Influence of Off-resonance in Myocardial T1-mapping using SSFP based MOLLI Method

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Introduction: Frequency dependence of SSFP imaging is well known and results in dark band artifacts. Myocardial T1-mapping methods such as MOLLI [1] use single shot SSFP readout and are prone to error in T1-measurement that is frequency dependent. The readout excitation flip angle used in MOLLI is typically low to reduce the influence of the readout on the inversion recovery and thereby improve T1-measurement accuracy. However, a significant error in T1 results at relatively small off-resonance frequencies that may be less well appreciated. This error is not related to the frequency response of the inversion which is nearly constant by design, but arises due to the fact that off resonance significantly affects the signal observed during the transition to steady-state typical in single shot imaging, making each inversion time measurement different, and ultimately resulting in biased T1 values.

Methods: A waveform level Bloch simulation of the MOLLI T1-mapping method was implemented to study errors in T1-mapping, their dependencies and their sensitivities of various sequence and protocol design parameters. The simulation included the RF excitation pulse waveform and gradients in order to accurately model the variation in flip angle across the slice profile. Results are provided for a specific MOLLI protocol which used a 5(3)3 sampling scheme acquiring 8 images in 11 heartbeats, FA=35°, TR= 2.8 ms, TImin=105 ms, TIshift=80 ms. Experimental validation was performed using CuSO4 doped agar gel phantoms with varying concentrations resulting in various combinations of T1 and T2. In-vivo measurements of off-resonance maps due to variation in B0-field was performed in n=18 subjects using a multi-echo GRE sequence and using a standard shim to determine typical expected variation in frequency. In-vivo T1-maps were acquired with several intentional adjustments to the linear shim to illustrate the apparent variation in measured T1 with off-resonance.

Results: The steady state response of SSFP readout vs frequency (Fig 1) for various flip readout excitation angles shows the familiar dark bands spaced 1/TR (T1/T2/TR=1000/45/2.8 ms). At 1.5T (Magnetom Avanto, Siemens Medical Solutions, Erlangen, Germany) using a standard shim, the mean off-resonance frequency in the LV myocardium was 28.8±23.4Hz (m±SD) and the maximum error was 82.8±36Hz. The error in T1-measurement (Fig 2) is calculated vs off-resonance frequency for T1 in the range 200-1200ms and myocardial T2=45 ms. At T1=1000ms, measured T1 varied by 10ms (1%) across ±50 Hz, and 20 ms (2.0%) across ±75 Hz.. This variation across frequency is in addition to the measurement error for on resonance tissue, which is due to the approximation used in the "Look-Locker" correction for influence of the readout. Experimental data from several phantoms (Fig 3) illustrate the off-resonance dependence. An in-vivo example (Fig 4) demonstrates the differing appearance of T1-maps with intentional changes to the linear shim currents thereby affecting the off-resonance across the heart; the T1 and off-resonance frequency in a septal ROI varied (left to right) from 1022 ms (18 Hz), 978 ms (56 Hz), 971 ms (76 Hz), and 904 ms (154 Hz).

Discussion and Conclusions: The off-resonance sensitivity of T1-mapping using the SSFP based MOLLI method is characterized. While SSFP steady state banding artifacts are well known, it is less well appreciated that there may be significant T1-mapping errors in regions that do not experience banding. This may lead to artifactual appearance with regional variation if there is field gradient due to imperfect shim. It is therefore important for T1-mapping to use an optimized local shim to minimize off-resonance in the myocardial region of interest.

References: [1] Messroghli, et al J Magn Reson Imag. 2007, 26:1081–6.

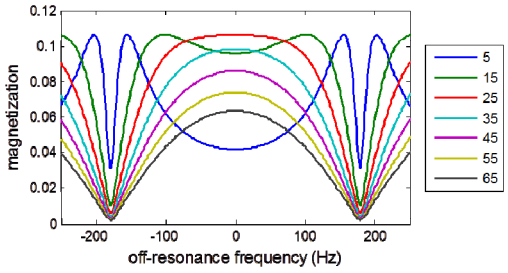

Figure 1. Steady state SSFP response vs off-resonance frequency for T1/T2/TR=1000/45/2.8 ms, for various readout excitation flip angles.

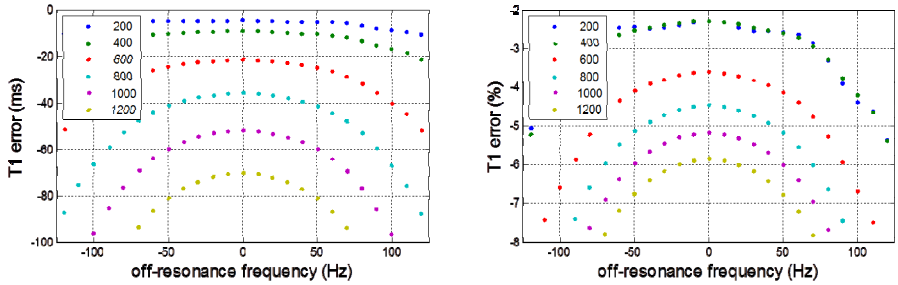

Figure 2. Simulated error in T1-measurement vs off-resonance frequency using specific MOLLI protocol for myocardial T2= 45 ms and various values of T1, in msec units (left) and expressed in % error (right).

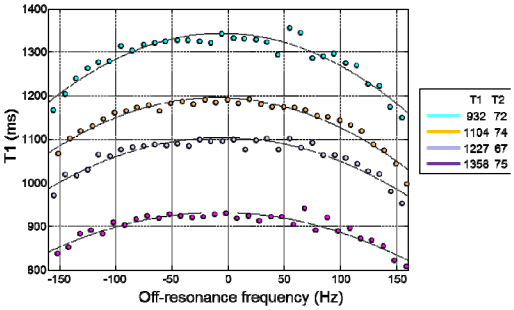

Figure 3. Measured error in T1 vs off-resonance for various CuSO4 agar gel phantoms.

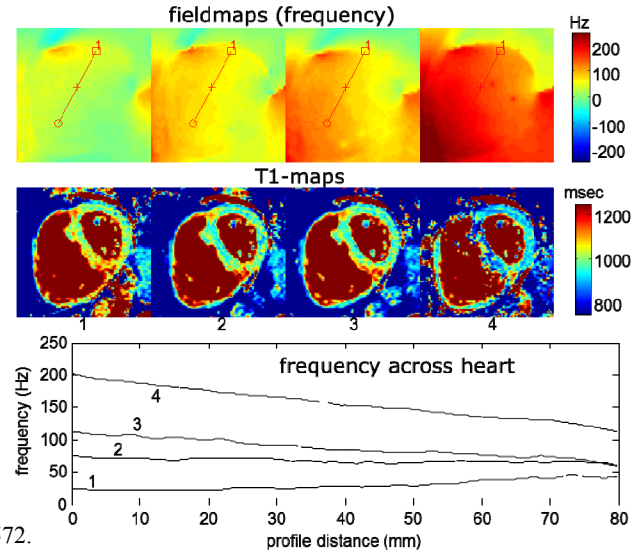

Figure 4. In-vivo field maps and corresponding off-resonance field maps for various shims illustrating differing appearance in T1-map across the heart.