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Cardiac Cine MR-Imaging at 3T: FLASH vs SSFP

Damian J. Tyler, PhD,[1,2] Lucy E. Hudsmith, MA, MCRP,[1] Steffen E. Petersen, DPhil, MD,[1] Jane M. Francis, DCRR, DNM,[1] Peter Weale, PhD,[3] Stefan Neubauer, MD, FRCP,[1] Kieran Clarke, PhD,[2] and Matthew D. Robson, PhD[1]

University of Oxford Centre for Clinical Magnetic Resonance Research (OCMR), John Radcliffe Hospital, Oxford, United Kingdom[1]
Cardiac Metabolism Research Group (CMRG), University Laboratory of Physiology, University of Oxford, Parks Road, Oxford, United Kingdom[2]
Siemens Medical Solutions, Oldbury, Bracknell, Berkshire, United Kingdom[3]

ABSTRACT

The implications of an increase in field strength, from 1.5 T to 3 T, for routine functional cardiac examinations have been systematically investigated. Flip angle optimization was carried out for identical SSFP and FLASH cine imaging sequences at 1.5 T and 3 T, which supported the use of 20° (FLASH 1.5 T and 3 T) and >60° (SSFP 1.5 T and 3 T). The optimized sequences were applied in a study of cardiac function in a group of ten normal volunteers. Both SSFP and FLASH sequences showed significant SNR increases in the myocardium and blood at 3 T compared with 1.5 T, increases of 48% and 30% (myocardium and blood, respectively) for the SSFP sequence and 19% and 13% for the FLASH sequence. The SSFP sequence also showed a significant increase in CNR (22%). Image quality assessment revealed that the SSFP acquisitions were superior to FLASH at both field strengths. Although SSFP contained more artifacts at 3 T, they would not prevent its clinical use. We conclude that cardiac functional examinations at 3 T should use SSFP sequences.

INTRODUCTION

Cardiac MR imaging at 1.5 Tesla (T) has proven to be the method of choice for a large number of clinical cardiac examinations. The emergence of the higher clinical field strength of 3 T (1, 2) has affected patient care for neuroimaging procedures, but it is not certain how relevant this field strength will be for cardiac examinations.

The functional cardiac exam provides the cornerstone for most cardiac MRI investigations. MRI at 3 T offers increased signal to noise ratio (SNR) compared with 1.5 T (3–7), but if it is to become a practical clinical tool it must be capable of performing this functional exam reproducibly, without the presence of artifacts that would prevent accurate quantification. This exam can be performed using either the Steady State Free Precession (SSFP) or the Fast Low Angle SHot (FLASH) method. Previous work using SSFP imaging (also known as FIESTA, Balanced FFE, and True-FISP) at 3 T (2, 6, 8) had limited parameter optimization and made no systematic comparisons with 1.5 T or with FLASH. Past studies have found the SNR of SSFP to be improved at 3 T (versus 1.5 T) by between 20% and 150% (4–6), but there were artifacts that may or may not be problematic. A range of approaches to improve the image quality have been described, but to date no systematic study has assessed the performance of a carefully configured, but standard, 3 T clinical MRI system.

Increasing the magnetic field strength to 3 T yields larger magnetic field distortions that can introduce image artifacts into SSFP acquisitions (8–11), which may be a fundamental restriction of the method. Owing to this concern over the artifacts of SSFP, this work has also investigated the FLASH approach, which was historically the preferred approach, for cardiac function at 1.5 T before the emergence of SSFP. These sequences have been investigated at both 1.5 T and 3 T and on the same group of subjects.

Sequence optimization has been performed to maximize the contrast of these sequences at each field strength, for which we find different results to the existing theoretical work. The optimised sequences were used for volume studies, as

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Correspondence to:
Damian J. Tyler
OCMR (University of Oxford Centre for Clinical Magnetic Resonance Research)
John Radcliffe Hospital
Oxford, OX3 9DU, UK
Phone: ++00 44 1865 221321
email: damian.tyler@physiol.ox.ac.uk

if performed in the clinical environment, and were assessed quantitatively.

THEORY

The major source of artifact in the SSFP sequence occurs due to the magnetic field sensitivity of the sequence. The resonance condition is only obeyed within a certain frequency "band" (8). The width of the "band" over which no artifacts will occur is inversely proportional to the sequence repetition time (TR) of the SSFP sequence. Consequently, this favors the use of short TR (typically 2–4 ms), which explains why, with the emergence of high-performance gradient systems, SSFP has become relevant for cardiac imaging.

The heart is a difficult organ to shim owing to the complex field patterns in that region of the body (e.g., due to the lungs) (12–14), but also due to the motional parameters of the heart and blood, which are additionally complicated by breathing. By doubling the magnetic field strength from 1.5 T to 3 T, we double the frequency variations in and around the heart that are due to susceptibility differences, and consequently increase the chance of some parts of the image having a frequency that is outside the SSFP "band."

Specific absorption rate (SAR) or radio-frequency (RF) heating effects also limit the SSFP exam. SAR increases as the square of the field strength, and the SSFP sequence uses large RF pulses at a fast TR. Basic solutions to this problem are to decrease the requested flip angle, or to increase the duration of the RF pulse (whilst maintaining its area, and hence decreasing its amplitude). The former will affect image quality via SNR and contrast to noise (CNR); the latter approach will increase the TR and hence make the SSFP "band" narrower and increase the chance of image artifacts.

Relaxation rates at 1.5 T and 3 T are known to differ by as much as 20–40% (15–18). The calculations for optimal SNR and CNR both depend on excitation flip angle (an extrinsic parameter) and the T_1 and T_2 of the blood and myocardium. Consequently, one needs to re-evaluate the optimal flip angle for these studies at 3 T, which we have done empirically here, whereas a theoretical approach was used previously (8).

The final important difference between 1.5 T and 3 T for cardiac imaging is the increased magneto-hydrodynamic effects that can affect triggering from the ECG waveform (19), which are linearly dependent upon the magnetic field strength. We have assessed our triggering accuracy empirically.

METHODS

All images were acquired on a 1.5 T (∼63 MHz) Siemens Sonata (Siemens, Erlangen, Germany) and a 3 T (∼123 MHz) Siemens Trio (Siemens, Erlangen, Germany). Both systems used identical (25A) software and were equipped with identical high performance gradients (40 mT/m 200 T/m/s per axis). Cardiac array coils (Siemens) were used (6-channel anterior, 2-elements of integrated spine array at 1.5 T; 4-channel anterior and 4-channel posterior at 3 T). Subjects were positioned in the head-first supine orientation and equipped with headphones. In each case, identical ECG triggering hardware was used (Active ECG, Schiller Medical, supplied by Siemens Medical Solutions), which utilized 3-ECG electrodes and included amplification within the magnet. The ECG was generated by selection of the two leads that produced the most reliable triggering. In all cases the 3 electrodes were positioned at the apex of the heart, and the electrodes were not removed from the patient between their scans at 1.5 T and 3 T (which were performed consecutively and in a random sequence). This is not a vector ECG system (20), as has been used in previous studies. At 3 T, the first level of RF heating (<4 W/kg) was used but at 1.5 T this higher level was not necessary for any of the subjects and <3 W/kg was used.

Sequence parameters were chosen so that we could directly compare the signal, contrast and noise behavior at the two field strengths and so, where possible parameters were kept constant, basing the acquisition on a near optimum 1.5 T protocol. Identical SSFP and FLASH acquisition parameters were chosen at both field strengths with the exception of the excitation angles, which were optimized for each sequence at each field strength. The parameters for the sequences used here were:

- SSFP; FOV 350 × 306, 7 mm slice (3 mm gap for multi-slice), 1.82 × 1.82 mm resolution, GRAPPA with ×2 acceleration and 29 reference lines, TE 1.42 (1.47 ms at 3 T), TR 3.12 ms (3.17 ms at 3 T), retrospective ECG gating yielding 25 frames per cardiac cycle, 14 lines per segment, sampled temporal resolution of 43.70 ms (44.38 ms at 3 T), and a 930 Hz/pixel bandwidth. Breath-hold time of 7 heartbeats. The differences in TE/TR between the two field strengths results from the slightly longer RF pulses used at 3 T to enable large flip angles within the SAR limits.
- FLASH; as SSFP above but, TR 5.48 ms, TE 2.75 ms, 2.28 × 2.82 mm resolution, 9 lines per segment, sampled temporal resolution of 49.3 ms, with 350 Hz/pixel bandwidth. Breath-hold time of 9 heartbeats.
- SSFP frequency pilot; FOV 350 × 292, 7 mm slice thickness, single shot acquisition per heart beat with a trigger delay of 350 ms. TE 1.3 ms, 144 phase encode lines, TR 3.1 ms, GRAPPA with ×2 acceleration and 29 reference lines. Flip angle of 60°, with 930 Hz/pixel bandwidth. Frequency offsets from −200 Hz to 200 Hz in 40 Hz steps. Breath-hold time 11 heartbeats.

These product sequences and parameters are proven to yield high-quality images at 1.5 T and so can be considered a reference standard. For practical reasons in this work, we used the frequency piloting approach (10, 21) but did not shim the system on a per-person basis owing to the known problems with shimming the heart.

Institutional Review Board permission was obtained for this study. To determine the optimal contrast the following protocol was used at both field strengths on 5 normal subjects (3 males, age 33 ± 3 years (mean ± SD), weight 72 ± 15 kg):

1. localization of the short axis;

2. SSFP frequency pilots in mid-ventricular short axis and horizontal long-axis orientations followed by selection of optimal frequency offset;
3. FLASH acquisitions of a mid-ventricular short-axis slice, using the parameters above, and with flip angles: 10°, 12°, 14°, 15°, 16°, 18°, 20°, 25°, 30°, 35°;
4. SSFP acquisitions of the same mid-ventricular short-axis slice using the parameters above, and with flip angles: 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40°, 45°, 50°, 55°, 60° (also 65°, 70°, 75° and 80° at 1.5 T).

Once the optimal flip angle had been determined, we used each of the 4 methods (1.5 T FLASH, 1.5 T SSFP, 3 T FLASH, 3 T SSFP) to acquire a full stack of slices through the myocardium in 10 normal subjects (5 males, age 28 ± 5 years weight 70 ± 16 kg). Two scan operators performed the 1.5 T and 3 T examinations with the same operator for each volunteer at both field strengths. In 5 cases, 1.5 T preceded 3 T by <1 hour and in 5 cases, 3 T preceded 1.5 T by <1 hour. In 50% of cases SSFP preceded FLASH and in the others FLASH preceded SSFP.

The following acquisition protocol was used:

1. localization of the short axis.
2. SSFP frequency pilots in mid-ventricular short axis and horizontal long-axis orientations, followed by selection of optimal frequency offset;
3. FLASH acquisitions of short-axis slices covering the whole ventricle using the parameters above, and with a flip angle of 20°;
4. SSFP acquisitions of short-axis slices covering the whole ventricle using the parameters above, and with a flip angle of 60° (at 3 T, the largest flip angle possible was used if 60° was not achievable with the SAR limits).

Image SNR and CNR were determined by measuring the noise in a background region of the image and calculation of the noise after taking account of the chi-squared noise distribution due to multiple RF coils. This approach appears to underestimate the noise when parallel imaging/reconstruction approaches are used, but identical parallelization should yield identical bias.

We developed a scoring system to assess the image quality:

4 = Perfect image of left ventricle (LV) and right ventricle (RV), no significant artifacts in these regions, blood pool well defined.
3 = Perfect image of LV, no artifacts in this region, blood pool well defined, RV can be measured despite some artifacts.
2 = LV and RV can be measured despite some artifacts.
1 = LV can be measured despite some artifacts, RV cannot be measured with any degree of confidence.
0 = LV and RV cannot be measured with any degree of confidence.

Two qualified observers assessed the images in a blinded fashion to determine the image quality in each of the images, and through the cardiac cycle.

RESULTS

Results of optimization

Figure 1 shows the variation of SNR and CNR with flip angle at 1.5 T and 3 T for SSFP and FLASH. Figures 2 and 3 show typical example images acquired with the SSFP (Fig. 2) and FLASH (Fig. 3) sequences at 1.5 T and 3 T over a range of excitation angles.

At 1.5 T, excitation angles of 20° for the FLASH acquisition and 60° for the SSFP acquisition were chosen. For the FLASH sequence, the choice of 20° was made despite the fact that CNR was optimal at excitation angles of 25–30°. This was because the intensity in the blood pool became extremely flow-dependent at these higher excitation angles resulting in very difficult boundary differentiation. For SSFP a flip angle larger than 60° improved contrast with no observed disadvantages. We chose to use 60° for consistency with literature values that have been used for this sequence.

At 3 T, flip angles of 20° for the FLASH acquisition and 60° for the SSFP acquisition were chosen. These turned out to be identical flip angles to those at 1.5 T. For the FLASH sequence, the curves showed similar flip angle dependence to 1.5 T. The 20° flip angle yielded the best compromise between SNR and contrast when the flow was slow. For SSFP at 3 T, the flip angle dependence also mirrored that at 1.5 T, but in this case SAR played a key role, as in many cases it was difficult to obtain a flip angle above 60°.

Results of ECG gating

ECG traces were corrupted by the high magnetic field, an effect that was greater at 3 T than at 1.5 T. Obtaining an accurate and reliable trigger was not found to be a problem in any of the subjects studied. In some cases after placing the volunteer into the magnet, the selection of leads was changed from the initial choice. This was due to magneto-hydrodynamic effects that occur at 1.5 T, doubling in amplitude at 3 T, and are seen as a potential problem at this higher field strength. In none of these cases did the ECG leads require repositioning.

Results of volume studies

Table 1 outlines the image quality assessment from the different sequences and different field strengths.

The 3 T SSFP images showed a significant increase in myocardial and blood SNR when compared with 1.5 T (myocardium 48 ± 6%, $p < 0.001$, blood 30 ± 4%, $p < 0.001$)

Table 1. Assessment of short axis stacks

		SCORE					
		4 (best)	3	2	1	0 (worst)	Average
SEQUENCE	1.5 T SSFP	8	5	1	0	0	3.5
	3 T SSFP	1	8	5	0	0	2.7
	1.5 T FLASH	2	0	10	2	0	2.1
	3 T FLASH	2	5	6	1	0	2.6

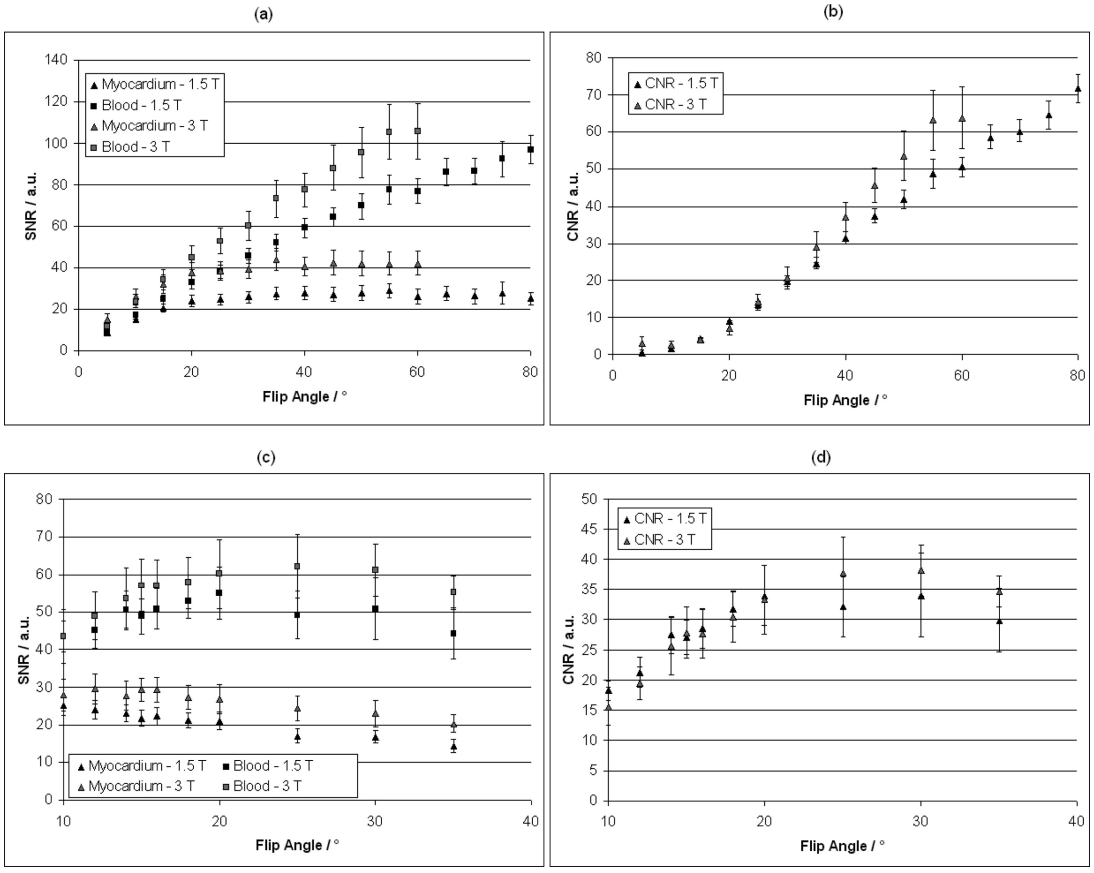

Figure 1. Variation of SNR in the myocardium and blood and CNR at 1.5 T and 3 T for the SSFP sequence (A, B) and the FLASH sequence (C, D).

and significant increase in CNR ($22 \pm 5\%$, $p < 0.001$). The 3 T FLASH images also showed a significant increase in myocardial and blood SNR when compared with 1.5 T (myocardium $19 \pm 7\%$ $p = 0.006$, blood $13 \pm 6\%$ $p = 0.01$), but with no significant change in the CNR.

The SNR data also revealed strong negative correlations between the measured SNR and the weight of the volunteers for both SSFP and FLASH sequence at 1.5 T and 3 T. This is demonstrated by the example shown in Fig. 4 for SSFP myocardial SNR at 1.5 T and 3 T.

DISCUSSION

Optimization

Increasing the field strength improved the SNR of both of these imaging sequences, although a significant CNR increase was only seen for the SSFP sequences. The optimal choice of flip angle at 3 T was extremely similar to that chosen at 1.5 T. This result disagrees with previous theoretical work at 3 T where an optimal excitation of 42° was proposed compared with 54° at 1.5 T (8). We are confident that this divergence between simplistic theory and measurements is explained by the importance of in-flow phenomena in the SSFP sequence (22, 23). Indeed the consequences of inflow explain the similarities in the optimal excitation flip angle of these two methods. Differences in the optimal flip angle at the two different field strengths might be expected due to the known differences in the T_1 values. But in a system where the spins are moving in and out of the slice faster than the relaxation rate, it is clear that the T_1 differences will have little effect on the optimal flip angle.

Similarly it is inflow effects that result in the artifacts seen with the FLASH sequence that limited our flip angle at 1.5 T. With the SSFP sequence, it was clear that increasing the flip angle (across the range studied here) improved the amount of signal from the blood pool. This was found to be true at both 1.5 T and 3 T; therefore, it is perhaps surprising that a higher flip angle is not the preferred choice at 1.5 T. In this work we selected 60° for 1.5 T and attempted to achieve a 60° pulse at 3 T, although in many cases this was not achievable (average excitation angle $= 56° \pm 4°$). We can only assume that the popular choice of 60° (when a higher angle would yield higher SNR) at 1.5 T relates to the problems that are found when one tries to analyze images with higher blood pool intensity. These problems occur as the endocardial boundary delineation requires a different image window setting than that for defining the epicardial boundary.

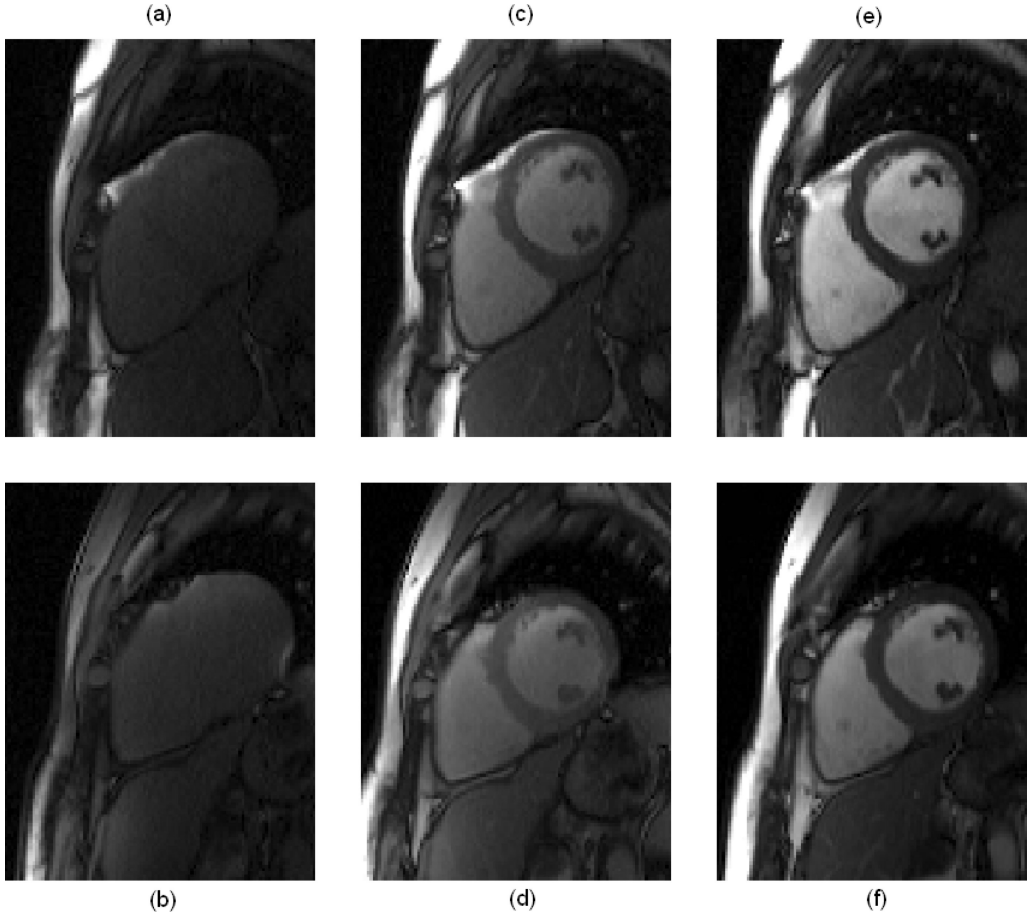

Figure 2. Example mid-ventricular, short axis SSFP images acquired at 1.5 T (A, C, E) and 3 T (B, D, F), acquired with excitation angles of 10° (A, B), 30° (C, D) and 60° (E, F).

SNR

This work has found SNR increases between 1.5 T and 3 T of 19% and 13% (myocardium and blood) for the FLASH and 48% and 30% for the SSFP sequences. The SNR for SSFP and FLASH at 1.5 T and 3 T has also been found to be strongly dependent upon the volunteer's weight and with Pearson correlation coefficients between $r = -0.58$ and $r = -0.87$. Variability of SNR between volunteers has already been described (6), and we believe this is due to changes in sensitivity of RF coils (either positioning, or loading effects). SNR has been found to increase at 3 T compared with 1.5 T by 20–80% (6), 103% (4) and 150% (5).

The simplest theory would indicate a 100% improvement in SNR at 3 T versus 1.5 T, and many studies in the brain have seen improvements of around 70–80%. It is not clear whether our moderate SNR improvement is due to hardware that has not been as thoroughly optimized at 3 T (versus the 1.5 T hardware) or whether the basic physics of MR at this higher field (i.e., B1 drop off in transmission, B1 drop off in reception, shorter T_2^*) limit our SNR to this degree. The differences in RF pulses between 1.5 T and 3 T is one element of the experiment which may further confuse this comparison, but as can be seen from literature values, SNR comparison between 1.5 T and 3 T is a difficult task.

Function studies

In this work we have adopted a pragmatic view to data acquisition. We have performed careful examinations but haven't used any specialist approaches. Image assessment demonstrated that both FLASH and SSFP yielded images that could be analyzed at both field strengths. For analysis, it would appear that the best images were still the SSFP images at 1.5 T, the 3 T SSFP were the next best having improved SNR and CNR but suffering from increased artifact which although not prohibitive to analysis did not aid image interpretation. SSFP provided better images than FLASH independent of the field strength selection. For the FLASH sequence, the 3 T acquisitions were appreciably better than the 1.5 T acquisitions. The increase in SNR is still present, but the artifacts that can be found in the 3 T SSFP sequence were not present and hence FLASH at 3 T provided images that were easier to analyze than the equivalent 1.5 T images.

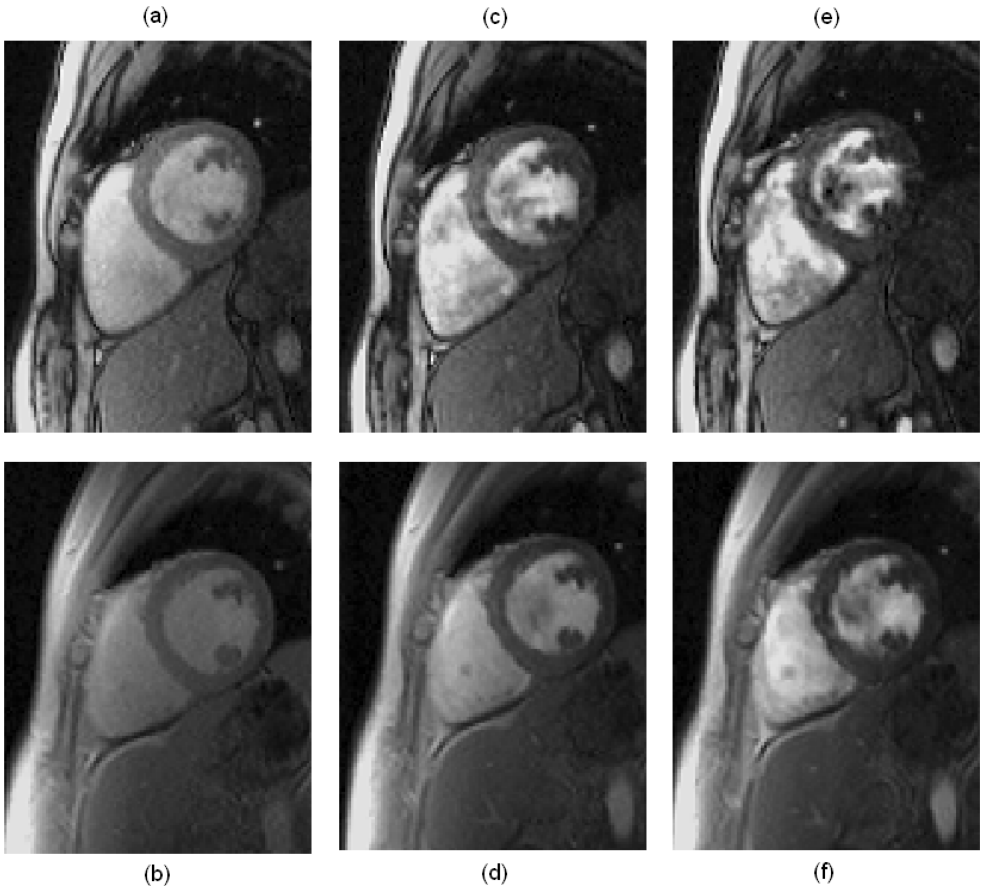

Figure 3. Example mid-ventricular, short axis FLASH images acquired at 1.5 T (A, C, E) and 3 T (B, D, F), acquired with excitation angles of 10° (A, B), 20° (C, D) and 30° (E, F).

Although ranked best (1.5 T SSFP) to worst (1.5 T FLASH), all these sequences provided high quality images that could be used to assess cardiac function. Further, the 3 T protocols were optimized for contrast but not for spatial resolution or to minimize artifacts, and so it is likely to be possible to further improve these protocols.

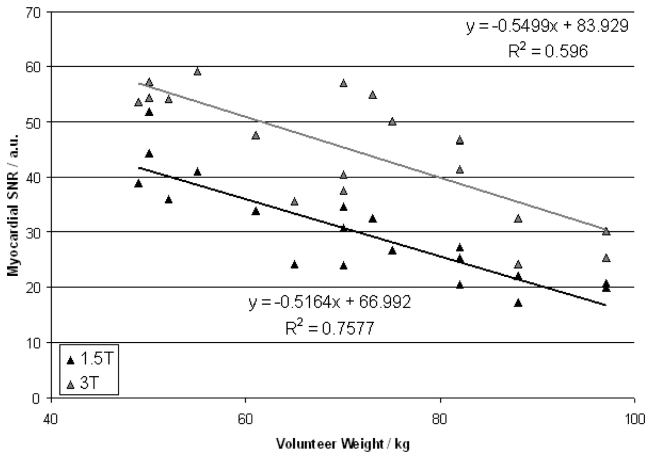

Figure 4. Variation of SNR with patient weight for the myocardium in mid-ventricular short axis SSFP images.

Several improvements are possible in the SSFP exam at 3 T. These include:

- improved cardiac gating, which though adequate in all these studies, can be a problem at 1.5 T, and is likely to be even worse at 3 T;
- decreasing the SSFP artifacts, which though acceptable for analysis were not perfect;
- increase RF pulse flip angle for the SSFP sequence to yield maximal contrast;
- optimization of the parameters, which would use some of the redundant increases in SNR at 3 T to provide improvements in scan-time, resolution or breath-hold time.

CONCLUSIONS

High quality cardiac functional images could be acquired at 3 T using SSFP and FLASH imaging methods. Optimal excitation angles of 60° (or as high as can be achieved within SAR limits) for SSFP and 20° for FLASH were found. The FLASH approach was more reliable and of higher quality than

the equivalent 1.5 T acquisition, having improved SNR. The SSFP-based approach also had increased SNR but was more sensitive to off-resonance artifacts. However SSFP still yielded higher quality images than FLASH at 3 T. For this reason we believe that functional assessment at 3 T should use SSFP-based methods. Improved shimming, RF pulses and shorter TR will help to remove the residual problems with this approach.

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