency. In this case, significant variations of the gradient delay over the echo train are observed which cannot navigator readouts, which are far away from the k=0 echo. Figure 1c) shows the temporal change of the residual ghost level for a fMRI scan with a spherical phantom with a 1025 Hz echo-spacing frequency close to the mechanical resonance.

Conclusion: We have demonstrated that gradient delays can vary across the echo train for certain EPI sequences. The temporal variation of gradient delays increases the closer the chosen sequence operates to the mechanical resonance frequency of the system. Accurate and robust correction of the Nyquist ghost in EPI requires determination of the gradient delays at the echo time of the EPI sequence. In addition, it is beneficial to avoid mechanical resonance frequencies of the gradient coil.

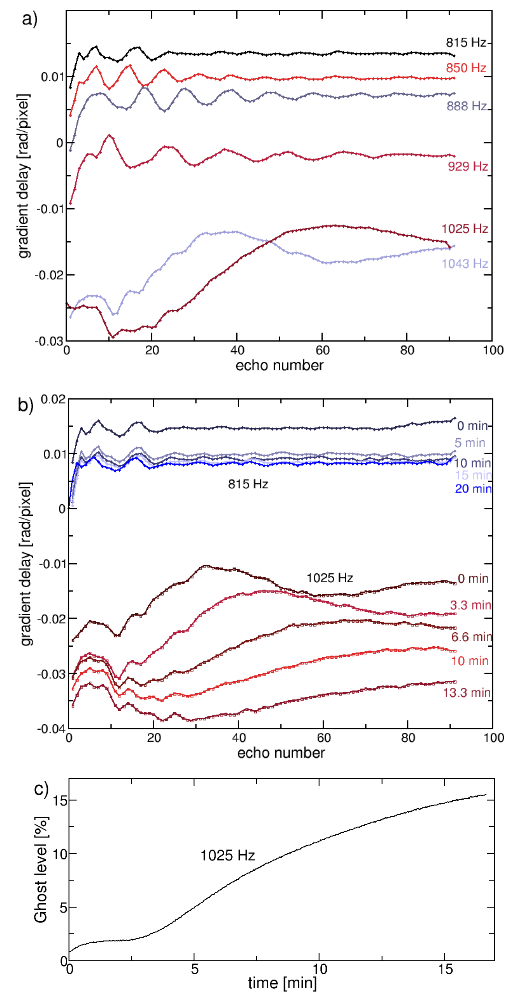

Figure1: a) Gradient delay as a function of the echo number for six different readout frequencies. b) Gradient error as a function of the echo number for two different echo-spacing frequencies over the time series of a scan (in steps of 5 and 3.3 minutes respectively). c) Temporal evolution of the residual ghost level close to the mechanical resonance.

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References:
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