Real-time B0 and first order shim correction during motion correction with cloverleaf navigators

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Introduction and Background

"Shim navigators" have been used to detect shim changes [1] and cloverleaf navigators have been used for real-time motion correction during brain imaging [2]. The cloverleaf navigator follows a path in k-space including a 90º arc in each of the three perpendicular planes and three traversals through the center of k-space along the three principal axes (Figure 1). Navigators are inserted at regular intervals throughout an imaging sequence such as 3D FLASH. Rigid body translations and rotations are extracted from the navigator signal and used to rapidly correct the imaging gradients in real-time. We demonstrate that zero and first order spatial changes in the B0 field, due to changes in subject position, breathing, and effects such as heating of the shim iron, can also be extracted from the cloverleaf navigator signal. By modifying the RF hardware center frequency and the offsets on the X, Y and Z gradients, we can correct for these effects in real time during imaging.

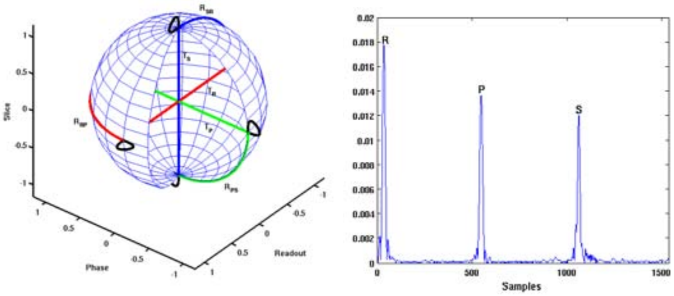

Figure 1: Cloverleaf navigator path (left) and signal (right).

Methods

Zero order offsets in the B0 field appear as a linear phase roll across the navigator readout that is independent of the applied gradient. This affects the accuracy of the translation estimates from the navigators and may result in shifts in the reconstructed image. A B0 offset is equivalent to a transmit/receive frequency offset.

Let **N** be a complete set of N complex samples of a navigator, $\mathbf{N}^{\mathrm{ref}}$ be the reference navigator from the navigator map (or the first navigator in the scan), T_{N} be the time from the RF pulse to the first navigator sample and T_{dwell} be the dwell time for navigator samples.

Define $\mathbf{T}=[\ T_{\mathrm{N}}\ \ T_{\mathrm{N}}+T_{\mathrm{dwell}}\ \ldots\ T_{\mathrm{N}}+(N\text{-}1).\ T_{\mathrm{dwell}}]$. Then the frequency offset Δf relative to the reference is

$$\Delta f = \tfrac{1}{2\pi}\phi(\mathbf{N}/\mathbf{N}^{\mathrm{ref}})\mathbf{T}^{+}$$

where the division is scalar, and $\mathbf{T}^{+}$ denotes **T**'s pseudoinverse. This is corrected either by adding the opposite phase to navigator and image samples or by adjusting the transmitter/receiver frequencies in real time during imaging.

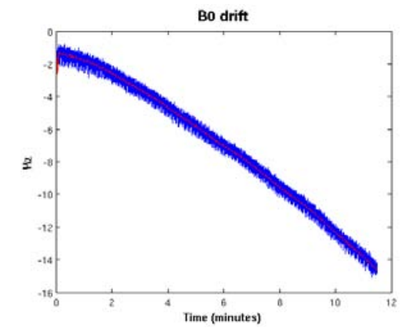

Figure 2: Estimated (blue) and feedback (red) frequency drift during gradient intensive 3D FLASH (stationary phantom).

First order spatial B0 changes (linear shim changes) appear in the navigator as shifts in the peaks measured during the three straight traversals through the center of k-space. Shifts correspond to the projections of the X, Y and Z shim errors onto the corresponding imaging axes.

For a given traversal, let the echo time TE represent the expected interval between the RF excitation pulse and the peak, assuming uniform B0. Let t_E represent the observed echo time. Let $G(t)$ represent the amplitude of the gradient applied during the traversal. Let ΔG represent the first order B0 term (gradient offset) in this direction due to inaccurate shim (assumed constant for the duration of one repetition time of the sequence). Then the k-space trajectory along this axis in the presence of the shim error is

$$k'(t) = \int_0^t (G(\tau) + \Delta G)\, d\tau$$

Since $k'(t_E) = 0$, it follows that

$$\int_0^{TE+\varepsilon_{TE}} (G(\tau) + \Delta G)\, d\tau = 0$$

where ε_{TE} is the observed shift in the peak t_E-TE.

Assuming the peak does not wander out of the constant gradient section of the navigator, i.e. $G(t) = G_T$ for $\min(0, \varepsilon_{TE}) < t - TE < \max(0, \varepsilon_{TE})$, the gradient offset ΔG is given by

$$\Delta G = -G_T \varepsilon_{TE} / (\mathrm{TE} + 2\varepsilon_{TE})$$

Assuming also that the signal peak in the center of k-space is smooth and spherically symmetrical, the gradient offsets on the three axes can be calculated independently. The peak amplitude does not decrease in its projection on the other axes because the corrections are rapidly fed back every repetition time along with the translation and rotation corrections. Linear shim corrections are implemented as offsets on the gradient amplifiers in the Siemens hardware and can therefore be switched as rapidly as regular gradient pulses in the sequence.

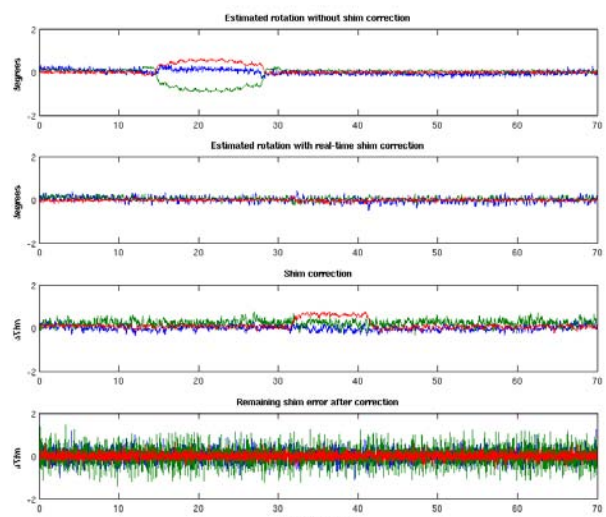

Figure 3: Uncorrected rotation estimates (top row), corrected rotation estimates (2nd row), shim estimates (3rd row) and unfiltered shim error after correction (bottom row) for stationary phantom with body loader introduced briefly into magnet bore near phantom (blue, green, red = rotations about slice, phase, read axes; shim on X, Y, Z gradients).

Results and Conclusion

We implemented rigid body motion correction with real-time zero and first order B0 correction using cloverleaf navigators on a 1.5T Siemens (Erlangen, Germany) Avanto. To test frequency drift, we ran an unusually gradient-intensive protocol to heat up the shim iron (3D FLASH with cloverleaf navigator every TR=12 ms, extra gradient spoiling, TE=2.11 ms, 224 x 1 mm axial slices, 256x256 matrix, 256 mm field of view, bandwidth 930 Hz/px, 11:32 min:s). Figure 2 shows the detected and feedback frequency drift value. To test the effect of shim, we positioned the Siemens body loading phantom outside the scanner bore and moved it into and out of the bore during a shorter protocol to induce a momentary shim change. Figure 3 shows the rotation/shim estimates with/without real-time shim correction.

Zero and first order B0 correction improves the accuracy of motion estimates, and therefore indirectly improves image quality. At high resolutions and in other sequence types (e.g. EPI), the B0 errors may be directly visible in the image as shifts and distortions. Real-time B0 and motion correction may ameliorate these effects.

Acknowledgement

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References

1. Ward HA, Riederer SJ, Jack CR, Magn Reson Med 2002, 48:771-780. 2. Van der Kouwe AJW, Dale AM, ISMRM, Kyoto, 2004.