Review Article

Cardiovascular Magnetic Resonance at 3 Tesla: Advantages, Limitations and Clinical Potential

Constandinos Pamboucas, Petros Nihoyannopoulos

Department of Cardiology, Hammersmith Hospital, Imperial College, London, UK

Key words: **High field strength, signal-to-noise ratio, 3 Tesla, magnetic resonance imaging.**

Manuscript received: December 12, 2005;
Accepted: February 24, 2006.

Address:
Constandinos Pamboucas

58 Sifnou St., 10446 Athens, Greece
e-mail: *pamboucas@yahoo.co.uk*

Cardiovascular magnetic resonance (CMR) imaging is playing a rapidly expanding role in twenty-first century cardiology, with extensive clinical applications for standard magnetic resonance (MR) systems operating at a field strength of 1.5 Tesla (T).[1] Recently, there has been growing clinical and research interest in cardiac imaging at higher magnetic field strengths (3 T or more).[2,3]

High field imaging is attractive because it has the potential to improve the signal-to-noise ratio (SNR) significantly compared to imaging at 1.5 T, because of the increased polarisation of spins. With novel pulse sequence design, this SNR boost can be used to improve spatial and/or temporal resolution. In addition, the increased SNR allows one to take advantage of parallel imaging techniques, such as sensitivity encoding (SENSE), that have emerged as major tools for speeding up data acquisition. With respect to cardiac examinations, parallel imaging allows the use of shorter breath-holds; this in turn reduces the radiofrequency (RF) energy deposition in the subjects, which is a concern when imaging at a higher field strength. With parallel imaging, the gain in speed is traded for a reduced SNR, according to MR physics theory. The SNR loss with parallel imaging might be compensated for by the inherent gain in SNR at the higher static field strength.[4]

Apart from the advantages, several adverse effects of higher field strengths should be taken into account. These drawbacks include mainly increased static field (B_0) inhomogeneities and shorter T_2^* values, which may cause dark banding and susceptibility artefacts, and RF power deposition limitations which may remove flexibility for general sequence design (specific absorption rate should not exceed 4 W/Kg).[3,5] Other potential impediments include increased T_1 values, RF field (B_1) distortions and changed tissue dielectric constants or body dielectric resonances. Furthermore, at higher field strengths efficient myocardial motion suppression (reliable R-wave triggering) becomes more challenging as a result of the amplified magneto-hydrodynamic effect.

In terms of comparison between standard (1.5 T) and high field strength, morphological and functional cardiac imaging using spin-echo or conventional gradient-echo sequences, respectively, show clearly improved results at 3 T.[6,7] Currently, balanced steady-state free precession (SSFP) techniques represent the method of choice for assessing cardiac function at 1.5 T. SSFP techniques may also benefit considerably from the higher SNR at 3 T, despite the presence of artefacts (mainly dark bands) caused by disruption of the steady state due to static field inhomogeneity (Figures 1 and 2).[8,9] Moreover, it has been demonstrated that the application of higher field strengths is beneficial for myocardial tagging techniques, since the saturation bands show prolonged duration compared to 1.5 T.[10]

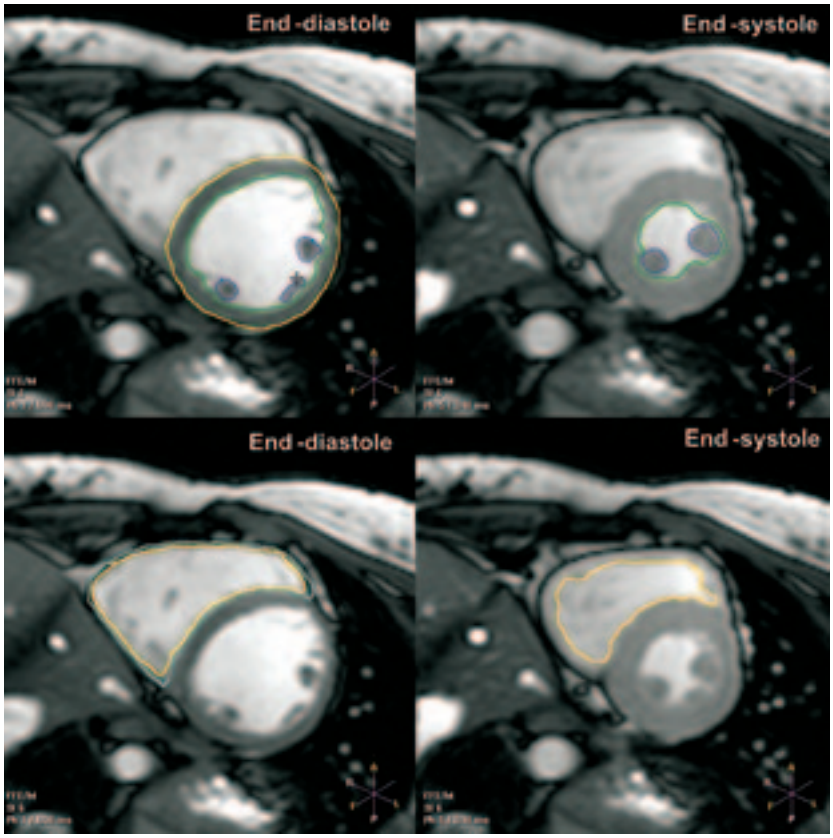

Figure 1. Short-axis steady-state free precession (SSFP) cine images from a healthy volunteer, obtained on a 3 T magnetic resonance system with the use of parallel imaging. The endocardial contours of the left and right ventricle have been manually traced at end-diastole and end-systole, while the epicardial outlines have been drawn in end-diastole. Right and left ventricular volumes and mass can be measured from a set of short-axis slices covering both ventricles from base to apex using Simpson's method. The SSFP technique is the pulse sequence of choice for acquisition of volumetric data sets of the left and right ventricle at 1.5 T. However, the implementation of the SSFP technique in conjunction with parallel imaging is suitable for cardiac volumetric and functional assessment at high field strength.

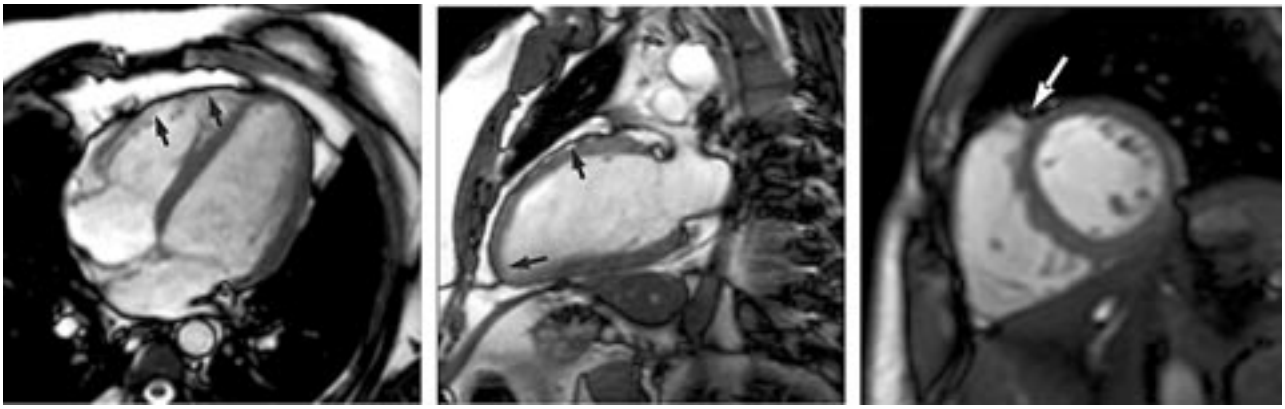

Figure 2. Four-chamber (left), two-chamber (middle) and short-axis (right) views on cine images from a healthy adult subject, acquired with the steady-state free precession (SSFP) technique at 3 T. Balanced SSFP sequences offer excellent blood-myocardium contrast, and this is extremely useful for functional cardiac imaging. However, this sequence is very sensitive to susceptibility effects, whereas increased static field inhomogeneity at 3 T may disrupt the steady state causing dark banding artefacts (arrows). Several correction methods, such as careful tuning of the resonance frequency and local optimisation of magnetic field homogeneity (shimming), are used in order to overcome these high field strength drawbacks.

The advantages of high field strength have also been demonstrated in MR coronary angiography. A preliminary study showed that 3 T MR coronary angiography is feasible in humans. The enhanced SNR facilitates acquisition with small voxel size. Extensive proximal-to-mid coronary segments, as well as small-

er-diameter branching vessels, can be displayed.[11] A clinical study compared directly spiral MR coronary angiography at 1.5 T and 3 T. The coronary images at 3 T demonstrated improved SNR and contrast-to-noise ratio with subsequent improvement in the image quality at the expense of susceptibility artefacts. Another direct comparison between 1.5 T and 3 T demonstrated that MR coronary angiography at 3 T using a three-dimensional breath-hold SSFP sequence is feasible. However, image quality at 3 T was more variable than at 1.5 T, with increased susceptibility artefacts and local brightening as the result of increased B_0 and B_1 inhomogeneities. These findings suggest that further methodical optimisation of pulse sequence design is needed to enhance the use of higher field strengths in MR coronary angiography.[12,13]

Promising results have been obtained in MR imaging of coronary artery wall at 3 T. Because of the relatively small size of coronary vessels and their central location within the thorax, improvement in SNR is of paramount importance. Thus, with higher field strengths, coronary vessel wall imaging is likely to benefit from the gain in SNR. Recent studies have demonstrated the feasibility of *in vivo* high field coronary vessel wall imaging, using either a free-breathing black-blood fast gradient echo technique with respiratory navigator gating and real-time motion correction, or a black-blood turbo spin echo sequence under breath-hold as well as free-breathing conditions. Further improvements in resolution and image quality are required to detect and characterise coronary atherosclerotic plaque. [14,15]

Another MR application that is likely to benefit from high field strength is MR spectroscopy for the detection of myocardial viability. This technique assesses viability by quantifying regional myocardial metabolism and chemistry. However, it is limited by poor spatial resolution at 1.5 T field strength and it has therefore not gained widespread use as a method of detecting viable myocardium. It is anticipated that, with magnets of higher field strength, interest in detecting and quantifying subcellular myocardial constituents may be further stimulated.[16]

Recently, it was shown that comprehensive cardiac imaging at high field strength is feasible.[17] This comprehensive protocol included morphological and functional cardiac imaging, phase-contrast flow measurements, perfusion and viability studies and coronary angiography. With regard to perfusion, it has been shown that 3 T improves contrast in first-pass myocardial perfusion imaging over a range of gadolinium doses.[18] Interestingly, the delayed gadolinium-contrast enhancement technique,[19] a highly promising and powerful tool for the assessment of myocardial viability, may derive benefit from the SNR gain provided by 3 T (Figure 3).

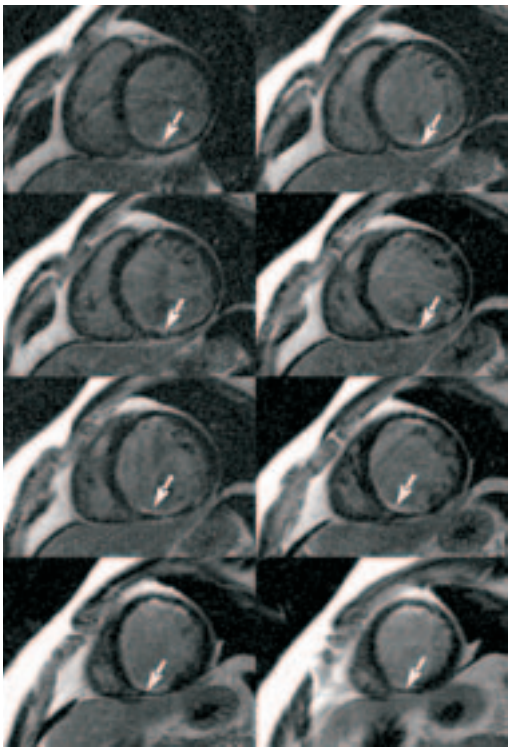

Figure 3. Contiguous mid-diastolic short-axis images (displayed from base to apex) obtained at 3 T by using an inversion-recovery fast gradient-echo pulse sequence after the intravenous administration of gadolinium contrast. With this technique, termed delayed enhancement imaging, irreversibly damaged myocardium (infarction) is depicted as hyperenhanced (bright). In this particular patient, a chronic, subendocardial inferior infarction is depicted (arrows). Note that the extent of the hyperenhancement involves almost 50% of the wall thickness, whereas the rest of the inferior wall is nonenhanced (black), suggesting viable myocardium. The major advantage of delayed enhanced cardiovascular magnetic resonance is its excellent spatial resolution and the consequent ability to assess the transmural extent of viability. The boost in the signal-to-noise ratio offered by 3 T field strength may further increase this ability.

Presently, the clinical use of 3 T MR systems for cardiac imaging is increasing in Europe and the United States. There are important MR safety issues at high field strengths with regard to the management of patients with metallic implants and devices. RF heating and mechanical field interaction are related to field strength and are likely to be more problematic at 3 T. Certain devices, such as heart valve prostheses, appear safe at 3 T. However, safety issues are much better documented at 1.5 T, whereas many of the current safety assessments cannot simply be extrapolated to the higher field strengths and stricter safety criteria are required. [20]

In conclusion, the advent of 3 T MR scanners will make a significant contribution to CMR, in both the clinical and research arenas, and cardiac imaging at 3 T may become an important application in the near future. Although high-field scanners have the potential to enhance the capabilities of CMR in several important areas, some major problems at higher field strength have to be solved before 3 T scanners can really replace the well-established MR systems operating at 1.5 T for each clinical application.

References

1. Mavrogeni S, Rademakers F, Cokkinos D: Clinical application of cardiovascular magnetic resonance. Hellenic J Cardiol 2004; 45: 401-405.
2. Dougherty L, Connick TJ, Mizsei G: Cardiac imaging at 4 Tesla. Magn Reson Med 2001; 45: 176-178.
3. Schick F: Whole-body MRI at high field: technical limits and clinical potential. Eur Radiol 2005; 15: 946-959.
4. McGee K, Debbins J, Boskamp E, et al: Cardiac magnetic resonance parallel imaging at 3.0 Tesla: Technical feasibility and advantages. J Magn Reson Imaging 2004; 19: 291-297.
5. Nayak KS, Cunningham CH, Santos JM, et al: Real-time cardiac MRI at 3 Tesla. Magn Reson Med 2004; 51: 655-660.
6. Hinton DP, Wald LL, Pitts J, et al: Comparison of cardiac MRI on 1.5 and 3.0 Tesla clinical whole body systems. Invest Radiol 2003; 38: 436-442.
7. Michaely HJ, Nael K, Schoenberg SO, et al: Analysis of cardiac function - comparison between 1.5 Tesla and 3.0 Tesla cardiac cine magnetic resonance imaging: preliminary experience. Invest Radiol 2006; 41: 133-140.
8. Schar M, Kozerke S, Fischer S, et al: Cardiac SSFP imaging at 3 Tesla. Magn Reson Med 2004; 51: 799-806.
9. Wintersperger BJ, Bauner K, Reeder SB, et al: Cardiac steady-state free precession CINE magnetic resonance imaging at 3.0 Tesla: impact of parallel imaging acceleration on volumetric accuracy and signal parameters. Invest Radiol 2006; 41:141-147.
10. Gutberlet M, Schwinge K, Freyhardt P, et al: Influence of high magnetic field strengths and parallel acquisition strategies on image quality in cardiac 2D CINE magnetic resonance imaging: comparison of 1.5 T vs. 3.0 T. Eur Radiol 2005; 15: 1586-1597.
11. Stuber, M, Botnar, et al: Preliminary report on in vivo coronary MRA at 3 Tesla in humans. Magn Reson Med 2002; 48: 425-429.
12. Yang P, Nguyen P, Shimakawa A, et al: Spiral magnetic resonance coronary angiography-direct comparison of 1.5 Tesla vs. 3 Tesla. J Cardiovasc Magn Reson 2004; 6: 877-884.
13. Bi X, Deshpande V, Simonetti O, et al: Three-dimensional breathhold SSFP coronary MRA: a comparison between 1.5T and 3.0T J Magn Reson Imaging 2005; 22: 206-212.
14. Botnar RM, Stuber M, Lamerichs R, et al: Initial experiences with in vivo right coronary artery human MR vessel wall imaging at 3 Tesla. J Cardiovasc Magn Reson 2003; 5: 589-594.
15. Koktzoglou I, Simonetti O, Li D: Coronary artery wall imaging: initial experience at 3 Tesla. J Magn Reson Imaging 2005; 21:128-132.
16. Evanochko W: Cardiovascular MRS: a literature review. J Cardiovasc Magn Reson 2005; 7: 611.
17. Gutberlet M, Noeske R, Schwinge K, et al: Comprehensive cardiac magnetic resonance imaging at 3.0 Tesla: feasibility and implications for clinical applications. Invest Radiol 2006; 41: 154-167.
18. Araoz P, Glockner J, McGee K, et al: 3 Tesla MR imaging provides improved contrast in first-pass myocardial perfusion imaging over a range of gadolinium doses. J Cardiovasc Magn Reson 2005; 7: 559-564.
19. Pamboucas C, Schmitz S, Nihoyannopoulos P: Magnetic resonance imaging in the detection of myocardial viability: The role of delayed contrast hyperenhancement. Hellenic J Cardiol 2005; 46: 108-116.
20. Prasad S, Pennell D: Safety of cardiovascular magnetic resonance in patients with cardiovascular implants and devices. Heart 2004; 90; 1241-1244.