True T1 Mapping with $SMART_1Map$: A Comparison with MOLLI

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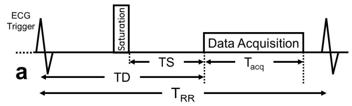
Introduction: $SMART_1Map$ (Saturation Method using Adaptive Recovery Times for cardiac T1 Mapping) is a new single-point T1 mapping technique [1]. Unlike Look-Locker (LL) approaches, such as MOLLI [2], which yield an “apparent” T1 (or T1*), $SMART_1Map$ directly measures true T1. Because T1* is a function of imaging parameters, it is always shorter than T1, and correction methods are required to estimate the true T1. This work compared the T1 accuracy of $SMART_1Map$ and MOLLI against IR spin-echo in phantom experiments under several imaging conditions.

Methods: Analogous to gold-standard spin-echo methods for T1 measurement, $SMART_1Map$ uses a series of single-point saturation-recovery experiments, each consisting of a saturation pulse, a recovery time TS during which free T1 relaxation occurs, and a balanced SSFP readout (Fig. 1). Short TSs (< RR interval) are acquired within a single heartbeat and are automatically and evenly distributed between the shortest user-selected TS and trigger delay (Fig. 1a). Longer TSs (up to 4xRR), which have not been accurately quantified until now, are performed across multiple heartbeats using a novel adaptive recovery time method (Fig. 1b). Although MOLLI assumes a constant heart rate for TIs that span several heartbeats, these long recovery times are in fact heart-rate-dependent. In order to accurately quantify long TSs, $SMART_1Map$ adapts the recovery time to changing heart rates by measuring all heartbeats in real time. For example, consider TS=2xRR with a nominal heart rate of 60 bpm. If the heart rate increases to 70 bpm on the second heartbeat, $SMART_1Map$ would correctly report TS=1857 ms rather than the nominal 2000 ms. This feature makes $SMART_1Map$ insensitive to intra-scan heart rate variations. A phantom composed of a range of T1s and T1/T2 ratios was scanned with single-shot MOLLI and $SMART_1Map$ (52 k_y lines) on a GE MR450w scanner. Eight TIs were acquired in 14 heartbeats for MOLLI (2, 2, and 4 heartbeats per LL block), and 5 TSs in only 9 heartbeats were acquired for $SMART_1Map$ (1, 1, 1, 2, and 4 heartbeats after saturation). Recovery times (TI, TS) ranged from 100 to 4000 ms. Data was fit to the equation $\mathbf{A} - \mathbf{B}\exp(-t/\tau)$ to find the time constant τ for MOLLI (τ = T1*) and $SMART_1Map$ (τ = T1). T1 was estimated for MOLLI using the LL correction T1 = ($\mathbf{B}/\mathbf{A}$–1)T1* [2, 3]. Scans were repeated at simulated heart rates of 60, 75, and 100 bpm and with different readout window durations (T_{acq}) (205, 235, and 368 ms). T_{acq} was changed by adjusting the frequency-encoding resolution (and thereby TR).



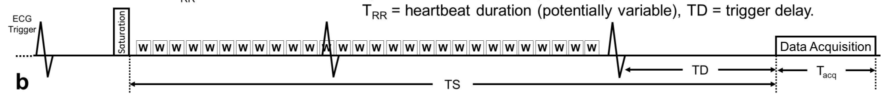


Figure 1. $SMART_1Map$ pulse sequence. **a**. Imaging with TS < T_{RR} is performed within one heartbeat. **b**. Imaging with TS > T_{RR} is performed across multiple heartbeats; thus, TS is heart-rate dependent. When TS > T_{RR}, wait pulses (W) are played out during portions of the cardiac cycle that are not normally timed by the pulse sequence. T_{RR} = heartbeat duration (potentially variable), TD = trigger delay.

Results: Average T1 errors over all measurements were 0.9±3.4% for $SMART_1Map$ and -4.8±13.3% for MOLLI (Fig. 2). Comparisons of $SMART_1Map$ with MOLLI for variations in heart rate and T_{acq} are shown in Figure 3. In general, T1 was underestimated using MOLLI, with the underestimation increasing with longer T_{acq} and higher heart rate. $SMART_1Map$ exhibited consistent accuracy, showing no dependence on T1, T_{acq}, or heart rate.

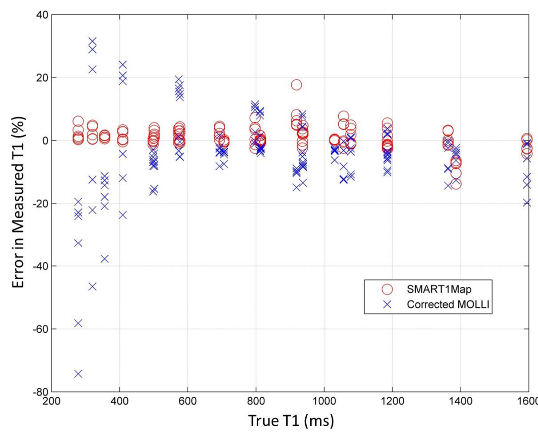


Figure 2. Percent error in measured T1 for all experiments from $SMART_1Map$ and MOLLI compared with true T1 from IR spin-echo.

Discussions: $SMART_1Map$ yielded more accurate T1 measurements than MOLLI under all conditions. As expected, T1* measured with MOLLI underestimated true T1, while the corrected T1 yielded improved results at some T1s but not at others. The pattern of the MOLLI error as a function of T1 in Figure 1 is similar to the results presented in [2], and the overall error of around -5% for clinical T1s is consistent with the general findings in previous MOLLI studies [2,4,5]. The higher errors for MOLLI at lower T1s could be problematic for post-contrast-enhanced imaging, where T1s are expected to be less than 500 ms. MOLLI also showed sensitivity to changes in heart rate and T_{acq}. These effects are all likely due to the LL correction, the applicability of which has yet to be validated. In contrast, $SMART_1Map$ demonstrated consistently accurate results that were independent of T1, heart rate, and T_{acq}. In an in vivo companion to this study, four volunteers were scanned using MOLLI and $SMART_1Map$, with average (N=12) myocardial T1 values of 1013 ms and 1193 ms, respectively. The in vivo MOLLI results were consistent with other MOLLI-based studies [2,4,5], and the $SMART_1Map$ results were similar to those from other single-point methods (1219 ms [6] and 1175 ms [7]).

Conclusions: $SMART_1Map$ offers several distinct advantages over MOLLI: 1) As a saturation method, it is more efficient than inversion recovery. 2) As a single-point acquisition, it is insensitive to imaging parameters and directly measures true T1 without the need for correction. 3) The use of adaptive recovery times via cardiac cycle timing ensures the accuracy of long recovery times, a point which has previously been overlooked in cardiac imaging. As a result, $SMART_1Map$ should be highly robust to variable imaging conditions.

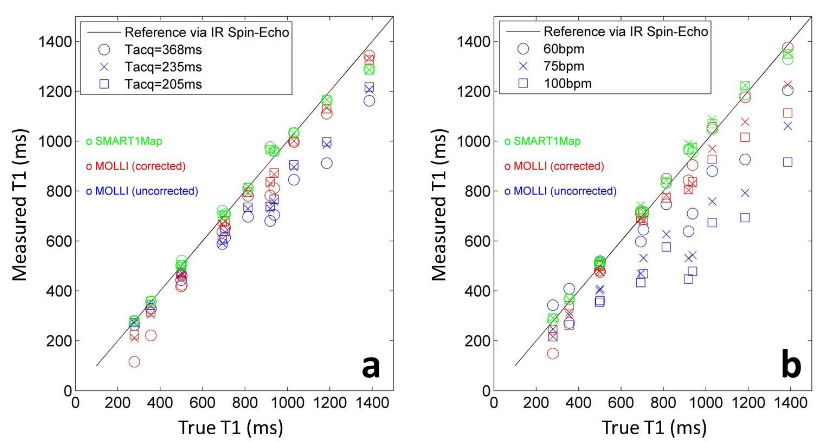


Figure 3. T1 accuracy for $SMART_1Map$, uncorrected MOLLI, and corrected MOLLI as a function of T_{acq} (**a**) and heart rate (**b**).

References: [1] Slavin, Proc. ISMRM, 2012, p.1244. [2] Messroghli, MRM 2004, 52:141. [3] Deichmann, JMR 1992, 96:608. [4] Messroghli, Radiology 2006, 238:1004. [5] Piechnik, JCMR 2010, 12:69. [6] Wacker et al., MRM 1999, 41:686. [7] Chow et al., Proc. ISMRM, 2012, p.395.