Understanding Flow Artifacts and Localized Frequency Determination in Cardiac SSFP Imaging

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Introduction:

Balanced steady state free precession (SSFP) techniques offer excellent contrast between myocardium and blood at a high signal-to-noise ratio. At 1.5T, SSFP imaging has become the method of choice for the assessment of cardiac function. Recently it has been reported that frequency offsets due to either wrong resonance frequency determination (F_0) or field inhomogeneity cause flow related artifacts in SSFP imaging (1,2). This prompts for an improved shimming and F_0 determination procedure for SSFP imaging, in particular at 3.0T given the larger field inhomogeneities at the higher field strength. The purpose of this work was to understand flow and resonance frequency dependent artifacts in SSFP imaging and to develop a shimming and F_0 determination method for artifact free SSFP imaging.

Methods:

Simulations incorporating field inhomogeneity, variable flow, "out-of-slice" contribution and phase encoding for spatial localization were performed on a PC using MATLAB (MATLAB, Natick, MA). Longitudinal and transversal magnetization were calculated using the numerical solutions of the Bloch equations for a SSFP cine acquisition. The magnetization matrix incorporated static cardiac muscle and flowing blood including an "out-of-slice" segment which was not affected by the excitation radiofrequency pulses. Image profiles along the x direction with 128 phase-encode steps were reconstructed using the Fast Fourier transform. Three different flow patterns were simulated: no flow, constant flow of 50cm/s, and sinusoidal flow. The following parameters were used: flip angle = 40°, TR = 3.8ms, FOV = 320mm, heart rate = 60bpm, 20 cardiac phases, $T1_{blood}$ = 1512ms, $T1_{muscle}$ = 1115ms, $T2_{blood}$ = 141ms, $T2_{muscle}$ = 41ms.

For localized 2[nd] order shimming (3) and F_0 determination, a software tool was implemented on a PC. The shim procedure is based on a measured field (B_0)-map. The calculated shim corrections are then added to the measured B_0-map and used to calculate the optimal F_0 at the "phase center" of the shimmed region of interest.

SSFP short axis views were acquired on a 3.0T Intera whole body MR system (Philips Medical Systems, Best, The Netherlands) using the same parameters as for the simulation.

Results:

One line of a short axis image was simulated in phase-encode direction (Figure 1). The second dimension in the figures is the time dimension with 20 heart phases.

Figure 2 shows the results of the simulation. Field inhomogeneity of 600 Hz across the tissue volume leads to two dark bands, one in the muscle and one in the blood pool (Figure 2B). In-flow into the slice increases the signal as a function of flow velocity (Figure 2C). A frequency offset (location close to a dark band) significantly increases the signal intensity of the flowing blood (Figure 2D) as has been shown by Markl et al in (1). In addition, artifacts (Figure 2D) along the phase-encode direction are present. In case the frequency offset is accompanied with variable flow, severe time-varying artifacts (Figure 2E) become visible along the phase-encode direction.

This "through-plane flow transient" artifact is also seen in-vivo if the resonance frequency is not properly determined. In Figure 3, a single time-frame during flow deceleration of a cine short-axis SSFP acquisition obtained with localized 2[nd] shimming is shown for (a) an acquisition at optimal F_0 and (b) an acquisition at a frequency offset of 100Hz.

Discussion:

In this work it is shown that "through-plane flow transient" artifacts emerge at locations close to dark band artifacts if there is through-plane flow of variable velocity. Spins flowing into the imaging plane at the position of a dark band will generate magnetization of high variance in phase and magnitude as they are still in a transient phase and will, therefore, cause false phase encoding.

Using localized shimming and F_0 determination, flow-related artifacts are efficiently reduced facilitating artifact-free cine SSFP imaging at 3.0T.

References:

[1] Markl M. et al., Proc ISMRM, p.293, 2003
[2] Li W. et al., Proc ISMRM, p.1568, 2003
[3] Schär M. et al., Proc ISMRM, p.174, 2003

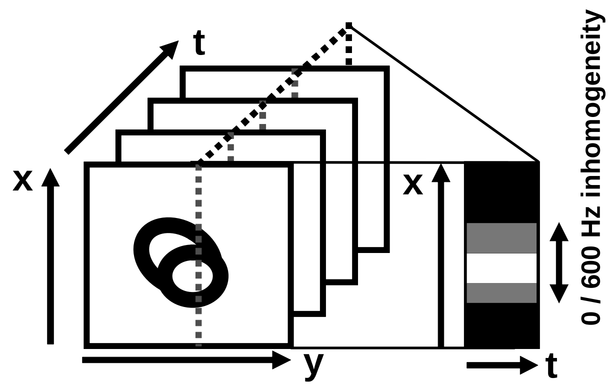

Figure 1: The simulations are performed for one line of a short axis view image along phase-encode direction (x) for 20 heart phases within the cardiac cycle. Field inhomogeneity (0 or 600 Hz) is applied linearly over the muscle-blood tissue.

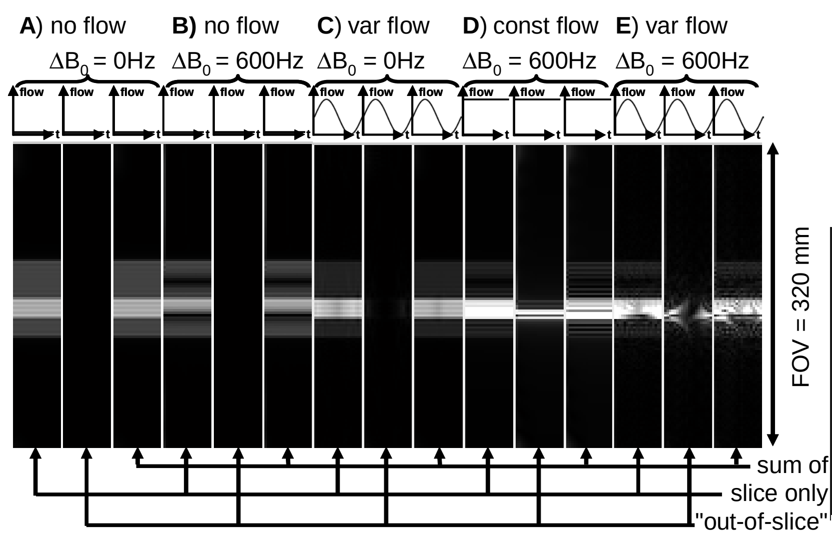

Figure 2: Simulations for different flow patterns and with or without field inhomogeneity ΔB_0. The constant (const) flow and the maximum of the sinusoidal (var) flow were both 50cm/s. Simulations show the severe, time varying "through-plane flow transient" artifact only in case of variable flow and frequency offset. Contrast was cut in half for C), D) and E) compared to A) and B) as the maximum signal intensity was more than doubled.

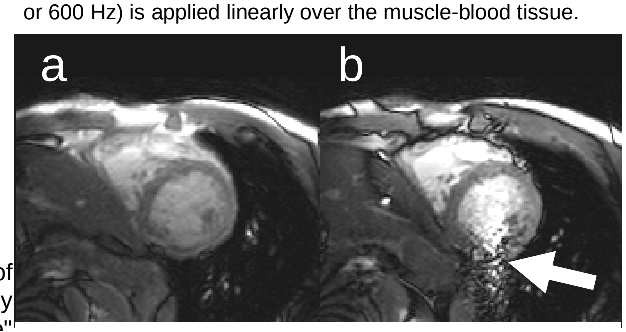

Figure 3: a) Short axis SSFP function time-frame at early diastole measured with localized 2[nd] order shimming and optimal F_0 as calculated with the proposed method. **b)** The same acquisition as in a) with a frequency offset of 100 Hz causing a through-plane flow transient artifact (white arrow).