Human cardiac T_1 measured at 7 Tesla

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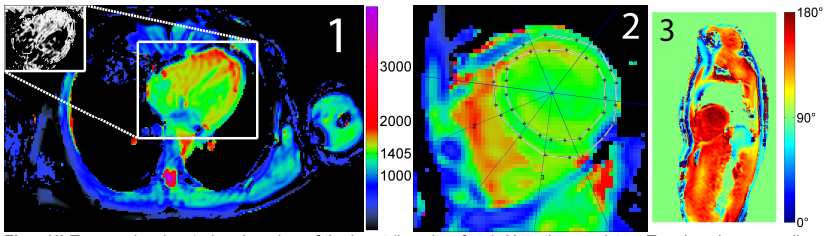
Quantitative parametric mapping of longitudinal relaxation is a desirable in vivo MR experiment that can characterise tissue independently of specific implementation details. In cardiac MRI, modified Look-Locker schemes for inversion recovery (IR) such as ShMOLLI[1,2] are effective at measuring T_1 in a single short breath hold. Cardiac MRI at 7T is still in its infancy, comprising proof-of-concept[3] and assessment of cardiac volume and function[4]. Our aim here is to produce an inversion pulse in the heart at 7T and use it to measure myocardial T_1 at 7T.

Methods: Five volunteers (3m+2f, 26-65y, 51-82kg, 1.57-1.91m) were recruited in accordance with local IRB ethical approval and scanned in a Magnetom whole-body 7T MRI scanner (Siemens), with a 16-element flexible stripline TEM transceiver array[5] driven by 16×1kW RF amplifiers each with independent phase and gain (CPC) with ECG triggering. The few data sets collected during ECG triggering anomalies were discarded and repeated. For each volunteer, the RF transmit profile was optimised by B_1-shimming[6] to give a region of strong, uniform excitation around the heart. Siemens shim WIP 450 was then used for B_0-shimming in a 8×8×8cm cube covering the heart. Planning was performed using retro-gated CINE FLASH images. T_1 maps were then recorded using an 11 heartbeat variant of ShMOLLI, where the inversion pulse was upgraded from the standard 10ms hyperbolic secant (HS) pulse and recovery was extended from 1 to 2 heartbeats to guard against errors due to the higher T_1 values anticipated at 7T. In addition to the original TrueFISP, imaging was performed with FLASH: in mid-diastole (TD ~425ms), with resolution 3.5×3.5×8mm, FOV 45cm, matrix 128x76 interpolated to 256x152 before analysis, and GRAPPA acceleration 2. SAR was monitored in real time to ensure it was within permissible limits. All volunteers were also asked about warming; none was reported. Validation experiments used phantoms comprising ultrapure water doped with Gd (Magnevist) with a 16-element Tx/Rx head coil and the TEM coil.



Figs. (1) T_1 map showing 4-chamber view of the heart (in units of ms). Note the consistent T_1 values in myocardium, but T_1 in the blood pool is corrupted by in-flow. Inset: Quality of fit R^2 (greyscale black<=0.995, white=1). **(2)** T_1 map in the same volunteer showing a mid-short-axis view of the heart. Segments drawn on the image were used for analysis. **(3)** Effectiveness of HS8 inversion pulse with uniform inversion in heart and good in liver.

Analysis: For each pixel in the magnitude images, ShMOLLI performs a three-parameter non-linear fit to $M(t) = A - B\exp\left(-t / T_1^*\right)$ and calculates the quality of fit R^2 and $T_1 \approx T_1^*\left(B/A - 1\right)$ as shown in Fig. 1. Myocardium was segmented manually using only the raw magnitude data (giving segments such as in Fig. 2). From the septal, anteroseptal or mid-septal 60° segments in each breath hold, the one with the highest mean R^2 value was selected. That segment's mean and standard deviation of T_1 was the "final result" for that series.

Results: Inversion efficiency was tested with FLASH ShMOLLI in a coronal slice for hyperbolic tangent, HS and HS8 pulses[7] with durations of 10-30ms. As the inversion pulse voltage or duration was increased, the region of inversion expanded to cover an increasing area of the chest and a saturation band, indicating the effective extent of the inversion pulse, could be seen moving towards the abdomen and neck. At 30ms, inversion efficiency drops and artefacts appear. The best results were obtained with a 10ms HS8 pulse of 12.8kW peak power, with SAR ~1.5W/kg for a 14s breath hold. Phantoms showed a linear dependence of R_1 (0.4–4.6s^{-1}) on Gd concentration (0–1mM) for T_R=600–1500ms. Myocardial T_1 measured in the septum with FLASH at 5° was 1405ms (N 8, σ 50). Using the 3 four-chamber views gave 1424ms (41) and 5 short-axis views gave 1394ms (56). Increasing the FLASH flip angle gave T_1 = 1341, 1271, 1192 for 5°, 10° and 15°. TrueFISP at 25° gave 1435ms (N 8, σ 66).

Discussion: Normal myocardial T_1 is 980ms at 1.5T, and 1198ms at 3T[8]. The T_1 values here continue this upward trend. Encouragingly, there is no significant difference in the measured T_1 for different slice orientations. The FLASH results show that T_1 will be underestimated if the flip angle is too large. Tests at 3T show that decreasing the imaging flip angle increases noise in the T_1 map without bias. Under-powered inversion pulses cause ShMOLLI to underestimate T_1. At 7T, we used the maximum attainable inversion power and decreased the imaging flip angle until image quality suffered. Thus, the true myocardial T_1 should at worst be only a little higher than our estimate.

At 1.5T and 3T, TrueFISP is best for T_1 mapping: it yields high SNR and minimally perturbs T_1 recovery. At 7T, B_0 inhomogeneity gives TrueFISP banding artefacts and off-resonance effects that corrupt T_1 recovery. The TrueFISP resolution at 7T was limited by SAR remaining after the inversion pulse. FLASH imaging was preferable: it suffers minimal B_0 artefacts, has lower SAR requirements and a 5° flip angle allows good T_1 recovery.

At 3T, ShMOLLI gives consistent T_1 throughout the myocardium and the blood pool. Yet, Figs. 1-2 show that at 7T, the blood T_1 appears to vary significantly between the left- (~1350ms) and right-ventricular (~1650ms) blood pools. Most likely neither is accurate; e.g. porcine blood T_1 is 2164ms at 7T.[9] The inset in Fig. 1 shows that R^2 values are also significantly lower in the blood than in the myocardium. This effect is probably due to in-flow of blood from regions where the inversion pulse was less effective.

Conclusions: Our FLASH HS8 variant of ShMOLLI gives the first effective measurements of cardiac T_1 in vivo at 7T, where HS8 adiabatic pulses provide uniform inversion of the whole heart. The T_1 of myocardium is 1405ms (±50) at 7T compared to 980ms at 1.5T, and 1198ms at 3T[8].

Acknowledgements: Funding from NIHR Oxford Biomedical Research Centre; Merton College Oxford; The Royal Society; NIH-NIBIB-EB000895; NIH-NIBIB-EB006835; NIH-NIBIB-EB007327; NIH-NCRR-P41-RR08079; Keck Foundation.

References: 1. Piechnik, S *et al. Proc. ISMRM* (2010); 2. Messroghli, DR *et al. Magn. Reson. Med.* **52**, (2004); 3. Snyder, CJ *et al. Magn. Reson. Med.* **61**, (2009); 4. Suttie, JJ *et al. Heart* **96**, (2010); 5. Ugurbil, K *et al. MAGNETOM Flash* (2010); 6. Van De Moortele, PF *et al. Magn. Reson. Med.* **54**, (2005); 7. Tannus, A & Garwood, M. *J. Magn. Reson., Ser A* **120**, (1996); 8. Piechnik, SK *et al. J Cardiov Magn Reson.* **In Press,** (2010); 9. Dobre, MC, *et al. Proc. ISMRM* (2005).