# MOLLI $T_1$ Values Have Systematic $T_2$ and Inversion Efficiency Dependent Errors

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**INTRODUCTION** Diffuse myocardial fibrosis occurs in various cardiomyopathies and has been assessed with myocardial and blood pool $T_1$ values before and after intravenous gadolinium[1]. The MOLLI sequence[2] has been widely used for quantitative $T_1$ mapping and is known to underestimate myocardial $T_1$ values at higher heart rates[4], however its dependence on $T_2$ values and inversion pulse efficiency has not been explored. We investigate its accuracy in phantoms, in-vivo, and with Bloch equation simulations, and compare to a new saturation-recovery $T_1$ mapping technique.

**METHODS** Phantoms: 14 $NiCl_2$ doped agarose phantoms with a broad range of $T_1$ and $T_2$ values to simulate blood or myocardium at various levels of edema and gadolinium concentrations were imaged on a 1.5 T Siemens Avanto MRI. Gold standard spin-echo (SE) experiments with TR>5s and 90° flip were used, with inversion-recovery (IR) at 16 TIs (100–5000ms) to measure $T_1$, and 7 TEs (11–200ms) to measure $T_2$.

A common MOLLI implementation consisting of 2 inversion sets of 3 and 5 images, 75% partial Fourier, $TI_{min}$=110ms with 80ms increment, 35° flip, and TE/TR=1.03/2.4ms was used with a simulated HR of 60bpm. $T_1$ was calculated with a standard 3 parameter exponential fit and Look-Locker correction[3]. Inversion pulse efficiency was assessed using centric gradient echo k-space readout with a single image inversion set, repeated 16 times with TIs spanning 50–3000ms and fitting data to $\{Signal = A[1-2\eta\cdot\exp(-TI/T_1)]\}$, where A is a scaling factor and $\eta$ is inversion efficiency.

A new SAturation-recovery single-SHot Acquisition (SASHA) $T_1$ mapping technique was also used: single-shot SSFP images from 20 consecutive heartbeats with incremented TI spanning the RR interval in the last 19 images (no saturation in the first image), 70° flip, TE/TR 1.3/2.6ms, full k-space, and simulated HR of 60bpm. Saturation efficiency was assessed using centric gradient echo readout with 19 TIs (24–790ms) and a "no-saturation" image. Data was fit to $\{Signal = A[1-\eta\cdot\exp(-TI/T_1)]\}$, to calculate both $T_1$ and saturation efficiency ($\eta$).

In-Vivo: Myocardial and blood $T_1$ values were measured in 10 healthy volunteers at a mid-ventricular short-axis slice prior to and 20 minutes following 0.1mmol/kg Magnevist using both MOLLI and SASHA with parameters as described above, but with 10 images for SASHA. In two additional volunteers, $T_1$ mapping was performed in skeletal muscle (left and right latissimus dorsi) in an axial slice using inversion-recovery HASTE (IR-HASTE), MOLLI, and SASHA. IR-HASTE was performed with 6 TIs (100–4200ms) with an effective TE=13ms. Preparation pulse efficiency ($\eta$) was also assessed as above.

Simulations: Bloch equation simulations of MOLLI and SASHA were performed in MATLAB using actual acquisition and timing parameters, with SE-derived $T_1/T_2$ values (in phantoms) and measured preparation (saturation or inversion) pulse efficiency ($\eta$).

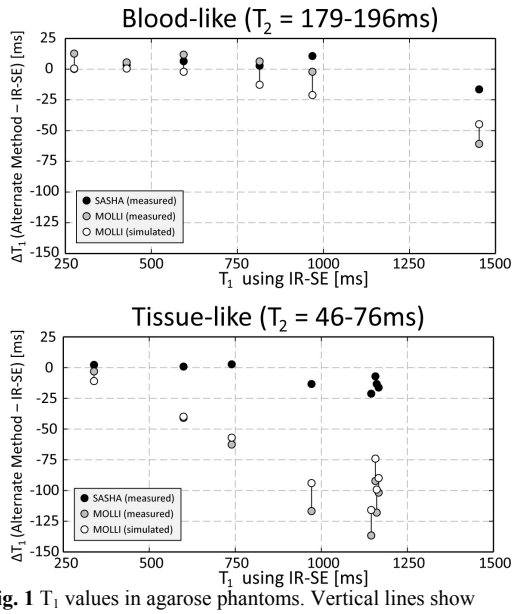


**Fig. 1** $T_1$ values in agarose phantoms. Vertical lines show difference between simulated and experimental MOLLI values.

**RESULTS** Phantoms: With a longer $T_2$ (blood-like), both MOLLI and SASHA $T_1$ values show good agreement with gold-standard IR-SE values, while phantoms with shorter $T_2$ (tissue-like) have substantial $T_1$ underestimation using MOLLI not seen with SASHA (**Fig. 1**). In phantoms, $\eta$ was found to be 97.5±1.2% for MOLLI's inversion pulse and 101.5±0.9% for SASHA's saturation pulse. Simulations using SE-derived $T_1$, $T_2$, and $\eta$ show good agreement with observed $T_1$ values for both MOLLI (1.7±1.0% absolute difference, vertical lines **Fig. 1**) and SASHA (0.8±0.4% difference, not shown).

Skeletal Muscle: SASHA mildly overestimated $T_1$ compared to IR-HASTE (1074±20ms vs. 1029±33ms), while MOLLI values were substantially lower (788±21ms). $\eta$ was 100.5±0.5% for SASHA but only 91.1±1.3% for MOLLI. Using a literature $T_2$ value of 33ms[5] for skeletal muscle, the measured $\eta$'s, and average IR-HASTE values, simulations predicted SASHA and MOLLI values of 1027 ms and 855 ms respectively.

Myocardium: Baseline MOLLI myocardial $T_1$ values (935.5±24.9 ms) in healthy subjects (5 male, 28.8±6.6yrs, 63.4±8.4 bpm) were similar to previously reported MOLLI values[3,4], but substantially lower than SASHA (1175.2±27.6 ms, **Table 1**). Differences are smaller for blood $T_1$ values (**Table 1**). Simulations using average SASHA $T_1$ as truth, 91% inversion efficiency (as measured in skeletal muscle), and literature[6] $T_2$ values of 50 ms for myocardium and 240 ms for blood predict baseline and post-Gd MOLLI $T_1$ values within 6% of actual measurements (**Table 1**).

| $T_1$ [ms] | Myocardium | | Blood | |
|---|---|---|---|---|
| | Baseline | 20min Post Gd | Baseline | 20 min Post Gd |
| **SASHA** (Measured) | 1175.2±27.6 | 752.9±48.2 | 1687.4±85.8 | 542.6±56.3 |
| **MOLLI** | | | | |
| Measured | 935.5±24.9 | 614.4±33.8 | 1514.1±107.5 | 524.9±55.2 |
| Simulation ($\eta$ = 91%) | 989.6 | 654.0 | 1464.5 | 500.8 |
| Simulation ($\eta$ = 100%) | 1085.9 | 717.3 | 1605.3 | 549.8 |

**Table 1.** $T_1$ values in 10 healthy volunteers.

**CONCLUSIONS** Myocardial MOLLI $T_1$ values are routinely 100–200ms lower than saturation-recovery based SASHA values, which can be explained by MOLLI's sensitivity to $T_2$ and inversion efficiency. MOLLI simulations predict $T_1$ values in good agreement with actual measurements when incorporating $T_2$ effects and measured inversion efficiency. Systematic $T_2$ effects reduce myocardial $T_1$s by ~100 ms, while a 91% inversion efficiency ($\eta$) measured in nearby skeletal muscle would explain the further 100ms underestimation, suggesting a similar non-ideal inversion efficiency in myocardium. Errors are smaller in the longer $T_2$ blood and also in phantom studies where higher inversion efficiency is achieved. $T_2$ dependent errors in MOLLI are inherent to all its variants due to the accumulated $T_2$ effect on magnetization between images within each inversion set and must be considered when deriving parameters such as extracellular volume fraction, which combine blood and myocardial $T_1$ values. Inversion efficiency must also be measured to ensure accurate $T_1$ values in MOLLI implementations. The saturation-recovery SASHA technique shows no $T_2$ dependence and good agreement with gold standard values in phantoms and skeletal muscle, with similar or shorter acquisition times.

**REFERENCES** [1]Flacke *et al*. Radiol 2001;**218**:703-10 [2]Messroghli DR et al. MRM 2004;**52**:141-6
[3]Piechnik SK *et al*. J Cardiovasc Magn Reson 2010;**12**:69 [4]Toussaint JF *et al*. MRM 1996;**35**:62-9 [5]Foltz WD *et al*. MRM 2003;**49**:1089-1097