Correction of RF pulse distortions, with application in radial imaging using SWIFT

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Background: The recently proposed 3D radial MRI technique. SWIFT (SWeep Imaging with Fourier Transform) [1], exploits a frequency-modulated pulse to accomplish nearly simultaneous excitation and reception. SWIFT uses the concept, initially recognized in [2], that the resulting spectrum is expressible as the convolution of the resulting NMR signal with the RF-pulse that the spins experience. In this approach, removal of the RF pulse from the NMR signal through correlation (a.k.a. deconvolution) requires accurate knowledge of the RF waveform that the spins experience. Yet, due to distortions occurring in the transmitter channel, this function is typically different from the digital waveform that was requested. There are several sources for consistent distortions of the pulse shape including amplifier non-linearity and amplitude induced phase modulation [3], which can be compensated by amplifier mapping, and smaller phase delays in the resonant circuitry [4], which requires more challenging hardware solutions. With SWIFT, the inevitability of persistent RF distortions is observable as a bullseye artifact, which can degrade image quality significantly. The present paper introduces a method for correcting these deleterious effects, without explicit knowledge of them or their origin.

Theory: Utilizing the theoretical notation in [1], the measured signal $r(t)$ can be expressed as in Eq. (1), where $x(t)$ is the RF pulse that the spins experience, and $h(t)$ is the free induction decay (FID) due to short pulse excitation (impulse response). The correlation with an expected pulse function $x_{\text{exp}}(t)$ in the frequency domain gives a spectrum H_{calc} (Eq. (2)), which is different from the spectrum of the spin system H (Eq. (3)). Here the RF pulse distortions are considered as any persistent effect, i.e., $x(t)= x_{\text{exp}}(t)+\Delta x(t)$,. For radial acquisitions the persistent distortion of the RF pulse can be estimated from the data itself. The premise for doing this is that the **average** projection of all directions is smooth, and that the error is the same for all views. The corrected projection can then be determined from Eq. (5), which requires division with the average projection ($\overline{H_{calc}}$) and multiplication with the filtered averaged projection ($\overline{\overline{H_{calc}}}$).

$$r(t) = h(t) \otimes x(t) \quad \Leftrightarrow \quad R(\omega) = H(\omega)X(\omega) \tag{1}$$

$$H_{\text{calc}} = R / X_{\text{exp}} \tag{2}$$

$$H_{\text{calc}} = (X / X_{\text{exp}})H \tag{3}$$

$$\overline{H_{calc}} = \sum\nolimits_{all\ views} H_{calc} \quad \& \quad \overline{\overline{H_{calc}}} = LP(\overline{H_{calc}}) \approx \overline{H} \tag{4}$$

$$H_{\text{corrected}} = \frac{\overline{\overline{H_{calc}}}H_{calc}}{\overline{H_{calc}}} = \frac{\overline{\overline{H_{calc}}}(X / X_{\text{exp}})H}{\overline{H}(X / X_{\text{exp}})} \approx H \tag{5}$$

Methods: Measurements from both 9.4T animal and 4T human systems, on which we have implemented SWIFT, have been investigated for exhibiting these bullseye artifacts. The function $\overline{\overline{H_{calc}}}$, the low-pass filtering of $\overline{H_{calc}}$, was estimated with a strongly windowed FFT (a hamming window to the power 30). This was consistently found to remove the artifact. Corrections with standard hamming filtering and subsequent polynomial filtering (Savitzky-Golay, 5^{th} order and frame size 61) have in some cases proved sufficient. The images were constructed using gridding with a Kaiser Bessel function.

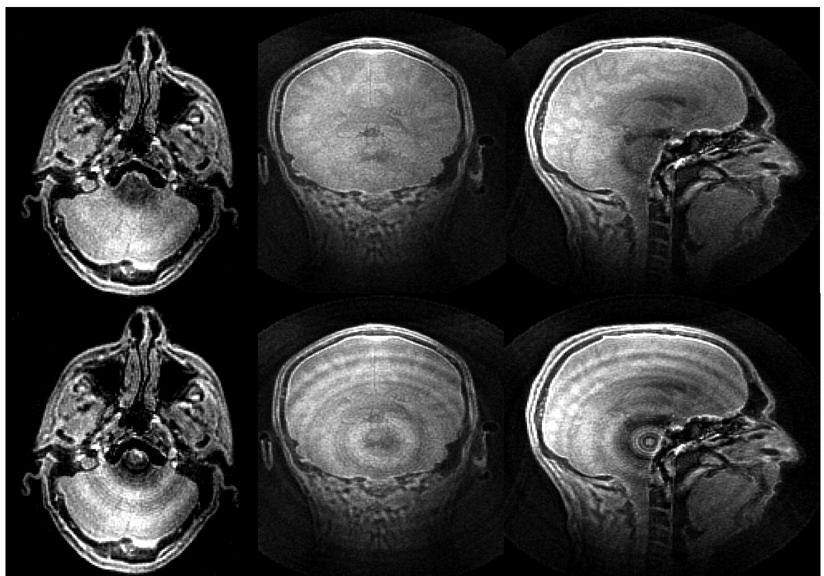

Figure 1. Whole head imaging at 4 T, acquired with a hyperbolic secant (HS1) pulse, TR = 6.1 ms, nominal flip angle = 4°, 96000 independent spokes, FOV = 35x35x35cm, acquisition time ~10 min, isotropic resolution of 1.37x1.37x1.37.

Results and Discussion:
Pulse imperfections due to electronic components and fundamental physical limitations are real and confounding factors for performing advanced MR experiments. Yet, with the future of MR tending toward non-Cartesian radial sequences and frequency swept pulses, corrections for such effects are needed. Here we have identified the origin of the dominant bullseye effect (i.e., that spins experience a distorted RF waveform), and propose a powerful data driven method for its correction - leading to images of clinical quality. Whole head imaging with SWIFT is now possible (Figure. 1), in which the resolution and contrast are excellent. Bullseye removal requires no additional acquisitions or modifications to existing protocols.. Long range (low frequency) perturbations relative to the object will be realized as an intensity modulation, correctable by standard intensity correction techniques – which can not handle high frequency modulations. In addition to the proposed post-processing technique it has been verified through additional direct measurements of the RF pulse that the solution of Eq. (1) can be corrected by correlation using the measured RF (data not shown).

References: [1] Idiyatullin, J Magn Reson, 2006. [2] Dadok, J Magn Reson, 1974 [3] Chan, MRM 1992, [4] Barbara, J Magn Reson 1991

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