Local Linear Shimming for Cardiac SSFP Imaging at 3T

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Abstract
The steady state free precession (SSFP) sequence is the method of choice for the assessment of cardiac function at 1.5T. The higher B₀ field inhomogeneities at 3T cause large artifacts near the posterior vein of the left ventricle. Therefore more attention has to be paid to the shimming procedure. A local shim tool based on B₀-maps was implemented to calculate the shimming parameters. The available linear shim sets at the 3T system were used to suppress artifacts for in-vivo imaging. Nearly artifact-free SSFP cardiac images are demonstrated.

Introduction
Steady state free precession (SSFP) sequences, also called balanced fast field echo or true FISP [1], offer a high contrast between myocardium and blood. The signal-to-noise ratio is higher in comparison to standard spoiled gradient echo protocols. SSFP therefore is suitable to study the function of the heart [2]. Shorter T2* values and the larger B₀ inhomogeneities within the left ventricle (LV) make fast imaging of the heart more difficult at 3T compared to lower field strengths [3]. Especially adjacent to the posterior vein of the LV (PVLV) high B₀ field inhomogeneities were measured.

The purpose of this work was to develop a local shim tool to correct for the B₀ field inhomogeneities in the LV in order to acquire artifact-free images.

Methods
We implemented a local shim tool using IDL (Research Systems, Inc., Boulder, CO) on a PC. The shimming procedure is based on a B₀-map. The B₀-map is the difference of two phase-images measured at different echo times (TE) and it therefore reflects the field inhomogeneities. The two phase-images were measured with a multi-slice dual echo gradient echo sequence. On the modulus image the region of interest (ROI) is selected. Possibly the B₀-map has to be unwrapped.

Using a linear shim the field inhomogeneities can be accounted for with

\[ \Delta B₀(x, y, z) = B₀_x \cdot x + B₀_y \cdot y + B₀_z \cdot z \]

Therefore the gradient offsets Gₓ, Gᵧ, and Gz have to be determined. The measured B₀-map is the phase φ accumulated during \( \Delta t = TE_1 - TE_2 \) as given in

\[ \phi(x, y, z) = \Delta t \cdot \Delta B₀(x, y, z) \]

In the 12-bit phase images a scale of 4096 is equivalent to 2π. With the gyromagnetic ratio of protons \( \gamma/2\pi = 42.577 \, MHz/T \) an array B for all points r within the ROI is defined as

\[ B(r) = \frac{4096 \cdot 42.577 \cdot \Delta t}{\gamma} \]

The shimming parameters are calculated solving the equation

\[ AX = B \]

with \( A = \{x, y, z, 1, \ldots\} \), an array for every point in the ROI, \( X \) the parameters to be evaluated (the shim gradients with the offset frequency \( \Delta f_0 = \{G_x, G_y, G_z, \Delta f_0\} \), and B as defined above. The equation is solved using a constraint Levenberg-Marquardt least-squares maximization (MINPACK-1) provided by C.B. Markwardt (NASA/GSFC Code 662, Greenbelt, MD 20770).

Measurements were performed on a 3T Intera MR whole body system (Philips Medical Systems, Best, The Netherlands) equipped with a transmit/receive body coil and a 6-element cardiac coil. For the acquisition of the B₀-map one cardiac epi element was used, for the SSFP scans a five element coil array was positioned around the subject’s chest.

The images were acquired in healthy volunteers. After the survey scans the B₀-map was measured at the position of the planned SSFP function scan: 3 overimposing (5mm) slices with a thickness of 10mm and a field of view of 330mm by 264mm. The acquisition was vector ECG-triggered with a trigger delay of 500ms. Respiratory motion was compensated using a navigator echo based gating and tracking technique using a gating window of 5mm. The navigator was placed in feet-head direction on the dome of the right hemi-diaphragm. The data of the B₀-map was evaluated on the PC as described above.

At the same position two single slice, breath-hold SSFP series were performed with a field of view of 330mm by 264mm (scan resolution 214x160) and a slice thickness of 8mm. In the 12s breath-holds 19 heart phases were acquired. The other parameters were TR: 3.4ms, TE: TR/2, and flip angle 45°. The first scan was performed with a standard shim and the second scan with the local linear shim settings.

Results
In Figure 1 the procedure for shimming is shown for one slice of the B₀-map. ROI selection on the modulus image is shown in Figure 1 A). Only the posterior part of the LV, where the highest gradients are seen (Figure 1 B), was selected. The calculated linear shim corrections for this position are plotted in 1 C). Figure 1 D) shows the expected B₀-map after correction, which is the sum of 1 B) and 1 C).

In Figure 2 phases 8 (B, C) and 13 (A, C) out of the 19 phases are shown. In the upper row are the images acquired with the standard shim settings and in the lower row are the ones with the local linear shim. In the images without the local shim large artifacts are visible near the PVLV. Using the local shim settings these artifacts are suppressed. A small artifact remains in the image at systole (arrow in Figure 2 D).

Discussion
A local shim tool based on B₀-maps was successfully implemented. It was demonstrated that local linear shimming is necessary for SSFP cardiac function imaging at 3T.

References