Simultaneous T1 mapping, cine imaging, and IR-prepared imaging of the rat heart using Small Animal Look-Locker Inversion recovery (SALLI)

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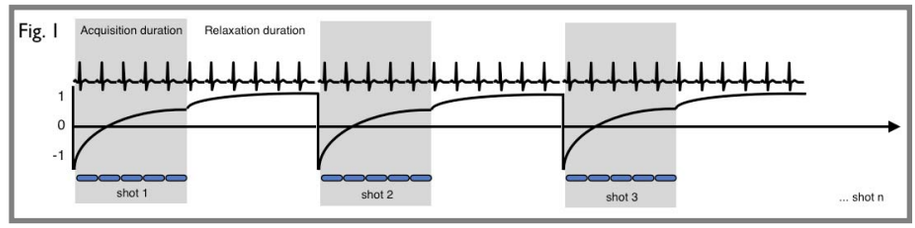
Background: T1 mapping of the heart in rodents is challenging due to high heart rates, preventing the use of non-segmented MRI techniques that have been developed for human studies. We propose a novel acquisition and reconstruction scheme generating cardiac T1 maps, cine images and inversion recovery (IR)-prepared images at the same time.

Methods: Small Animal Look-Locker Inversion recovery (SALLI) combines a segmented, retrospectively gated, IR-prepared Look-Locker type pulse sequence with a multimodal reconstruction framework.

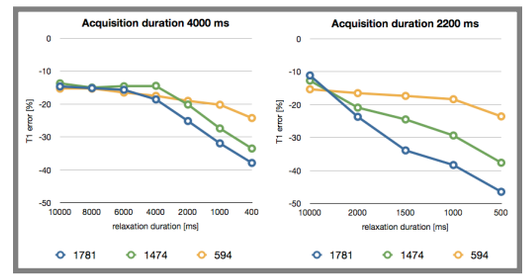
1) **Pulse sequence details.** Fig. 1 illustrates the pulse sequence scheme. After an ECG-triggered non-selective (adiabatic) inversion pulse, radial non-balanced steady-state free precession (SSFP) cine data acquisition is performed over several cardiac cycles for a predefined period of time ("acquisition duration", AD). Thereby every RR-interval is divided into a user-defined number of heart phases and only one shot of the cine acquisition is collected per inversion. Upon completion of a subsequent waiting period ("relaxation duration", RD), the whole process is repeated for the next shot. Additionally, a method referred to as "temporal undersampling" is implemented to accelerate the acquisition. When setting temporal undersampling to a factor of R, only a fraction of 1/R of profiles required for a fully sampled image is sampled in every heart phase. The sampling pattern in temporal dimension is modified such that either R subsequent heart phases or the same heart phase of R subsequent cardiac cycles can be collected to form a fully sampled dataset.

2) **Image reconstruction.** Reconstruction of the acquired image data is performed offline, either during the scanning session on the host computer or after the session on a separate computer, using a customized reconstruction framework (ReconFrame, Gyrotools, Zurich, Switzerland). Three types of images are reconstructed:



   a. **T1 maps**. For each cardiac cycle encompassed by the acquisition, a raw image is reconstructed from all available image data acquired during a predefined time window within the RR interval. From these raw images, a T1 map is generated by performing 3-parameter curve fitting for each pixel. Values are corrected for deviations caused by the Look-Locker type read out as described in the literature.
   b. **Cine images**. Using the T1 map, the time point within the AD is determined where all longitudinal magnetization within the field of view has recovered by at least 90% ($T1_{90\%}$). Cine images for a predefined number of cardiac phases are reconstructed from all image data available for each phase beyond $T1_{90\%}$. If temporal undersampling by a factor R is used for image acquisition, full image data sets are reconstructed by combining at least R neighbouring cardiac cycles.
   c. **IR-prepared images**. For a predefined time interval after inversion, a set of IR-prepared images with predefined steps of inversion time (TI) is reconstructed from all image data available within the time interval.

3) **MRI experiments**. All experiments were carried out on a whole-body 3 Tesla MRI system (Achieva, Philips Medical System, Best, The Netherlands) equipped with a QuasarDual gradient system (80 mT/m, 200 mT/m/ms slew rate), using a dedicated solenoid coil for rat hearts (PulseTeq, Gloucestershire, UK). Imaging parameters included: cardiac phases 12, field-of-view 64x64 mm, voxel size 0.6 x 0.6 x 3.0 mm, NSA 2, temporal undersampling factor 2, flip angle 10°, TR 5.4 ms, TE 2.3 ms.



   a. **Phantom studies**. T1 accuracy of SALLI depending on RD was assessed in three fluid phantoms with nominal T1 values of 594, 1474, and 1781 ms for two different ADs (4000 ms and 2200 ms). An internal ECG simulator was used to simulate a heart rate of 300/min.
   b. **In-vivo studies**. SALLI was performed in two 12-week-old Sprague-Dawley rats, with one of them having undergone surgical ligation of the left anterior descending coronary artery (LAD) 12 h prior to MRI in order to create an acute anterior myocardial infarction. For MRI, animals were anesthetized with Isoflurane and placed onto an animal cradle. ECG signal was derived from electrodes attached to the skin. After collection of native SALLI data, contrast agent (Gd-DTPA, 0.3 mmol/kg) was applied via a 26 G cannula placed into a tail vein, and further data were acquired.

Results: Figure 2 illustrates the results of the phantom measurements. With 4000 ms of AD, there is a systematic underestimation of T1 by approximately 15% as long as RD reaches 4000 ms (for maximal T1 times of 1500 ms) or 5000 ms (for maximal T1 times of 1800 ms). With 2200 ms of AD, there is a systematic underestimation of T1 by approximately 18% for a T1 value of 600 ms as long as RD reaches 1000 ms. Figure 3 shows SALLI images acquired in-vivo in a rat with acute anterior myocardial infarction (heart rate 290/min) using a 4000/5000 (AD/ RD) scheme for pre-contrast (A) and a 2200/1000 scheme for post-contrast (B) situations (C: diastolic cine; D: IR-prepared late gadolinium enhancement image). Native T1 values for non-infarcted myocardium (1066 and 1095 ms) and blood (1273 and 1375 ms) were similar in both animals and were in good agreement with the literature. In the area of infarction (arrow), T1 was elevated by 16% before and shortened by 71% ten minutes after administration of Gd-DTPA.

Discussion: SALLI provides ECG-gated T1 maps and uses the acquired data to generate cine data sets and IR-prepared images at the same time, enabling simultaneous assessment of quantitative signal changes, cardiac function, and late gadolinium enhancement (after application of contrast media). This approach saves acquisition time and facilitates registration of the different modalities since all images arise from the same source data. There are several mechanisms by which the performance of the technique can be adapted to given imaging needs: a) AD and RD can be adjusted to the maximum expected T1 of the tissue of interest (e.g. 600 ms for post-contrast myocardium at 3 Tesla); b) temporal undersampling or low numbers of cardiac phases can be used where cine data is of less interest; c) increasing the NSA is helpful where optimal spatial resolution is required. In contrast to other T1 mapping approaches, where the relaxation curve is influenced at intervals determined by individual heart rate, there is no heart rate dependency expected for T1 values obtained with SALLI since there is a permanent readout of predefined duration (e.g. 4000 ms) that does not change with heart rate. However, the reproducibility of T1 values obtained with SALLI needs to be investigated in further studies.

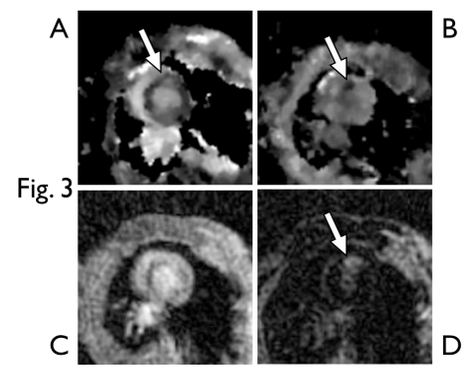


Fig. 3

Conclusion: We present a novel method for simultaneous generation of cardiac T1 maps, cine images, and IR-prepared images in rodents. SALLI was implemented on a whole-body 3 Tesla MRI system. Phantom studies were carried out to determine optimal sequence parameters for pre- and post-contrast situations. Initial in-vivo studies in rats with and without myocardial infarction could demonstrate that, unlike conventional methods, SALLI enables time-efficient analysis of cardiac T1 relaxation times, function and scar using a single image data set.