A Method for Calibrating Inter-subsystem Hardware Delays on an MRI Machine

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Introduction
If the timing of the gradient, rf transmit, rf receive, and rf demodulation waveforms are not coincident, image artifacts will result. Herein, a methodology is suggested for the systematic quantification of HW delay differences and associated sequence design techniques that can be applied to multiple imaging methods to minimize the effect of these timing errors through common and systematic sequence design. The proposed method is entirely image based and implemented completely in software (SW), which maximizes its applicability to varied hardware (HW) platforms. Reducing the dependence of sequences on specific HW is of importance to manufacturers as they move through generations of HW, and to researchers who construct MRI systems utilizing off-the-shelf HW components. Finally, calibration of such inter-system delays should improve the robustness of associated image post-processing methods.

For example, if the gradient waveform and rf receive chain are not in sync an error in the presumed location of the echo in a conventional imaging experiment will result leading to a linear phase artifact in the resulting image. Most MRI methods, however, are fairly robust with respect to small timing delays between different HW components. The use of magnitude images effectively deals with the aforementioned timing error. Methodologies relying on phase information, however, must either be calibrated to avoid such errors, and/or use post-processing to remove their effects. Further, methods which rely on coincidence of field and rf echoes require correlation between the rf transmit, gradient, and rf receive HW. HW calibrations may be employed to minimize such timing errors, but they do not easily translate between systems with different HW components. Phase sensitive techniques and advanced imaging techniques, such as EPI, could still require post-processing to be applied due to the resolution of the correction and system variability issues, but ensuring reasonable initial conditions for the post-processing techniques improves their robustness.

In order to identify the timing differences between different HW components it is desirable to identify imaging methodologies which are particularly sensitive to timing errors, and for which gross artifacts are observed. Conventional EPI is one such imaging methodology. k-space is being traversed in a back and forth pattern during an EPI readout. If the start of sampling is not coincident with gradient activity then an error in the echo location will result. As lines of data are traversed in opposite directions, the error will result in an opposite timing shift t0 in every other line of k-space data. The resulting image will contain N/2 ghosts with stripes in the frequency encoding direction. Therefore, the FOV is offset in the frequency encoding direction. Thus, the FOV is offset, and the rf demodulation delay was modified until ghosting was again minimized. At this point, it was assumed that both the rf receive and rf demodulation waveforms were correctly aligned with the gradient amplifier waveform. This process can be repeated for each physical axis of the gradient.

Results
Timing delays between the gradient, data sampling, and rf demodulation waveforms were successfully aligned to within 1 microsecond accuracy. This calibration method has been successfully employed on systems with different HW delays characteristics, and has proven to be robust and easy to implement. Calibrating the waveform timing using this method has led to very robust success of subsequent de-ghosting routines performed during EPI reconstruction.

Discussion
The delays determined using this method can be applied to improve the robustness of other imaging techniques which rely upon accurate system timing. This method has been implemented as a system calibration technique, intended to be performed as part of routine maintenance, or installation. However, automated ghosting evaluation and numeric searches could be applied to this method determine optimal timing values. In this implementation, this method could be applied on a study by study basis.

References