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Simultaneous Multi-Slice Imaging for Native Myocardial T₁ Mapping: Improved Spatial Coverage in a Single Breath-Hold

Sebastian Weingärtner^{1,2,3}, Steen Moeller², Sebastian Schmitter^{2,4}, Edward Auerbach², Peter Kellman⁵, Chetan Shenoy⁶, and Mehmet Akçakaya^{1,2}

¹Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN, United States

²Center for Magnetic Resonance Research, University of Minnesota, Minneapolis, MN, United States

³Computer Assisted Clinical Medicine, University Medical Center Mannheim, Heidelberg University, Mannheim, Germany

⁴Medical Physics and Metrological Information Technology, Physikalisch-Technische Bundesanstalt, Berlin, Germany

⁵National Heart, Lung, and Blood Institute, National Institutes of Health, Bethesda, MD, United States

⁶Cardiovascular Division, Department of Medicine, University of Minnesota, Minneapolis, MN, United States

Abstract

Purpose—To develop a saturation-recovery myocardial T₁-mapping method for the simultaneous multi-slice acquisition of three slices.

Methods—Saturation Pulse-Prepared Heart-Rate Independent Inversion Recovery (SAPPHIRE) T₁-mapping was implemented with simultaneous multi-slice imaging using FLASH readouts for faster coverage of the myocardium. Controlled aliasing in parallel imaging (CAIPI) was used to achieve minimal noise amplification in three slices. Multi-band reconstruction was performed using three linear reconstruction methods: Slice- and in-plane GRAPPA; CG-SENSE; and Tikhonov-regularized CG-SENSE. Accuracy, spatial variability and inter-slice leakage were compared with single-band T₁-mapping in a phantom and in six healthy subjects.

Results—Multi-band phantom T₁-times showed good agreement with single-band T₁-mapping for all three reconstruction methods (Normalized root-mean-square error < 1.0%). Increase in spatial variability compared with single-band imaging was lowest for GRAPPA (1.29-fold), with higher penalties for Tikhonov-regularized CG-SENSE (1.47-fold) and CG-SENSE (1.52-fold). In-vivo multi-band T₁-times showed no significant difference compared with single-band (T₁-Time ± inter-segmental variability: Single-Band: 1580 ± 119ms, GRAPPA: 1572 ± 145ms, CG-SENSE:

Correspondence to: Dr. Sebastian Weingärtner, Electrical and Computer Engineering, University of Minnesota, 200 Union Street SE, Minneapolis, MN 55455, USA, Phone: 612 625 1343, sweingae@umn.edu.

Competing Interests

SW and MA are inventors of a pending U.S. and European patent entitled “Methods for scar imaging in patients with arrhythmia”, which described the SAPPHIRE imaging sequence.

1579±159ms, Tikhonov: 1586±150ms; ANOVA: $p=0.86$). Inter-slice leakage was smallest for GRAPPA (5.4%), and higher for CG-SENSE (6.2%) and Tikhonov-regularized CG-SENSE (7.9%).

Conclusion—Multi-band accelerated myocardial T_1 -mapping demonstrated the potential for single-breath hold T_1 -quantification in 16 AHA segments over 3 slices. 1.2 to 1.4-fold higher in-vivo spatial variability was observed, where GRAPPA-based reconstruction showed the highest homogeneity and the least inter-slice leakage.

Keywords

Myocardial T_1 mapping; Simultaneous Multi-Slice Imaging; Multi-band; saturation recovery; SAPPHIRE

Introduction

Quantitative imaging of the heart using Magnetic Resonance Imaging (MRI) has recently emerged to a major focus area within the cardiac MRI (CMR) community. The quantification of various relaxation parameters (T_1 (1,2), $T_{1\rho}$ (3,4), T_2 (5–7), T_2^* (8,9)) has revealed clinical sensitivity to a wide range of ischemic and non-ischemic cardiomyopathies (10–12). In particular, the spatially resolved assessment of the longitudinal relaxation time T_1 (referred to as T_1 mapping) shows promising potential to enhance quality of CMR for prognosis and diagnosis of cardiomyopathies (13).

Parameter maps of the myocardium are commonly obtained from a series of single-shot images with different contrast-weightings, all of which are acquired during a single breath-hold. Three slice coverage in short axis orientation is recommended for evaluation, as it captures the heterogeneity across left ventricle better than single slice acquisitions (14). Conventional myocardial T_1 mapping methods acquire only a single-slice per breath-hold, necessitating rest periods between subsequent breath-holds, which lead to patient discomfort and long scan times. Furthermore, repeated breath-holds may compromise image registration (15–18).

Free-breathing T_1 mapping methods have been proposed to improve patient comfort and enable increased spatial resolution or coverage. In these techniques, respiratory motion compensation may be performed via prospective triggering (19) or gating based on diaphragmatic image navigators (20–22), retrospective self-gating (23,24), or prospective slice-tracking (25). However, respiratory gating and triggering lead to increased scan times, while tracking potentially induces blurring in the presence of heavy breathing. Consequently, a fast single breath-hold acquisition is the preferred approach.

Image acceleration techniques, such as parallel imaging, are frequently used in breath-held myocardial T_1 mapping, in order to provide sufficient spatial resolution in the single-shot acquisitions during the brief diastolic quiescence (14). Compressed sensing has also been used to improve spatial resolution in T_1 mapping in a single-breath hold (26,27). However, these approaches, as commonly used, do not affect the coverage or the total acquisition time, thus not changing the breath-hold duration.

Simultaneous multi-slice (SMS) or multi-band (MB) imaging is an alternative acceleration technique for acquiring multiple slices simultaneously (28), where the only SNR reduction compared to single-slice imaging is due to coil geometry (29). In MB imaging, the simultaneous excitation of multiple slices is achieved by playing an excitation pulse, which is obtained as the sum of pulses at different resonance frequencies, corresponding to different slice locations (30). To decrease the noise-amplification from un-aliasing, better encoding has been proposed with Controlled aliasing in volumetric parallel imaging (CAIPIRINHA) (29). Here, cyclic-phase shifts, or equivalent a sheared under-sampling pattern, is used to induce a shifted object position benefitting 3D and 2D SMS un-aliasing (31).

MB imaging has become a popular tool in neurological applications (32), however, its use in cardiac applications has been limited, due to unfavorable coil geometries used in body imaging. MB imaging has been used in myocardial perfusion imaging with a 2-fold MB and 2.5-fold in-plane acceleration (33), as well as 3 to 5-fold MB and no in-plane acceleration (34). Cardiac cine imaging with 2-fold MB and 3-fold in-plane acceleration at 3T (35), and with 2 to 3-fold MB and 2 to 4-fold in-plane acceleration at 7T (36) have also been investigated. However, its effect on myocardial MR parameter quantification and precision has not been explored.

In this study, we sought to evaluate the potential of MB imaging to accelerate myocardial T_1 mapping and to enable 16-segment quantification in a single breath-hold. A Saturation Pulse Prepared Heart-rate Independent Inversion REcovery (SAPPHIRE) sequence, with CAIPIRINHA-MB accelerated FLASH imaging was proposed for the simultaneous acquisition of three slices. T_1 time accuracy and precision were compared to conventional single-band (SB) SAPPHIRE imaging in phantom scans. In-vivo results are presented for native T_1 mapping in healthy subjects.

Methods

Sequence

Figure 1a depicts the schematic of the proposed pulse-sequence. Combined sinc-excitation pulses (bandwidth-time-product, $BWT=2.0$, pulse-duration=1.0ms) at three frequencies were employed for MB excitation in the FLASH imaging readout of a SAPPHIRE (37) sequence, using hybrid saturation/inversion preparation for T_1 sensitization. 15 images with different inversion times were acquired during a single-breath hold. All inversion times are confined to a single heart-beat, resulting in an acquisition over 15 heart-beats. The inversion times are linearly distributed between the minimal inversion time (185 ms in this study) and the maximum inversion time, determined by the start of the diastolic phase. For phantom imaging, the maximum inversion time was selected as 760 ms, corresponding to a heart-rate of 60 bpm. Pulse phases of the three base excitation pulses were cycled with a phase increment of $2\pi/3$ from slice to slice, to achieve a field-of-view (FOV) shift of $1/3$ in the images between adjacent slices. Additionally a constant slice-specific phase-shift was added to each individual pulse phase, previously optimized to minimize peak B_1^+ amplitude to reduce SAR burden of the sequence (38,39).

All MB and SB T_1 mapping were performed at 3 Tesla field-strength with a single-shot ECG-triggered FLASH sequence with the following imaging parameters: Uniform in-plane undersampling=2, FOV=320×320mm², spatial resolution=2.0×2.1mm², slice thickness=10mm, slice gap=10mm, partial-Fourier=6/8, #phase-encode lines=69, TR/TE/FA=4.0/2.0ms/10°, bandwidth=505Hz/Px, linear k-space ordering, inversion-pulse: 2.56ms tan/tanh adiabatic full passage (40), saturation-pulse: 4-compartment WET (41). 24 reference lines were acquired in the k-space center for each image.

To enable the reconstructions for slice unaliasing, a 1-second reference scan was used to acquire low-resolution images of 3 slices, during free-breathing and without ECG-gating (FOV=320×320mm², spatial resolution=2×5mm², slice thickness=10mm, TR/TE/FA=3.6/1.8ms/10°, bandwidth=500Hz/Px). For comparison, an additional 3 heart-beat reference scan with the same parameters was also acquired, with end-diastolic ECG-triggering and breath-holding.

Reconstruction

The acquired raw data with MB-aliasing and in-plane acceleration were exported from the scanner, and the T_1 -weighted images were reconstructed offline in Matlab (The Mathworks, Natick, MA, USA) using three different linear reconstruction approaches: i) Multi-slice unaliasing performed using slice-GRAPPA (42), followed by in-plane GRAPPA (43), whose kernels were calibrated from the low resolution reference scan, with (5,5) and (5,4) kernel sizes, respectively. The final images were generated using a coil-sensitivity weighted combination of the individual coil images. ii) A CG-SENSE (44) reconstruction for slice and in-plane unaliasing. CG-SENSE was used instead of SENSE to utilize the signal from the fully-sampled MB-encoded k-space center. Coil-sensitivity maps for each band and each coil were generated from the reference scan. iii) The reconstruction in ii) with additional Tikhonov regularization (45). A separate sub-study, detailed in the Supporting Information S1 and Supporting Figure S1, was performed to empirically optimize the Tikhonov regularization parameter as 0.05.

For each of the three methods, following the MB slice and in-plane unaliasing, phase-sensitive fitting, as proposed for inversion recovery T_1 mapping (15) was performed on the final T_1 -weighted images to obtain T_1 maps (Fig. 1b).

Phantom Imaging

All imaging was performed at a 3T Siemens Magnetom Prisma (Siemens Healthcare, Erlangen, Germany) system using a 30-channel receiver coil-array.

Phantom imaging for T_1 quantification accuracy and precision, was performed using SB and MB SAPHIRE in a cylindrical phantom containing multiple spherical compartments of Gadolinium or sucrose doped agarose-gel, with T_1 and T_2 times in the in-vivo range (T_1 : 200–2500ms, T_2 : 50–250ms, (46)). All scans were performed with 10 repetitions to allow assessment of noise-dependent variation.

In-vivo Imaging

The study was approved by the institutional review board, and written informed consent was acquired before each examination. Imaging was performed in six healthy subjects (3 male; 36 ± 16 years) with no contraindications to MRI. Native T_1 maps were acquired using conventional SB and proposed MB SAPHIRE in these short-axis slices. Conventional SB SAPHIRE was performed in three breath-holds for coverage of the three slices. MB SAPHIRE images of matching slices were acquired in a single breath-hold. Free-breathing and breath-hold calibration scans were acquired prior to the multi-band acquisition.

Data Analysis

Phantom accuracy was defined as the deviation of the average T_1 time within manually drawn region-of-interests (ROIs), averaged over all repetitions. Spatial variability was assessed as the standard deviation across the ROI in the homogenous phantom vials, averaged over all repetitions.

Leakage analysis was performed using the respective MB reconstruction on spatially shifted SB acquisitions (31). The 3 slices from the SB acquisitions, corresponding to no saturation preparation, were shifted to match the FOV shifts of the MB acquisition. Then, each of these shifted slices were run through the three separate reconstruction algorithms, using the kernels/coil sensitivity maps as generated from the respective reference scans. Ideally, this leads to only the original input slice being reconstructed, with no signal content in the other two slices. Thus, the leakage was defined as the resulting residual signal in the two non-input slices. This was repeated for the other two shifted SB slices. Using the linearity of the reconstructions, the total leakage in each slice was generated by addition of the leakages from the three shifted SB slices as inputs.

In-vivo T_1 and leakage maps were evaluated in manually drawn ROIs, delineating the endo- and epi-cardial contours, while carefully avoiding areas of partial-voluming. Quantitative comparison of the T_1 times and T_1 time spatial variability was performed according to the American Heart Association (AHA) 16 segment model (47). In-vivo T_1 time spatial variability was defined as the inter-segment variation.

Statistical differences in the T_1 times, and inter-slice leakage were assessed using one way ANOVA with subsequent paired Student's T-Tests. Kruskal-Wallis group analysis and Wilcoxon signed rank tests were used to statistically compare spatial variability of T_1 time. P-values < 0.05 were considered to be significant for group tests, and Bonferroni correction was applied for pair-wise tests with significance levels of 0.0083 for T_1 time and spatial variability comparison (6 tests) and 0.017 for Leakage analysis (3 tests).

Results

Phantom Imaging

Figure 2 depicts the results of phantom imaging, showing good agreement between SB T_1 mapping and all MB reconstruction methods, with minor differences between the three reconstruction techniques (Normalized root-mean-square error (NRMSE): GRAPPA: 0.62%,

CG-SENSE: 0.66%, Tikhonov: 0.59%). Spatial variability in the homogeneous T_1 phantom shows the highest increase for the non-regularized CG-SENSE reconstruction and only minor changes for GRAPPA (Variability relative to single-band T_1 mapping: GRAPPA: 1.29 ± 0.16 , CG-SENSE: 1.52 ± 0.33 , Tikhonov: 1.47 ± 0.34).

In-vivo Imaging

Figure 3 shows representative T_1 maps acquired in two subjects with single- and multi-band SAPHIRE, using the free-breathing calibration scan. All volunteer scans are shown in Supporting Figure S2. Conventional SB acquisition produces visually homogeneous T_1 maps (T_1 time $\pm$ spatial variability, Subject #1: 1572 ± 95 ms, Subject #2: 1546 ± 126 ms). For the MB T_1 scans, reconstruction with slice GRAPPA resulted in the least amount of spatial variability (Subject #1: 1567 ± 111 ms, Subject #2: 1563 ± 139 ms), providing images that are visually comparable to SB imaging. Tikhonov-regularized CG-SENSE also provided images with comparable quality, although with slightly increased spatial variability (Subject #1: 1567 ± 112 ms, Subject #2: 1583 ± 155 ms). CG-SENSE showed the strongest increase in spatial variability (Subject #1: 1563 ± 118 ms, Subject #2: 1593 ± 170 ms). By visual inspection CG-SENSE based reconstructions showed higher leakage, especially in the basal slice, while less leakage was observed for slice GRAPPA. The same trend is observed in the leakage maps of the three reconstruction techniques (Figure 4): Leakage using GRAPPA reconstruction appears visually homogeneous and noise-like. Increased structure but reduced noise-like variation can be observed using CG-SENSE, while the highest leakage is observed with regularized CG-SENSE.

Bullseye representations of the quantitative evaluation of myocardial T_1 times, in-vivo spatial variability and inter-slice leakage for MB and SB T_1 mapping across all subjects in the 16 AHA segments are depicted in Figure 5. For MB acquisitions, all reconstruction techniques result in T_1 values comparable to the SB reference (ANOVA $p=0.86$). As in phantom scans, the increase in spatial variability is the least for GRAPPA, followed by Tikhonov-regularized CG-SENSE, and CG-SENSE (Kruskal-Wallis $p=0.07$, pair-wise $p=0.031$, except for GRAPPA vs. Tikhonov-regularized CG-SENSE: $p=0.44$ and CG-SENSE vs. Tikhonov-regularized CG-SENSE $p=0.094$). However, the Tikhonov-regularized reconstruction also shows the highest inter-slice leakage, in particular in segments #2, #5 and #6 of the basal slice. GRAPPA showed the most uniform leakage performance across segments with the smallest mean (Kruskal-Wallis $p=0.22$; GRAPPA vs. Tikhonov $p=0.25$, GRAPPA vs. CG-SENSE $p=0.031$, CG-SENSE vs. Tikhonov-regularized CG-SENSE $p=0.031$).

The same trend can be observed in blood T_1 times. No significant difference was found between SB and the three MB reconstructions (ANOVA: $p=0.98$, SB 2043 ± 80 ms; GRAPPA: 2034 ± 71 ; CG-SENSE: 2042 ± 94 ms; Tikhonov-regularized CG-SENSE: 2026 ± 93 ms). Blood T_1 time spatial variability was 1.3 to 1.6-fold higher using MB compared with SB T_1 mapping, but differences were not found to be significant (Kruskal-Wallis: $p=0.102$, SB 130 ± 13 ms; GRAPPA: 170 ± 31 ; CG-SENSE: 206 ± 82 ; Tikhonov-regularized CG-SENSE: 172 ± 51 ms).

In our study, no visual difference was observed when performing the MB reconstructions using the free-breathing vs. breath-held calibration scans. T_1 maps reconstructed with GRAPPA using the different types of calibration data are depicted in Figure 6. There were no significant differences among the T_1 values ($p>0.57$) or the spatial variability ($p>0.59$) for the two types of calibration data. GRAPPA displayed the highest amount of resilience to changes in the calibration data (relative difference: T_1 : $0.015\pm0.269\%$, Variability: $0.223\pm2.28\%$). CG-SENSE reconstructions showed a slight but non-significant trend of increased variability with the free-breathing calibration-data (relative difference CG-SENSE: T_1 : $-0.472\pm1.03\%$, Variability: $-7.82\pm11.9\%$, relative difference Tikhonov-regularized CG-SENSE: T_1 : $-0.517\pm0.994\%$, Variability: $-3.62\pm7.19\%$).

Discussion

In this study, we evaluated a multi-band imaging sequence for accelerated myocardial T_1 mapping that enables 16-segment quantification in a single breath-hold. We evaluated three linear reconstruction algorithms for unaliasing the MB data, and their effect on T_1 estimation and spatial variability. Phantom and in-vivo experiments show that all three methods show comparable accuracy to conventional single-band imaging, albeit at 1.2–1.4-fold loss in spatial variability.

Multi-band imaging suffers from decreased SNR due to unfavorable coil geometry in cardiac applications. Our results show that a combination of slice and in-plane GRAPPA showed the least noise amplification, with the least amount of inter-slice leakage and a uniform leakage profile across all the myocardial segments. Among the SENSE-based reconstructions, Tikhonov regularization reduced the effects of noise amplification. However, it also increased the inter-slice leakage, albeit most of the increased leakage being evident outside the heart, with the exception of some basal segments. Nonlinear reconstruction techniques with appropriate regularization can also be utilized for further removal of artifacts due to noise and leakage. However, these were not explored in the current study, in order to provide a uniform comparison of spatial variability and leakage for the linear reconstruction techniques.

The position of the heart is known to show major variations between separate breath-holds even in healthy volunteers. Hence, T_1 map acquisition of three short-axis slices in separate breath-holds provides potentially non-equidistant coverage with bias towards basal or apical T_1 times. As all slices are acquired simultaneously in MB T_1 mapping, equidistant and uniform coverage of the left-ventricle is ensured in a short-axis stack scan with the proposed technique.

In this study, MB reconstructions, in particular slice GRAPPA, were observed to be resilient to inter-scan motion between the calibration and the measurement data. This result is encouraging for the applicability of SMS imaging to cardiac applications, where potential mismatches in cardiac or respiratory phases might be unavoidable. The use of calibration scans without cardiac or respiratory gating is advantageous, as additional scan time requirements are minimized. Further studies are needed to verify this trend in other cardiac MR applications.

Myocardial T_1 mapping is most commonly performed using bSSFP imaging readouts, which are less disruptive to the longitudinal magnetization recovery curve (48). Recently, the use of FLASH imaging has been explored for inversion-recovery based T_1 mapping (49,50). Saturation-recovery T_1 mapping methods are known to allow for accurate T_1 quantification with FLASH imaging readout (51). Accordingly T_1 times assessed with FLASH SAPHIRE in healthy subjects are in good agreement with a recent study of steady-state free precession based saturation recovery T_1 mapping at 3T (41). FLASH imaging has been proven to be beneficial at 3T due to its resilience against off-resonance artifacts, which might be a major disruptive factor to bSSFP image quality at high field strengths. However, in T_1 mapping, this comes at the cost of reduced noise-resilience and increased end-diastolic imaging times. Due to the linear k-space ordering, and due to the fact that border zones are commonly excluded when evaluating myocardial T_1 maps, the increase in acquisition window duration caused by the long FLASH TR, has previously been reported to be not an issue at 1.5T (52). Nonetheless, the TR of the FLASH sequence can be further shortened by optimizing spoiling strategies or increasing imaging bandwidth as a trade-off against T_1 mapping precision. For multi-band imaging, FLASH has the additional advantage that MB phase cycling can be encoded in the RF phase of each band, rather than using encoding gradients as for EPI or SSFP imaging, which might introduce additional signal loss due to in-band dephasing (53).

In order to mitigate the reduced baseline SNR of FLASH imaging, T_1 maps were acquired over 15 heart-beats, in contrast to previous bSSFP-based SAPHIRE protocols, which use 9 to 11 images (37,41,54,55). The longer breath-hold duration was not disruptive in the study cohort. However, in critically ill patients or patients with respiratory restrictions, reduced sequence duration can be achieved at a trade-off against a slight loss in precision.

While multi-band T_1 mapping was demonstrated with a SAPHIRE saturation-recovery sequence design, this acceleration technique can straightforwardly be applied to other saturation recovery techniques, such as saturation-recovery single shot acquisition (SASHA) (56). In this study, we chose SAPHIRE instead of SASHA, due to recent results showing that SAPHIRE is more artifact resilient and more precise (41,54). The technique may also be applied to myocardial T_1 mapping where the T_1 recovery curve spans several heart-beats, such as the Modified look-locker inversion-recovery technique (MOLLI) and its variants (48,57,58). However, progressive saturation of the blood in several slices simultaneously, might lead to diminished signal from the blood pool over time, especially at high multi-band factors. Furthermore, the FLASH imaging readouts as used in the proposed multi-band acquisition substantially compromise the accuracy in commonly used inversion-recovery T_1 mapping sequences. Although tailored reconstruction schemes have been proposed to mitigate this effect (59), MB inversion-recovery T_1 mapping is beyond the scope of this work, but warrants further investigation.

All SAPHIRE T_1 maps in the current study were reconstructed using curve fitting to phase-sensitive data. This approach has previously been proposed for inversion-recovery T_1 mapping (15), resulting in reduced in-vivo variability as it eliminates the necessity to restore the signal polarity along the inversion-recovery curve. Furthermore, a Gaussian noise characteristic is maintained, potentially increasing T_1 mapping accuracy, when least-squares

fitting is used with low baseline SNR or when the T_1 -weighted myocardial signal falls close to the zero crossing. These advantages of phase-sensitive T_1 mapping can also be harvested in hybrid SAPHIRE T_1 mapping, as the dynamic range spans across both the positive and negative longitudinal magnetizations.

In this study, in vivo imaging was performed during breath-holding. However, in some patients, end-expiration breath-holding cannot be maintained even for short durations. In these cases, respiratory drift may corrupt the T_1 map quality and precision. Dedicated image registration algorithms have been proposed, to closely re-align the T_1 -weighted baseline images, despite the substantial contrast variations (16,17). Although, no significant motion-induced artifacts have been observed in our healthy cohort study, such registration techniques can be applied to MB T_1 mapping. Additionally, due to the simultaneous acquisition of multiple slices, similar motion can be expected and simultaneous registration of all three slices may be performed. This may help to reduce the dimensionality of the registration problem and improve the re-alignment of the baseline images in post-processing. Potential synergies of image registration and MB cardiac imaging will be explored in future studies.

This study has several limitations. Only a limited number of healthy subjects was included in this proof-of-concept study. Clinical evaluation of single breath-hold whole-heart T_1 mapping in larger cohorts exhibiting specific pathologies is warranted. Since the excitation bands in MB imaging have to be parallel, T_1 maps have only been evaluated in short-axis, to allow for the 16-segment analysis. Only a single MB acceleration factor of 3 was studied in this work to allow for T_1 mapping in a single breath-hold, in accordance with the coverage requirements of the SCMR T_1 mapping task-force consensus statement (14).

Conclusion

The proposed technique enables acquisition of native myocardial T_1 maps with improved spatial coverage, allowing for the quantification of the 16 AHA-segments over 3 slices in a single breath-hold. More than 3-fold savings in acquisition time is achieved in young healthy volunteers, at an increased T_1 spatial variability of 1.2 to 1.4-fold using a linear slice GRAPPA reconstruction.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

(a) Schematic description of the multi-band T₁ mapping sequence and (b) the reconstruction pipeline. A SAPPHERE sequence with combined saturation/inversion-recovery preparation is combined with FLASH imaging readout. The MB excitation pulses are obtained as the sum of three sinc single-band excitations at different frequency bands. Image reconstruction is performed to unalias the multi-band slices and the in-plane undersampling, with subsequent phase-sensitive fitting of the saturation/inversion-recovery curve to obtain quantitative T₁ maps.

Figure 2.

Phantom results depicting the accuracy (a) and spatial-variability (b) of the proposed technique in comparison with conventional SB imaging for three different linear reconstruction methods. The MB T_1 times show good agreement with the SB acquisition. 1.3 to 1.5-fold increase of noise variability is shown with the different MB reconstruction techniques compared to single-band imaging.

Figure 3.

Representative T_1 maps from two subjects, comparing a multi-band acquisition with various linear reconstructions to conventional single-band T_1 mapping. Increased heterogeneity of the T_1 times is observed using conventional CG-SENSE, compared with single-band T_1 mapping. GRAPPA and Tikhonov-regularized MB imaging achieves image quality that is visually comparable to single-band imaging, although Tikhonov-regularized CG-SENSE displayed increased inter-slice leakage, as apparent in subject #1.

Figure 4. Leakage maps comparing three multi-band reconstructions. The top row, presents the corresponding single-band images with no magnetization preparation, as used to generate the leakage maps. GRAPPA shows mild and noise-like leakage across the FOV. Slightly decreased leakage, albeit with increased intensity hot-spots is depicted for CG-SENSE. Tikhonov-regularized CG-SENSE displays the highest inter-slice leakage of the three methods, though the intensity hot-spots predominantly lie outside the myocardium.

Figure 5. Bullseye representation of myocardial T₁ times, T₁ time spatial variability and inter-slice leakage, as quantitatively analyzed according to the AHA 16-segment model. All three reconstruction methods show T₁ times comparable to single-band imaging, although with increased intra-segment variability. Slice GRAPPA shows the smallest increase in spatial variability compared to SB T₁ mapping and the smallest inter-slice leakage.

Figure 6.

Multi-band T_1 maps reconstructed with slice GRAPPA using free-breathing or breath-hold calibration data. The acquisition scheme for the calibration data is depicted in the top row. Images of six healthy subjects are presented below, along with the corresponding difference maps. Multi-band T_1 maps with both calibration data are of similar quality and differences are hardly noticeable by visual assessment. Difference maps reveal minor noise like changes when using a differently acquired calibration data set.