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MYOCARDIAL PERFUSION IMAGING

3 Tesla MR imaging provides improved contrast in first-pass myocardial perfusion imaging over a range of gadolinium doses

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Purpose. To compare myocardial enhancement during first-pass myocardial perfusion imaging at 3.0 Tesla (T) and 1.5T. *Materials and Methods.* First-pass myocardial perfusion imaging was performed on twelve normal subjects at 3T and 1.5T using an interleaved notched saturation recovery gradient echo pulse sequence. Subjects received either 0.10 mmol/kg for both scans (group 1), 0.075 mmol/kg for both scans (group 2), or 0.075 mmol/kg for the 3T scan and 0.10 mmol/kg for the 1.5T scan (group 3). *Results.* Contrast enhancement was significantly greater at 3T than at 1.5T for the 12 subjects whether enhancement was normalized to baseline signal intensity (2.58 ± 0.76 vs. 1.52 ± 0.37, $p < 0.0001$) or to noise (57.6 ± 19.7 vs. 14.7 ± 7.8, $p < 0001$). For each of the three groups, contrast enhancement was significantly greater at 3T versus 1.5T ($p < 0.0001$, $p < 0.001$, $p < 0.008$ when normalized to baseline signal; $p < 0.0001$ for all groups when normalized to noise). *Conclusion.* 3T improves contrast in first-pass myocardial perfusion imaging at either 0.10 mmol/kg or 0.075 mmol/kg.

Key Words: Perfusion; 3 Tesla; Contrast

1.   Introduction

First-pass perfusion imaging with gadolinium- (Gd) based contrast agents has performed reasonably well for the detection of coronary artery disease during pharmacological stress (1–5). Analysis of the images is often non-quantitative or semi-quantitative, in which abnormally perfused myocardium is detected by its slower uptake of contrast than adjacent, normally perfused myocardium. Therefore, first-pass myocardial perfusion imaging would likely benefit from methods that further accentuate the difference between abnormally and normally perfused myocardium.

Compared with conventional (1.5T) scanners, images acquired at 3T have been shown to have higher signal to noise (SNR) and contrast to noise (CNR) for peripheral vascular (6), neuro (7, 8), and cardiac applications (9–12). Empiric studies have shown a trend towards greater conspicuity of Gd contrast agents at higher field strengths

(13), and it is likely that first-pass myocardial perfusion imaging benefits from the scanning at 3T. However, the relationship between Gd dose, signal, and field strength is complex and not predictable in patients, and at higher field strengths T2* effects are more pronounced, which could lead to decreased signal from Gd-based contrast agents (13). Therefore, direct study comparison of first-pass myocardial perfusion imaging at 3T and 1.5T would be useful.

The primary purpose of this study was to compare myocardial enhancement during first-pass myocardial perfusion imaging with Gd-diethylenetriamine penta-acetic acid (Gd-DTPA) contrast material in normal subjects scanned at both at 3.0T and 1.5T. Secondary purposes were to compare SNR and LV blood pool signal.

2.   Materials and methods

2.1.   *Subjects*

Thirteen subjects were enrolled, but one subject withdrew following a contrast reaction. Consequently, twelve normal subjects without known coronary artery disease were included: 8 males, 4 females (mean age 33 years, ± 8.4

years, range 29–60 years). All subjects were scanned at 3T and 1.5T. The mean time between scans was 42 days, ± 22 days, range = 2–65 days. Written informed consent was obtained from all subjects, and the local institutional review board approved the study.

2.2. 3T and 1.5T scanners

3T scanning was performed on a GE Signa 3.0T, VH/i and 1.5T scanning was performed on a GE Signa cvi system (GE Medical Systems, Milwaukee, WI, USA). Both scanners had the same gradient performance: gradients of 40 mT/meter with a slew rate of 150 mT/m/msec. Identical four channel phased array torso coils, tuned to 64 and 128 mHz, were used for both scans.

2.3. Image acquisition

MRI perfusion imaging was performed using an interleaved notched saturation recovery gradient echo pulse sequence with an echo train of 4 (14, 15). The TR, TE, and TI for this imaging sequence vary with patient heart rate and so the mean value of these parameters were slightly different between the 1.5T and 3T scans (Table 1). The acquisition parameters were otherwise the same and included a field of view (FOV) = 32–40, phase FOV = 0.75, matrix 128 × 128, slice thickness 10 mm, gap = 0–5 mm, and bandwidth of 125 kHz. Short-axis slices (6–9, depending on heart rate) were acquired at every 1 or 2 (depending on heart rate) R-R intervals triggered by the ECG R-wave. From these, three were chosen for analysis.

To minimize field in homogeneity in 3T scans, shim gradients were determined by prescribing a small FOV (8 cm × 8 cm) image centered over the heart and performing an autoshim to determine the shim gradients. These shim gradients were then used in prescribing all subsequent scans (16). For 1.5T scanning, autoshimming was performed (GE Medical Systems, Milwaukee, WI, USA).

2.4. Contrast doses

For first-pass perfusion imaging, all subjects received intravenous (IV) doses of Gd-DTPA contrast material (Omniscan, Amershan Health, Princeton, NJ, USA). All IV sites were 18 gauge antecubital. Contrast material was injected at 5 cc/sec with 20 cc saline flush.

Subjects were divided into three groups depending on the concentration of contrast material received. In group 1

Table 1. MRI parameters at 3T and 1.5T

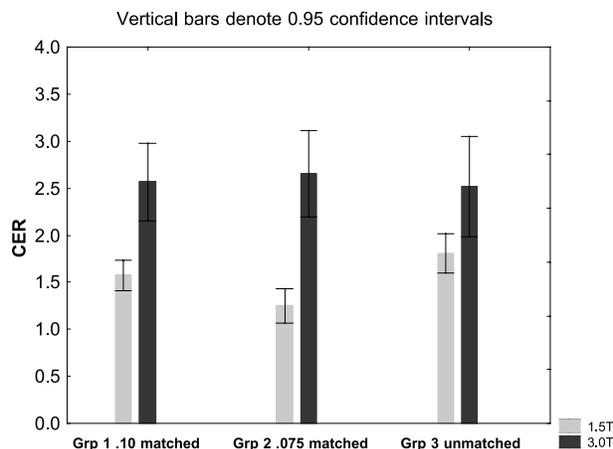| MRI parameter	3T	1.5T
TR (repetition time)	7.05 ± 0.54	6.63 ± 0.09
TE (echo time)	1.49 ± 0.12	1.23 ± 0.05
TI (inversion time)	192.00 ± 12.77	208.50 ± 28.70

All values are in msec.

Figure 1. CER by Gd concentration and field strength for all subjects. Between field strengths, 3T images provided significantly higher CER values for all groups: group 1: p < 0.0001, group 2: p < 0.0001, group 3: p = 0.008.

(n = 4), subjects received 0.075 mmol/kg of Gd-DTPA for the 3T scan and also for the 1.5T scan. In group 2 (n = 5), subjects received 0.10 mmol/kg for both scans. In group 3 (n = 3), subjects received 0.075 mmol/kg for the 3T scan and 0.10 mmol/kg for the 1.5T scan.

The use of variable and unequal concentrations of Gd-DTPA was chosen because of potential of decreased signal intensity with higher Gd concentration in the myocardium at 3.0T due to increased $T2^*$ effects. Although we did not formerly test for a specific threshold at which point $T2^*$ effects would predominate, group 3 patients allow a comparison of the high concentration of Gd-DTPA used at 1.5T in clinical exams to a lesser concentration at 3T, which might be necessary to avoid myocardial $T2^*$ effects.

2.5. Image analysis

Images were analyzed off-line with dedicated software (Cine, GE Medical Systems, Milwaukee, WI, USA). Three slices (apical, mid, and base) were analyzed, always excluding the first slice acquired. The slices were matched between the 3T and 1.5T scans for registration by anatomic landmarks. For each slice, three circular (approximately 5–7 mm^2) regions of interest (ROI) were selected: anterior myocardium, inferior myocardium, and left ventricular (LV) blood pool. These were copied through all cardiac phases automatically and adjusted manually for motion as necessary. Thus each subject had a total of 6 myocardial ROI's (anterior and inferior at each level: apex, mid-ventricle, and base) and 3 LV blood pool ROI's (one at each level: apex, mid-ventricle, and base). In our 12 subjects, there were therefore a total of 72 myocardial ROI's and 36 LV blood pool ROI's. Time intensity curves were created for each ROI.

Contrast enhancement ratio (CER) was defined as ([peak signal intensity—baseline signal intensity]/baseline signal intensity) for a specific myocardial ROI.

Table 2. Myocardial CER by ROI location and Gd

Group by Gd	Anterior ROI			Inferior ROI		
	1.5T	3.0T	P 1.5 vs. 3T	1.5T	3.0T	P 1.5 vs. 3T
Group 1	1.53 ± 0.20	2.52 ± 0.82	< 0.001	1.60 ± 0.40	2.62 ± 1.0	< 0.05
Group 2	1.14 ± 0.54	2.99 ± 1.09	< 0.001	1.36 ± 0.41	2.31 ± 1.07	< 0.01
Group 3	1.73 ± 0.34	2.66 ± 0.60	< 0.001	1.89 ± 0.42	2.38 ± 0.94	0.08

Gd − gadolinium-DTPA.
All doses are in mmol/kg.

Signal intensity change from baseline values to peak enhancement were also adjusted for background noise in a separate analysis ([peak signal intensity — baseline signal intensity]/standard deviation of mean noise) for an enhancement to noise ratio (ENR). Mean noise was measured from a circular ROI external to the chest wall.

Signal to noise ratio (SNR) was calculated from baseline images (prior to contrast arrival) and peak enhancement images by the formula: mean signal intensity myocardial ROI/standard deviation of mean noise.

2.6. *Statistical analysis*

Data are represented as mean ± standard deviation or 95% confidence interval. Comparison of variables across the three groupings was performed using one-way analysis of variance. Post-hoc comparisons were performed using a Fischer's Least Significant Difference (LSD) test. Comparisons within a group by magnetic field strength were performed using a paired two-tailed *t*-test.

3. Results

3.1. *Myocardial contrast enhancement ratio*

Overall, 3T images provided significantly greater CER than 1.5T images: 2.58 ± 0.76 at 3T vs. 1.52 ± 0.37, $p < 0.0001$ at 1.5T. CER was also significantly greater at 3T than at 1.5T for each of the three subgroups (group 1: $p < 0.0001$, group 2: $p < 0001$, group 3: $p = 0.008$, Fig. 1). Of note, perfusion
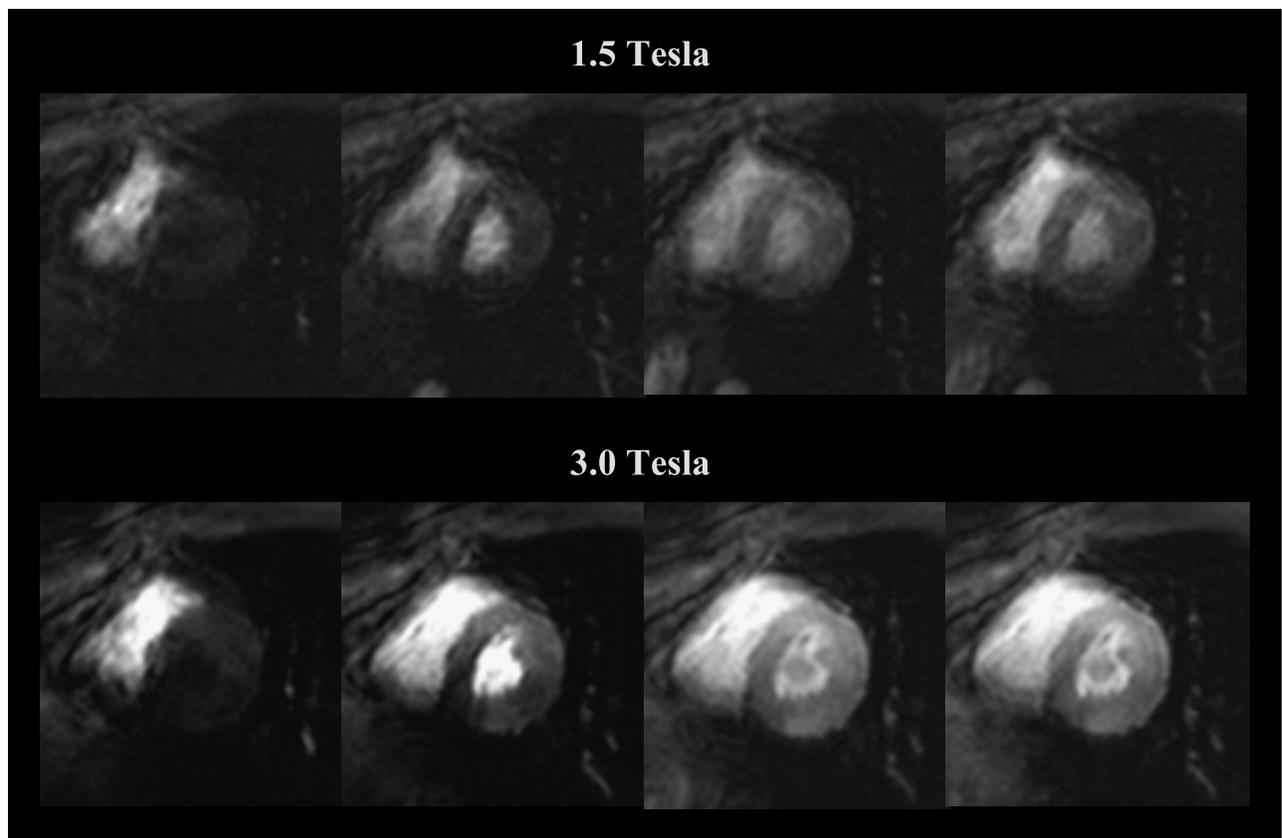

Figure 2. Comparison of perfusion image quality at 1.5T (top panel) and 3.0T (lower panel). First-pass myocardial perfusion MRI in a 35-year-old male injected with 0.10 mmol/kg Gd-DTPA for both studies.
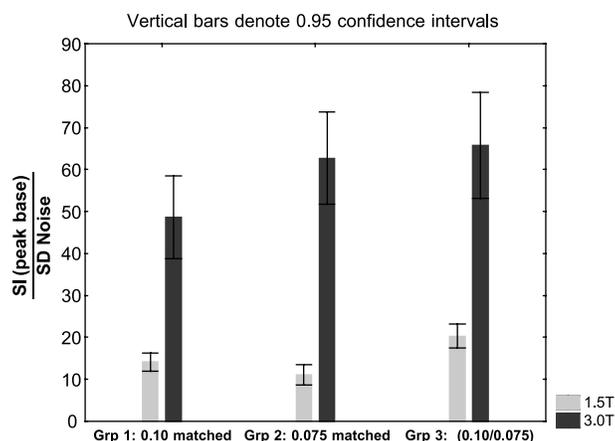
Vertical bars denote 0.95 confidence intervals

Figure 3. ENR by Gd concentration and field strength for all subjects. Between field strengths, 3T images provided significantly higher ENR values for all groups: group 1: p < 0.0001, group 2: p < 0.0001, group 3: p < 0001.

imaging at 3T with 0.075 mmol/kg of Gd-DTPA produced enhancement that was significantly greater than imaging at 1.5T using the higher 0.10 mmol/kg concentrations of Gd-DTPA (group 3). CER by anterior and inferior ROI locations are summarized in Table 2. A representative series of images at 1.5T and 3T in the same patient is shown in Fig. 2.

3.2. *Myocardial enhancement to noise ratio*

As with CER, signal enhancement corrected for noise (ENR) was significantly greater for the overall images at 3T than at 1.5T: 57.6 ± 19.7 at 3T vs. 14.7 ± 7.8 p < 0001 at 1.5T. ENR was also significantly greater at 3T than at 1.5T for each of the three subgroups (group 1 p < 0.0001; group 2 p < 0001; group 3 p < 0.0001; Fig. 3). Comparison of Figs. 1 and 3 shows that normalizing the signal enhancement to noise (Fig. 3) produces more dramatic differences between 3T and 1.5T than normalizing to baseline signal intensity (Fig. 1). ENR by anterior and inferior ROI locations are summarized in Table 3.

3.3. *Signal to noise ratio*

Overall, SNR was significantly higher for 3T images measured at peak myocardial enhancement than at 1.5T:

Table 4. SNR by field strength during first-pass Gd-DTPA Bolus[*]

	1.5T	3.0T	p 1.5T vs. 3T
Anterior ROI			
Baseline	11 ± 4	24 ± 7	< 0.0001
Peak enhancement	27 ± 9	88 ± 26	< 0.0001
Peak baseline	16 ± 6	64 ± 21	< 0.0001
Inferior ROI			
Baseline	9 ± 4	23 ± 11	< 0.0001
Peak enhancement	22 ± 9	75 ± 31	< 0.0001
Peak baseline	13 ± 6	52 ± 21	< 0.0001

[*]Three ROI determinations (anterior myocardium, inferior myocardium, LV blood pool) per location (apex, mid-ventricle, and base).

SNR at $3T = 82 \pm 26$ versus SNR at $1.5T = 25 \pm 8$, p < 0.0001. This was due to both increased signal at peak enhancement for 3T images as well as significantly reduced noise values. Background noise was significantly decreased (p < 0.0001) at 3T compared to 1.5T (Fig. 4). The SNR results by magnetic field strength and ROI location are shown in Table 4.

3.4. *Left Ventricular blood pool signal*

There was no difference in signal intensity within the blood pool between 0.075 and 0.10 mmol/kg doses at either 3T or 1.5T (Table 5). Paired time-intensity curves from the LV blood pool and anterior myocardial ROI are shown for a patient at both magnetic field strengths (Fig. 5).

4. Discussion

This study shows that imaging at 3T improves contrast in MR first-pass myocardial perfusion imaging at Gd concentration of either 0.10 mmol/kg or 0.075 mmol/kg or when using 0.075 mmol/kg at 3T and 0.10 mmol/kg at 1.5T. For each dose comparison, the myocardial contrast enhancement ratio ([peak signal intensity—baseline signal intensity]/baseline signal intensity) and enhancement to noise ratio ([peak signal intensity—baseline signal intensity]/standard deviation of mean noise) were significantly greater at 3T than at 1.5T. Therefore, at clinical doses, increased Gd conspicuity

Table 3. Myocardial contrast enhancement by ROI location and Gd

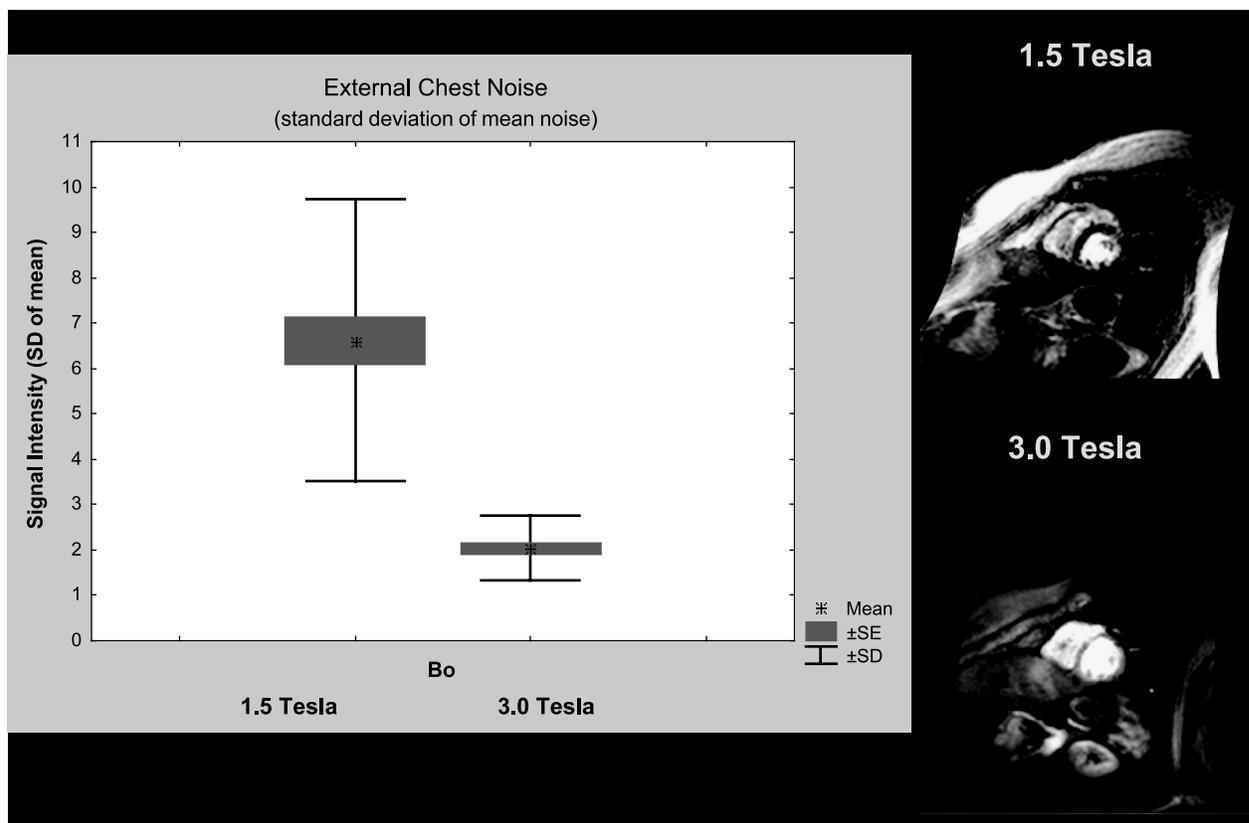| Group by Gd	Anterior ROI			Inferior ROI		
	1.5T	3.0T	P 1.5 vs. 3T	1.5T	3.0T	P 1.5 vs. 3T
Group 1	16.0 ± 5.8	55.6 ± 15.7	< 0.0001	12.2 ± 4.7	41.7 ± 12.1	< 0.0001
Group 2	11.8 ± 4.8	63.5 ± 19.8	< 0.0001	10.3 ± 3.5	62.0 ± 17.7	< 0.0001
Group 3	20.4 ± 5.2	77.0 ± 26.7	< 0.0001	20.3 ± 4.6	54.5 ± 30.5	< 0.0001

Gd–gadolinium-DTPA.
All doses are in mmol/kg.

Figure 4. Noise measurements at 1.5T and 3T. These values represent the mean and standard deviation for the group of the individual noise values obtained external to the chest wall. Noise was significantly reduced (p < 0.0001) at 3T compared to 1.5T.

outweighs signal loss from increased $T2^*$ effects at 3T. This even holds true when the 3T scan is performed at slightly lower dose than the 1.5T scan (group 3). This study supports the concept that first-pass perfusion studies are feasible at 3T and are likely to have advantages over those done at 1.5T.

The second finding in this study is that SNR for myocardial perfusion imaging is higher at 3T than at 1.5T. This supports the findings of other studies, which have shown increased SNR in other cardiac MRI applications and pulse sequences (9–12). Given that first-pass perfusion imaging sequences are usually low signal, this should be another advantage of 3T imaging.

The last finding was that there was no significant difference in LV blood pool at 3T than at 1.5T. Therefore, in the blood pool, where Gd concentration is highest, signal suppression from $T2^*$ effects negate the signal enhancement from higher field strength.

Table 5. Peak LV blood pool signal intensity

Bo	0.075 mmol/kg	0.10 mmol/kg	P
1.5T	354 ± 30	318 ± 21	NS
3.0T	364 ± 28	318 ± 20	NS

This study has several limitations. First, several imaging parameters differed slightly between the 3T and 1.5T scans (Table 1). Of note, the mean TI for the 3T scans was 16 msec less than that for 1.5T. These differences occurred because TI was dependent on heart rate, which was not exactly the same between scans for each patient. However, the overall differences in the scan parameters were small and should not account for the large differences in CER, ENR, and SNR seen in this study.

Second, for the 3T scans, manual shimming was performed, and for the 1.5T scans, autoshimming was performed. While some would argue that this would decrease field inhomogenities, which are a disadvantage of 3T scanning, current shimming technology is optimized for 1.5T, even on 3T scanners. In our estimation, performing the manual shimming on 3T scanners allowed for a more even comparison, as in the future shimming will be optimized on 3T scanners.

Third, we did not perform a linear dosing study to determine a dose range over which Gd concentration and signal have a linear relationship. Non-quantitative and semi-quantitative analyses require only a difference between abnormal and adjacent normal myocardium. Quantitative methods require accurate measure of an arterial input function. To achieve this, doses must be kept within the range where there is a linear relationship between contrast
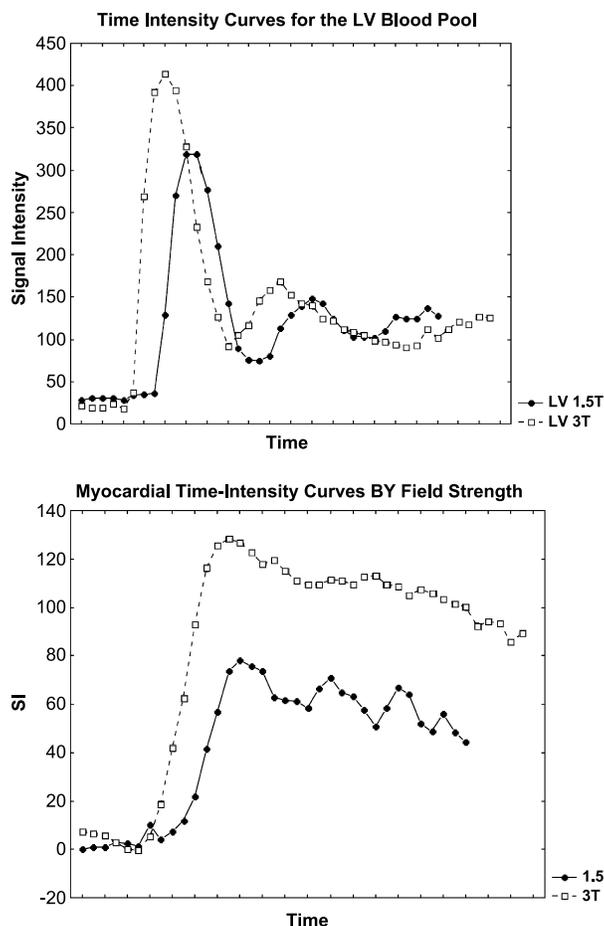
Time Intensity Curves for the LV Blood Pool

Myocardial Time-Intensity Curves BY Field Strength

Figure 5. Overlay plots of time-intensity curves from the LV blood pool (left) and myocardium (right) in a single subject injected with 0.10 mmol/Kg Gd-DTPA while scanned at 1.5T (solid line) and at 3T (dashed line).

concentration and signal in the blood pool. Therefore, further investigation will be required before 3T scanning can be applied for truly quantitative analysis of myocardial perfusion.

Finally, the authors did not compare 3T saturation/recovery imaging to steady state free precession-based perfusion imaging at 1.5T. Investigators have shown improvement in image signal during first-pass perfusion with Gd-DTPA using steady state free precession imaging (3), and comparison of such sequences at 1.5T with saturation recovery imaging at 3T would be of interest.

In conclusion, imaging at 3T improves both SNR and peak enhancement in MR first-pass myocardial perfusion imaging, when using either 0.10 mmol/kg or 0.075 mmol/kg. Future studies may be useful to determine whether the improved contrast translates into improved sensitivity or specificity of MR first-pass myocardial perfusion imaging for the detection

of coronary stenoses. The application to fully quantitative imaging remains to be determined.

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