Black-Blood Native T<sub>1</sub> Mapping: Blood Signal Suppression for Reduced Partial Voluming in the Myocardium

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**Purpose:** To study the feasibility of black-blood contrast in native T<sub>1</sub> mapping for reduction of partial voluming at the blood–myocardium interface.

**Methods:** A saturation pulse prepared heart-rate-independent inversion recovery (SAPPHIRE) T<sub>1</sub> mapping sequence was combined with motion-sensitized driven-equilibrium (MSDE) blood suppression for black-blood T<sub>1</sub> mapping at 3 Tesla. Phantom scans were performed to assess the T<sub>1</sub> time accuracy. In vivo black-blood and conventional SAPPHIRE T<sub>1</sub> mapping was performed in eight healthy subjects and analyzed for T<sub>1</sub> times, precision, and inter- and intraobserver variability. Furthermore, manually drawn regions of interest (ROIs) in all T<sub>1</sub> maps were dilated and eroded to analyze the dependence of septal T<sub>1</sub> times on the ROI thickness.

**Results:** Phantom results and in vivo myocardial T<sub>1</sub> times show comparable accuracy with black-blood compared to conventional SAPPHIRE (in vivo: black-blood: 1562 ± 56 ms vs. conventional: 1583 ± 58 ms, P = 0.20); Using black-blood SAPPHIRE precision was significantly lower (standard deviation: 133.9 ± 24.6 ms vs. 63.1 ± 6.4 ms, P < .0001), and blood T<sub>1</sub> time measurement was not possible. Significantly increased interobserver interclass correlation coefficient (ICC) (0.996 vs. 0.967, P = 0.011) and similar intraobserver ICC (0.979 vs. 0.939, P = 0.11) was obtained with the black-blood sequence. Conventional SAPPHIRE showed strong dependence on the ROI thickness (R<sup>2</sup> = 0.99). No such trend was observed using the black-blood approach (R<sup>2</sup> = 0.29).

**Conclusion:** Black-blood SAPPHIRE successfully eliminates partial voluming at the blood pool in native myocardial T<sub>1</sub> mapping while providing accurate T<sub>1</sub> times, albeit at a reduced precision. *Magn Reson Med* 000:000–000, 2016. © 2016 International Society for Magnetic Resonance in Medicine

**Key words:** T<sub>1</sub> Mapping; SAPPHIRE; MSDE; black-blood; partial voluming

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**INTRODUCTION**

Quantitative tissue characterization of the myocardium using cardiac MRI has emerged as a promising diagnostic tool with clinical value in numerous cardiomyopathies (1). Recently, native myocardial T<sub>1</sub> mapping has also shown prognostic value in pathologies with reduced myocardial wall thickness such as dilated cardiomyopathy (DCM) (2,3).

Myocardial T<sub>1</sub> mapping is commonly performed using a series of end-diastolic single-shot images acquired within a single breath hold (4,5). Variable magnetization preparation of the single-shot images induces varying T<sub>1</sub>-weighted contrast and enables voxel-wise T<sub>1</sub> quantification.

However, the limited duration of the diastolic quiescence requires rapid imaging and restricts the in-plane resolution. This leads to major partial voluming effects at the myocardial–blood interface due to substantial differences in their respective T<sub>1</sub> times. Partial voluming reduces the myocardial area that is suitable for quantitative evaluation, impairs the reproducibility, and hampers the depiction of thin structures (6).

Segmented acquisition of the T<sub>1</sub>-weighted images has been proposed to mitigate this shortcoming by improving the in-plane resolution (7–9). Similarly, T<sub>1</sub> quantification at systole has been proposed to increase the number of voxels within the myocardium that are not subject to partial voluming (10). However, residual partial voluming can still be expected even at higher resolutions or with increased myocardial wall thickness, especially in oblique orientations. Another approach to overcome this issue is blood suppression: In-flow saturation at the great vessels has been used to induce black-blood contrast (11) in the preclinical mouse model (12). Furthermore, a recent study presented preliminary data on the use of motion-sensitized driven-equilibrium (MSDE) (13) for black-blood T<sub>1</sub> mapping in humans (14). Both approaches achieved promising black-blood image quality but with reduced repeatability.

In this study, we sought to develop a MSDE-prepared black-blood native T<sub>1</sub> mapping method using combined saturation and inversion recovery magnetization preparation. Numerical simulations were performed to study the effects of blood suppression on partial voluming. Phantom scans and in vivo experiments in healthy volunteers were carried out to optimize the black-blood imaging parameters and to evaluate the proposed method on efficient blood signal suppression and homogeneous T<sub>1</sub> quantification.

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Grant sponsor: National Institutes of Health; Grant number: R00HL111410.
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COI: S.W. and M.A. 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. No other financial or nonfinancial competing interests exist for any author.

Received 13 May 2016; revised 5 July 2016; accepted 20 July 2016
DOI 10.1002/mrm.26378
Published online 00 Month 2016 in Wiley Online Library (wileyonlinelibrary.com).

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METHODS

Sequence
Black-blood $T_1$ mapping was performed using a modified saturation pulse prepared heart-rate-independent inversion recovery (SAPPHIRE) (15) technique. A MSDE preparation was inserted directly before the balanced steady-state free-precession (bSSFP) imaging readout (Fig. 1a). In a MSDE preparation, a nonselective 90°/−90° tip-down pulse, a series of one or more 180°/−180° refocusing pulses, and a final 90° tip-up pulse are used to encode the spin dephasing in the longitudinal magnetization (Fig. 1b). Strong gradients with identical gradient moments are placed before and after the refocusing pulses to induce dephasing of differentially moving tissue.

Numerical Simulations
Numerical simulations of a bicompartiment model have been performed to study the effect of partial voluming on the $T_1$ estimation in a SAPPHIRE sequence. A myocardial tissue compartment has been simulated with $T_1/T_2 = 1580\text{ ms}/50\text{ ms}$ and a blood compartment with $T_1/T_2 = 2300\text{ ms}/250\text{ ms}$. In this noise-free simulation, the signal strength of the myocardial compartment, relative to the blood compartment, was chosen as the signal-to-noise ratios (SNR) for myocardium over the SNR of blood obtained from literature values (16): without MSDE: myocardium/blood = 117/119; with MSDE: myocardium/blood = 95/11. The relative compartmental share between blood and myocardium was varied between 0% and 100%. The overall signal of the SAPPHIRE sequence with and without MSDE preparation was simulated using the Bloch-equations. $T_1$ times were obtained by fitting a three-parameter model to the simulated signal intensities using a nonlinear Levenberg-Marquardt least-squares optimization (17).

To study the visual effects of partial voluming, a numerical representation of a cardiac short-axis slice was simulated with blood and myocardial compartments of the left and right ventricle. The numerical phantom was generated with a matrix size of 1024 × 1024 pixels and subsequently down-sampled using bilinear interpolation in order to induce partial voluming. Matrix sizes after down-sampling werechosen to correspond to approximate pixel resolutions of 1.5 × 1.5 to 3.0 × 3.0 mm². To facilitate comparability between different resolutions, all images were then up-sampled to a reconstruction resolution of 0.5 × 0.5 mm² prior to further processing. Bloch equations were used to simulate voxel-wise signals of the numerical phantom using the same myocardium and blood compartments as described above. Subsequent fitting with a three-parameter model was used to generate the $T_1$ maps.

Imaging
All imaging was performed on a 3T scanner (Magnetom Skyra; Siemens Healthcare, Erlangen, Germany) with a 30-channel receive array.

All $T_1$ mapping sequences have been performed with the following imaging parameters: repetition time/echo time (TR/TE) = 2.9/1.0 ms, flip angle = 45°, bandwidth = 1085 Hz/Px, field of view = 400 × 300 mm², in-plane resolution = 2.1 × 2.1 mm², partial Fourier = 6/8, GRAPPA 2, number of phase-encoding steps = 56. The flip angle was adjusted if specific absorption rate (SAR) limitations were reached.

In the present MSDE implementation the black-blood gradients were played out with all three gradient coils, maximum gradient amplitude of 20 mT/m per axis, and...
a slew rate of 150 mT/m/ms leading to gradient ramp times of 0.14 ms. Motion-sensitizing gradient duration was maximized within the gaps between the respective tip-up/tip-down and the refocusing pulse. MSDE echo time was fixed to TE_{MSDE} = 11 ms, if not stated otherwise.

**Phantom**

Imaging has been performed in a static phantom to study B_1^+ uniformity of various MSDE preparation modules and to verify accuracy of the black-blood SAPPHIRE sequence.

The following three MSDE preparation modules with different combinations of radiofrequency (RF) pulses were tested for B_1^+ uniformity in a homogeneous phantom containing NaCl-doped water: 1) rectangular, 90° hard pulses for tip-down and tip-up and a single 180° MLEV refocusing pulse, as proposed in (16); 2) a rectangular 90° hard pulse for tip-down, an adiabatic 180° BIREF1 refocusing pulse, and a composite (270°–360°) tip-up pulse; and 3) a 0° three-compartment BIR4 pulse, with the MSDE gradients inserted symmetrically between the compartments (18,19). The timing of the RF pulses in the MSDE modules is detailed in Supporting Table S1. The echo time of the three MSDE modules was fixed to TE_{MSDE} = 15 ms. B_1^+ uniformity was assessed as the signal of a MSDE-prepared single-shot image, normalized by the signal of a single-shot image without MSDE preparation. The imaging parameters were as described above.

Furthermore, accuracy of the SAPPHIRE black-blood sequence was evaluated in phantom scans. The phantom was composed of seven vials containing agarose gel doped with various concentrations of gadoterate meglumine (Dotarem; Guerbet, Aulnay-sous-Bois, France) to achieve T_1 and T_2 times in the physiological range. The combination of composite pulses and the adiabatic refocusing was used for MSDE preparation in the remainder of the study. Conventional SAPPHIRE without MSDE preparation was performed as a black-blood sequence. The reference T_1 times obtained with the SAPPHIRE black-blood sequence were compared to conventional SAPPHIRE using Bland-Altman analysis.

**In Vivo**

The study was approved by the local institutional review board, and written informed consent was obtained from all subjects prior to scanning.

The black-blood preparation was optimized in a cohort of five healthy subjects (3 male, 29 ± 4 years old). Baseline images without saturation/inversion preparation, as acquired in the SAPPHIRE black-blood sequence, were obtained with varying the echo time TE_{MSDE} from 10 ms to 14 ms. The effectiveness of blood suppression was quantitatively analyzed as the contrast-to-noise ratio (CNR) between the left ventricular myocardium and the left ventricular blood pool. To capture the effects of stagnant blood in the CNR, manually drawn endocardial contours covering the entire left ventricular blood pool were used for signal analysis of the blood. Signal heterogeneity in the myocardium, caused by the MSDE preparation, was quantitatively analyzed as the coefficient of variation (COV) of the signal over the entire myocardium between the epicardial and the endocardial contours.

A separate cohort of eight healthy volunteers (4 male, 28 ± 4 years old) was recruited for T_1 time analysis. Imaging was performed using standard and black-blood SAPPHIRE in three short-axis slices and one four-chamber slice. T_1 times were evaluated using manually drawn regions of interest (ROIs). Average segmental T_1 times were assessed according to the American Heart Association (AHA) 6-segment model. Precision was obtained as the average intersegment variation. SNR of the baseline image without saturation/inversion preparation was analyzed for both sequences based on the signal of the two septal segments in the most basal slice over the standard deviation in a noise area corrected for the non-gaussian noise distribution. The average myocardial thickness was assessed between the manually drawn epicardial and endocardial contours: 1000 spokes through the center of mass were uniformly spread around the myocardium. Thickness was then defined as the average distance of the crossing point of the spoke with the endo- and epicardial border, respectively. T_1 time, T_1 time precision, and average myocardial ROI thickness were compared between conventional and black-blood SAPPHIRE on a per subject basis using Student t test. P values < 0.05 were considered to be significant.

Partial voluming effects in the myocardium were visualized by analyzing the transmural T_1 times in five rings around the myocardium from the endo- to the epicardial border. The rings were divided in three segments around the myocardium (septal, antero-, and inferolateral). Average T_1 time per segment and per ring was then compared between conventional and black-blood SAPPHIRE.

Inter- and intraobserver variability was studied for black-blood and conventional T_1 mapping. Two readers drew a total of three ROI sets (reader 1: ROIs A, ROIs B, reader 2: ROIs C). Intraobserver variability was studied comparing the T_1 times obtained with ROIs A and ROIs B on a per subject basis. To obtain the interobserver variability, the per subject mean of the T_1 obtained with ROIs A and ROIs B (average of reader 1) were compared to ROIs C (reader 2). One subject, where segments had to be excluded due to bSSP imaging artifacts, was excluded from the consistency analysis to avoid reproducibility errors caused by differential artifact inclusion. Inter- and intraobserver consistency were analyzed using the interclass correlation coefficient (ICC) based on Winer's adjustment of anchor points (20,21). The ICCs between the two sequences were statistically compared for inter- and intraobserver analysis using F statistics. Absolute agreement in the inter- and intraobserver reproducibility was assessed according to Bland-Altman analysis (22). Paired t tests were used to assess differences in the bias between the two sequences, and F tests were used to analyze differences in the variance of the agreement. A significance level of P < 0.05 was used for all statistical tests, and consistency intervals are reported for a 95% level.

Furthermore, quantitative analysis of the in vivo partial voluming was performed by retrospective alteration of the manually drawn ROIs, as proposed in (10). The binary ROI masks were eroded or dilated by up to two and four pixels, respectively, in order to decrease/increase the myocardial ROI thickness. The average T_1 times in the five septal
AHA segments, which are in the vicinity of both blood pools, were compared between conventional and black-blood SAPPHIRE at the various altered ROIs. Correlation between the septal T1 time and the ROI thickness were identified using Pearson’s correlation coefficient. Furthermore, one-way analysis of variance (ANOVA) was employed to test the T1 times at various ROI thicknesses for differences in the mean to exclude nonlinear trends. *P* values < 0.05 were considered to be significant.

**RESULTS**

**Numerical Simulations**

Figure 2 shows the T1 time in a simulated voxel with partial voluming at varying signal contributions of blood and myocardium using conventional and black-blood SAPPHIRE. A linear increase of the T1 time is observable with more blood contribution when using conventional SAPPHIRE. The blood-myocardial transition is substantially steepened using the proposed black-blood technique.

The visual impact of this partial voluming reduction on the numerical phantom is depicted in Figure 3. Using conventional SAPPHIRE, apparent myocardial thickness reduces with coarser sampling resolution, creating smoothed edges at the blood-myocardial interface. This trend is also highlighted in the line plots: Coarse sampling leads to flat slopes toward the blood pool and a reduced width of the plateau with uncorrupted myocardial T1 times. The black-blood preparation, on the other hand maintains steep slopes and a broad area with largely uncorrupted T1 times, as apparent in the line plots (Fig. 3b). This leads to increased myocardial thickness in the numerical phantom.

**Phantom**

The results of the B1+1 uniformity using three MSDE preparation modules are displayed in Figure 4. The BIR4 adiabatic module results in the least signal loss with the most homogeneous signal profile. The hybrid composite/BIREF1 module shows slightly increased signal loss with a signal drop toward the center of the phantom. This trend is strongly increased using the rectangular module. However, the relative SAR of the BIR4, composite/BIREF1, and the rectangular module were 9.6, 5.2, and 1.0, respectively. The composite/BIREF1 module was used for blood suppression as a tradeoff in the remainder of the study.

The Bland-Altman analysis of the phantom scans shows good agreement between the black-blood sequence and the conventional approach (see Supporting Figure S1): The average deviation was -3.9 ms (95% confidence interval [CI]: -15.4 ms to 7.6 ms) for phantom vials with T1 times between 100 and 1800 ms.

**In Vivo**

Figure 5 shows the analysis of MSDE-prepared single-shot images acquired with various echo times (TE_{MSDE}). Residual blood signal is readily visible in the exemplary images if the echo time is chosen too short (10 ms), causing decreased CNR. However, progressively strong signal void in the lateral area of the myocardium can be observed with increasing echo times due to increased

![Image](69x583 to 292x735)
motion during the preparation. This reflects as increased signal heterogeneity in the myocardium (COV) and causes a CNR drop for long echo times. $T_{E_{\text{MSDE}}} = 11\ ms$ shows substantially higher blood-myocardium contrast than shorter echo times, and reduced signal heterogeneity compared to long $T_{E_{\text{MSDE}}}$. This echo-time value was fixed for the remainder of the study to offer a tradeoff between blood suppression and signal void.

$T_1$ mapping was successfully performed in all healthy subjects; two out of 136 (1.5%) segments of the black-blood $T_1$ maps were excluded from further analysis due to bSSFP artifacts. The imaging flip angle was reduced by $2^\circ$ in one healthy subject due to SAR limitations. Representative $T_1$ maps acquired with conventional and black-blood SAPPHIRE are shown as myocardial overlays, together with the corresponding $T_1$-weighted baseline images in Figure 6. Good $T_1$ time homogeneity throughout the myocardium is observed with both techniques. Black-blood SAPPHIRE shows slightly increased variability by visual inspection. However, visually increased myocardial thickness is achieved with the black-blood sequence. The upper panel of Figure 6 shows the transmural analysis in a healthy subject and the corresponding $T_1$ map. Increased $T_1$ values are observed toward the blood pools with the conventional approach. No such elevation was seen using black-blood SAPPHIRE. Figure 7 depicts all baseline images used for the $T_1$ map generation, and the corresponding signal intensities in the myocardium and the blood pool, for the conventional and the black-blood sequence in one healthy subject. Black-blood SAPPHIRE shows comparable $T_1$ recovery curves to the conventional sequence in the myocardium, although at decreased intensity. Accordingly, the myocardial SNR in the baseline images of the conventional sequence was $76 \pm 42\%$ higher than with black-blood SAPPHIRE. The high-intensity blood signal in the conventional $T_1$ mapping sequence is successfully suppressed in the black-blood approach. However, the almost flat intensity curve in the blood pools of the black-blood sequence does not allow for extraction of the blood $T_1$ time.

No significant difference was found between the average $T_1$ times of the conventional and the black-blood approach ($1583 \pm 58\ ms$ vs. $1562 \pm 56\ ms$, $P = 0.20$), with slightly lower $T_1$ time in the black-blood sequence, especially in the septal regions (Fig. 8). However, as assessed by intra-segmental $T_1$ variation, precision is significantly increased using the black-blood approach ($63.1 \pm 6.4\ ms$ vs. $133.9 \pm 24.6\ ms$; $P < 0.0001$). The myocardial thickness in SAPPHIRE black-blood $T_1$ maps was significantly increased by an average of $50\% \pm 22\%$ compared to conventional SAPPHIRE, as detailed in Table 1.

Intraobserver consistency was characterized by an ICC of 0.939 (95% CI: [0.689, 0.989]) for the conventional sequence and an ICC of 0.979 (95% CI: [0.882, 0.996]) for the black-blood approach. This difference was not found to be significant ($P = 0.11$). Bland-Altman statistics showed slightly
lower intraobserver variability for the SAPPHIRE black-blood (bias: 1.3 ms, 95% CI: [−24.6, 27.3 ms]) compared with the conventional sequence (bias: −2.5 ms, 95% CI: [−37.7, 32.6 ms]). However, neither the difference in the bias ($P = 0.58$) nor in the variability of the differences ($P = 0.48$) was found to be significant. Interobserver consistency, on the other hand, was significantly lower using the conventional T1 mapping sequence compared to black-blood SAPPHIRE (mean, 95% CI): conventional 0.967, [0.822, 0.994] vs. black-blood: 0.996, [0.976, 0.999], $P = 0.011$.

Also, significantly lower bias was shown for the proposed sequence in the Bland-Altman analysis (mean, 95% CI): conventional $−20.2$ ms, [−46.5 ms, 6.0 ms] vs. black-blood: 1.3 ms, [−9.8 ms, 12.5 ms], difference in bias: $P = 0.003$, difference in variance: $P = 0.056$.

The quantitative analysis of the partial voluming, using erosion and dilation of the myocardial ROIs, is shown in Figure 9. Septal T1 times assessed with conventional SAPPHIRE show a strongly increasing trend for dilated ROIs ($R^2 = 0.99$), with significantly different T1 times at different ROI sizes ($P = 0.012$). SAPPHIRE black-blood shows good invariance to the ROI thickness over a wide range, with no increasing trend and no significant difference in the ANOVA ($R^2 = 0.29$, $P = 0.997$).

**DISCUSSION**

In this study, a MSDE-prepared SAPPHIRE sequence was proposed for blood signal-suppressed T1 mapping. Numerical simulations showed that black-blood T1 mapping benefits from decreased sensitivity to partial voluming effects and increased apparent myocardial wall thickness. Phantom T1 times of black-blood SAPPHIRE were in good agreement with the conventional sequence. In vivo T1 maps in healthy volunteers showed thorough blood suppression with the chosen MSDE module, and robust T1 quantification in myocardial ROIs with increased thickness for the tradeoff against decreased
Black-blood T$_1$ mapping successfully eliminated the T$_1$ time dependence on the ROI thickness and increased interobserver consistency, indicating the mitigation of partial voluming effects and high resilience to ROI alterations.

A MSDE preparation was employed for blood signal suppression in this study because it can be well integrated in a T$_1$ mapping sequence. Black-blood imaging using MSDE is clinically well established for plaque assessment in the coronary arteries (23). Active research efforts have focused on the optimization of MSDE preparations for plaque imaging (24–26). However, previous studies have shown substantial differences in the demands on the MSDE preparation for effective blood suppression in the left ventricle compared to the coronary arteries (16,27). Substantial differences in the flow patterns, with more shearing and less ordered motion in the left ventricle, require reduced motion-sensitizing gradient strength than for the coronary arteries: The optimal first-order gradient moment ($m_1$) was reported to be around 160 mT·ms$^2$/m for ventricular applications (16,27) and 800 to 1,600 mT·ms$^2$/m for plaque imaging (25,28). Hence, to account for these differences and to ensure optimal blood suppression that meets the requirements of quantitative imaging, a separate optimization of the MSDE preparation and the motion-sensitizing gradient strength was performed. A hybrid adiabatic/composite preparation module was chosen as a tradeoff between $B_1^+$ uniformity and SAR that enables thorough blood suppression in the healthy volunteer cohort, suitable for quantitative imaging. The assessed optimal echo time (TE$_{MSDE}$) leads to a first-order gradient moment of $m_1 = 168$ mT·ms$^2$/m, which is in agreement with previous reports (27).

To enable optimal blood suppression with minimal signal void in the myocardium, careful positioning of the preparation at a time point with minimal contractile motion of the heart is necessary. Imaging was performed at late end-diastole in order to accommodate the MSDE preparation well within the end-diastolic quiescence. A fixed echo-time TE$_{MSDE} = 11$ ms showed consistent T$_1$ map quality in the healthy cohort. However, in patients with high heart rates or arrhythmias, cardiac motion during the MSDE preparation might be unavoidable and potentially detrimental to the image quality in the proposed black-blood approach. Patient-specific adaption of the MSDE preparation should be performed in these cases to achieve optimal image quality. TE$_{MSDE}$ scouting has been previously proposed to enable efficient selection of the patient-specific optimal echo time (26). Also, alternative blood suppression schemes such as double-inversion recovery (29) or in-flow suppression (30).

**FIG. 7.** (a) Series of T$_1$-weighted baseline images with different inversion times and the corresponding T$_1$ map overlay, as acquired in the conventional and black-blood SAPPHIRE T$_1$ mapping sequence in one healthy subject. (b) Signal intensities of the septal myocardium and the left-ventricular blood pool in the baseline images shown in (a). T$_1$ recovery curves are obtained in the myocardium with both sequences. The high blood signal in the conventional T$_1$ mapping sequence is successfully suppressed with the black-blood approach, leading to minor differences in the blood signal across the inversion times.
might be more suitable for patients with arrhythmia or tachycardia and warrant further inspection.

$T_1$ maps are commonly evaluated using manually drawn ROIs. However, especially in pathologies with reduced myocardial wall thickness, such as DCM or transmural scars, there are often only a few voxels left within the myocardium that are not affected by partial voluming (3). This bears the risk that elevated $T_1$ times in this cohort merely reflect a change in the extent of partial voluming. Black-blood $T_1$ mapping might be a valuable tool to confirm actual changes in the underlying myocardial $T_1$ in these pathologies, while eliminating the impairment by partial voluming effects.

Heng et al. recently presented initial data on the use of a MSDE-prepared fat-water separated $T_1$ mapping sequence (14). The sequence was based on a saturation recovery single-shot acquisition design (31) during free breathing. Although thorough blood suppression enabled good depiction of the right ventricle, the $T_1$ quantification with their pilot protocol was impaired by issues with robustness, reproducibility, and $T_1$ uniformity. The strong gradients in the MSDE preparation sensitize the magnetization even for small displacements. Hence, potential reasons for a lack of reproducibility in (14) include signal loss resulting from respiratory motion during free breathing, and suboptimal placement of the MSDE preparation due to the long multi-echo imaging readout. In the present study, rapid imaging during a breath hold mitigated these error sources and enabled reproducible $T_1$ mapping in the left ventricle. However, depiction of the right ventricle is hindered by the lack of fat-signal suppression. Initial results for fat-suppressed $T_1$ mapping have previously been proposed, showing high image quality using spectrally selective saturation of the fat before the imaging pulses (32). A combination of fat- and blood-suppressed $T_1$ mapping bears great promise for improved image quality and full elimination of partial voluming caused by epicardial fat, and it warrants further investigation.

Despite careful optimization of the MSDE module, a residual loss in precision was shown to be the major disadvantage of the proposed black-blood SAPPHIRE technique compared to the conventional $T_1$ mapping. The loss in $T_1$ mapping precision after the MSDE preparation can be attributed to multiple factors: 1) a consistent loss in SNR

![Bulls-eye representation of $T_1$ times and precision in the 16 AHA segments across three slices (A = apical, M = midventricular, B = basal) acquired with conventional and black-blood SAPPHIRE. Similar $T_1$ times are assessed with both approaches, whereas significantly better precision is observed with conventional SAPPHIRE.](image)

**Table 1**

Average Myocardial ROI Thickness for Conventional and Black-Blood $T_1$ Mapping

<table>
<thead>
<tr>
<th>SHAX Slice</th>
<th>Conventional (mm)</th>
<th>Black-Blood (mm)</th>
<th>Difference*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apical</td>
<td>4.1 ± 0.7</td>
<td>6.2 ± 1.5</td>
<td>52% ± 24%</td>
</tr>
<tr>
<td>Mid</td>
<td>4.7 ± 1.1</td>
<td>7.3 ± 1.5</td>
<td>61% ± 33%</td>
</tr>
<tr>
<td>Basal</td>
<td>5.1 ± 0.8</td>
<td>6.8 ± 1.0</td>
<td>36% ± 22%</td>
</tr>
<tr>
<td>Average</td>
<td>4.6 ± 0.7</td>
<td>6.8 ± 0.8</td>
<td>50% ± 22%</td>
</tr>
</tbody>
</table>

*P < 0.05 for all differences. ROI, region of interest.
for all baseline images; 2) reduced resilience to imaging artifacts at lower SNR; and 3) increased variability among the baseline images. Our results indicate that the loss of the imaging SNR in the baseline images is the major source of increased variability. In addition to T2 decay during the MSDE preparation, pulse imperfections and residual bulk motion of the myocardium reduce the signal after the preparation. Diffusion-related signal loss during the MSDE preparation can be assumed to be of minor importance due to very low b-values in the preparation (< 1 s/mm2). Further loss in precision can be caused by increased susceptibility to imaging artifacts (e.g., fold-over) at lower SNR. Furthermore, additional variability among the baseline images can be induced in the proposed sequence due to differential patterns of residual motion in the myocardium.

The overall reproducibility in myocardial T1 mapping is paramount and affected by a number of factors, including the T1 mapping precision, the myocardial segment volume, and the inter- and intraobserver variability. On the one hand, reduced precision was shown for the proposed black-blood T1 mapping technique compared with conventional SAPPHIRE. On the other hand, an increase in the readily evaluable myocardial area has been facilitated using blood suppression, allowing for increased segmental sizes and potentially reducing the variability of segmental T1 times. Furthermore, the black-blood technique has shown high robustness toward variation of the ROI size. Correspondingly, our initial evaluation in a small cohort has indicated decreased interobserver variability with black-blood SAPPHIRE compared with the conventional sequence. Although these effects can be mitigated by observer training, this result is in line with a previous report on T2 mapping (33), showing that differential ROI delineation against the blood pool is a disruptive factor to the interobserver reproducibility. However, the differences in intraobserver variability were observed to be smaller, and no statistical significance was obtained given the small sample size. Hence, the assessment of the net overall effect on the reproducibility, inter- and intraobserver variability between black-blood, and conventional T1 mapping requires a larger cohort to substantiate the claims and allow for statistical significant findings. This is to be evaluated in a future study.

Residual blood signal after the MSDE preparation was found to be insufficient for robust estimation of the blood T1 time. This prevented the estimation of the extracellular volume (ECV) with the proposed technique. Because ECV estimation is the primary use of postcontrast T1 times, the evaluation in the present work was restricted to the native myocardium, and no T1 times after contrast injection were assessed. Separate assessment of a single, not spatially resolved blood T1 time of the blood pool is potentially feasible with a rapid free-breathing technique (34). This will be evaluated as a supplement to the proposed technique in future studies in order to allow for black-blood ECV mapping.

This study and the proposed method have several limitations. Only a small number of healthy subjects were included in this proof of concept study, and no reproducibility or sensitivity toward pathological alternation in the T1 time was assessed. Furthermore, the analysis of inter- and intraobserver variability was based on the assessments of two independent readers only. Increased consistency can be expected for larger cohorts due to learning effects on the readers or if common training is provided.

CONCLUSION
This study showed the feasibility of black-blood T1 mapping at 3T. SAPPHIRE black-blood allows for accurate T1 time quantification of the native myocardium that is robust to ROI alterations, and it eliminates partial voluming at the blood pools for the tradeoff against increased precision.

ACKNOWLEDGMENT
The authors would like to thank Dr. Peter Kellman for helpful discussions.

REFERENCES


SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article.

Sup. Table S1. Summary of the three MSDE modules, with the employed RF pulses and corresponding timing.

Sup. Fig. S1. Bland-Altman analysis of phantom T1 times assessed with conventional and black-blood SAPPHIRE. TEMSDE =11ms was used in the black-blood sequence. Good agreement with minimal average deviation is shown between the two sequences.