Cardiac MRI at 7T

Syllabus contribution: Matthew Robson

Field strength escalation has occurred over the last 10 years. Whilst 1.5T remains the most prevalent field strength the loss of 1T and the popularity of the 3T field strengths have driven the assumption that this escalation is beneficial. Simplistic extrapolation leads us to believe that we will find the answer to all of our problems at 7T.

In the brain, results have been shown at 7T that are not achievable at lower field strengths. Cardiac imaging at 7T offers similar headline benefits to those images of the brain. More field strength gives more SNR, added to which more field strength increases the T1 and hence increases the effect of contrast agents. This simple idea is appealing in a grant application, but in reality 7T has some serious problems.

This presentation examines the opportunities and challenges presented by cardiac imaging at 7Tesla. I will also try to predict how this technology will fit into the cardiac imaging picture.

Cardiac MRI Physics

Strengths of 7T for cardiac

A 7T system generates images and spectra whose signal-to-noise ratio (SNR) is nearly 5 times that at 1.5T, which is the conventional clinical cardiac imaging field strength. Further, 7T results in increased spectral resolution in MR spectroscopy, enabling the complex metabolic signatures to be more easily picked apart. This increase in SNR can be used in different ways. It can be traded for faster examination times, and owing to the physics of MRI a 4.6-fold SNR increase compared to 1.5T will yield data of the same SNR at 7T in less than a 20^{th} (the square of 7/1.5) of the acquisition time. Alternatively, the SNR can be traded for increased spatial resolution, which will allow voxel volumes to be decreased linearly with field strength. In this case 7T would allow voxels that are 4.6 times smaller to be imaged compared to 1.5T. Finally, MRS at lower field strengths has always been limited by large data variability, and the increased SNR can be used to substantially improve measurement accuracy, making individual subject assessment (rather than group assessment) feasible. As spatial/temporal resolution and measurement variability are two of the major limitations of MRI and MRS, these benefits are considerable.

In addition to the SNR increases, the contrast is also dependent on field strength. Proton T1's tend to increase and hence the effects of T1 contrast agents are larger at higher field strength. The increasing T1's have the further benefit of enabling more persistent spin tagging, this can be used for (i) functional assessment during the cardiac cycle, (ii) tagging blood to assess

cardiac perfusion via Arterial Spin Labeling techniques, (iii) MR angiography where we wish to suppress the non-blood signal, and (iv) dark blood imaging where we wish to increase the conspicuity of vessel walls.

Finally, parallel imaging acceleration should improve at ever higher field strengths. Simulation work suggests that the modifications in coil profile that occur as the field strength increases may allow higher acceleration factors than are possible at the lower field strengths. These results are derived in the head, but we might assume that these benefits will translate.

Problems with 7T for cardiac

7T cardiac has a number of minor disadvantages such as increased acoustic noise, long magnets, more distortion of the ECG wave, and the obvious increase in costs and installation issues. The magnetic field homogeneity is also worse at these higher field strengths as this phenomenon is linear in magnetic field strength. But, the major technical difficulty of MRI at 7Tesla lies in the RF. At 7Tesla the RF wavelength becomes comparable to the body dimensions, which causes some complex wave interference effects in our transmitted B1 field. In addition to the wavelength problem, the RF heating effects increase with the square of the field strength, and hence SAR (specific absorption ratio) becomes even more of a problem at this field strength.

The wavelength problem presents a whole new set of challenges to the MRI scientists. Without uniform B1 transmit fields we cannot do MRI in the way that we traditionally have. Ongoing work described later has made good headway in addressing this problem.

SAR and the limited peak B1 that amplifiers can provide presents a challenge at 7T. At the present time it is not possible to obtain a good quality inversion (i.e. 180deg) pulse in the human body owing to limits on the peak B1 power. Further it is unlikely that SSFP based methods will ever be feasible at 7T owing (at least in part) to the prohibitively high mean power of those methods (typically a short pulse of 60deg flip angle played out every 3ms). These SAR limitations will shape the available methods that we can use at 7T (i.e. no SSFP, late-enhancement will have to use a non-inversion method, dark-blood will need careful thought, etc).

To put these limitations into perspective, even at 3T there are substantial problems with cardiac imaging due to B1 homogeneity (perfusion pulses for example need careful thought at 3T[1]), RF heating (SSFP is often run with sub-optimal flip angles[2]) and peak B1 limitations (RF pulses are often longer than ideal) these are not problems in brain imaging at 3T, and hence it is clear that cardiac imaging at 7T will be much more challenging than brain imaging at 7T. These increased difficulties are due to the body being considerably larger than the head, and hence the effects of the wavelength of the RF being more substantial, and also due to the larger power that is needed for the same excitation flip angle in the torso (versus the head).

Results to date

Cardiac imaging at 7T is in its very early days (presently 2 groups are active in this field) and as yet no results have been shown at 7T that could not have been obtained at lower field strengths. Existing cardiac imaging work has focussed on addressing the RF problems of obtaining uniform B1 excitation fields so as to yield images that don't contain massive "RF holes". Dr Vaughan (Minessota) has been working to address this challenge using methods that have multiple separate transmit coils that can be driven independently[3,4]. By optimising the phase and amplitude of the different elements they can work to overcome the destructive interference effects that distort the uniform transmit field. The methods they use are known as "B1 shimming" and require tuning the system on a patient-by-patient basis as one of the first steps of the MRI exam. This pre-calculates the RF array scaling factors that are used in the subsequent exam. These methods are under continual development, but that group has demonstrated high quality FLASH images at 7Tesla in normal subjects where the heart is not obscured by these artefacts.

Most work to date has been on normal (or in some cases particularly small) volunteers to investigate how artefacts can be minimised. Present work is limited to basic FLASH imaging of the heart, and cine imaging of the heart using FLASH methods. Whilst these do form the building blocks of clinical applications, as yet no clinical questions have been investigated experimentally at 7T. This is a very active area of research though, and advances are coming all the time.

Deductions from other Field Strengths

Parallels can be made to the cardiac work at 3T. In that case it is possible (for example) to obtain higher SNR cardiac function images at 3T than 1.5T using SSFP. However, the images at 1.5T are not SNR limited, whilst at 3T the artefacts become more substantial. The net effect at 3T are images with additional (unnecessary) SNR, and additional (unwanted) artefact[2].

Further, although 3T does offer SNR benefits over 1.5T it is only in a small number of application areas, where 3T offers clearly superior image quality, and this is at the 3T field strength that is relatively mature in its development. The significant mainstream area where 3T demonstrates superior images is in perfusion imaging, although improvements are also seen in multi-nuclear methods, and with BOLD based cardiac methods. It is likely that 3T will offer small improvements in areas such at T2 weighting, late-enhancement, and other areas where signal changes are quite subtle and where higher image resolution might be desirable, but these benefits are not very large, and the strengths of 1.5T as a solid reliable workhorse are substantial.

For this reason when we extrapolate in field strength from 1.5T → 3T and hence on to 7T it is not so easy to assume that 7T cardiac imaging will offer much in the way of improvement, and it would be bold to suggest that 7T will ever provide a better clinical cardiac imaging tool.

There are patterns of effects that occur as we increase the field strength to 7T

1) SSFP is no longer tractable, owing to the artefacts (B0) and high SAR. At 1.5T these effects are minor in the heart (although apparent in surrounding tissues), at 3T these become a problem that can be managed but often degrades image quality in the heart, and at 7T these problems will make this approach impractical.
2) FLASH images, which at lower field strength are of quite poor quality improve considerably at the higher field strength. The SNR increases, and the CNR improves. Further this method suffers from none of the SSFP artefacts and the SAR of the FLASH sequence is very manageable.
3) Turbo spin-echo methods become de-powered as it is possible to use only short echo trains as the SAR problems increase.

Where might 7T make a difference for Cardiac MRI?

There are many challenges at 7T in overcoming the problems presented by the difficulties with RF. Generally speaking, to benefit from higher field strengths we need to be interested in a problem that cannot be solved at lower field strength, and that isn't crippled by the problems from going to higher field strengths. The application areas where 7T provide real optimism are those areas where the SNR or CNR are inadequate at lower field strengths.

These areas are summarised below as:

Coronary imaging

Using FLASH based acquisitions and contrast enhancement.; this application is the sleeping giant of MRI, and 7T may provide a long overdue breakthrough.

Perfusion

Providing higher contrast than is possible at 1.5T or 3T. Substantial improvements are seen going from 1.5 to 3T[5]. We might hope that a further improvement in image quality will relate to better sensitivity and specificity to disease.

Cardiac BOLD imaging

The contrast-to-noise of this method is also improved substantially in going from 1.5T to 3T. Even with this improvement the effects of BOLD contrast are quite small. 7T might enable increased contrast (the BOLD effect increases with field strength) and hence improve the visualization of oxygenation deficits, perhaps even enabling higher resolution evaluation of these changes.

Multi-nuclear spectroscopy (31P)

At 7T there should be substantial improvements in SNR (due to field strength, shortening of T1, and improved RF coils). These increases in SNR will be used to improve the reproducibility of the measurements, but also to allow metabolism to be assessed at a resolution equivalent to the AHA 17 segment model. These improvements may allow clinically practical metabolic imaging

Other areas such as spin labelling may also benefit from increased field strength, as may methods that image the whole heart very quickly (cardiac CT style acquisitions).

Even if 7T is to be a niche tool that provides excellent data in some of the above applications it will still be necessary for the 7T cardiac scanner to perform the other basic cardiac imaging exams, i.e. function, flow, late-enhancement etc, as without these it cannot perform in a stand-alone mode, which would make it redundant in anything other than a purest of research environments.

Conclusion

Cardiac MRI at 7T is in its infancy. Experiences at 3T suggest that cardiac MRI at 7T will present substantial technical challenges. I believe that some of the RF problems will be overcome and that we will be able to perform routine basic cardiac imaging at this higher field strength. A small number of clinical applications may see substantial improvement at 7T, which may make them clinically tractable.

References

1. Kim D, Gonen O, Oesingmann N, Axel L. Comparison of the effectiveness of saturation pulses in the heart at 3T. Magn Reson Med 2008;59(1):209-215.
2. Hudsmith LE, Petersen SE, Tyler DJ, Francis JM, Cheng AS, Clarke K, Selvanayagam JB, Robson MD, Neubauer S. Determination of cardiac volumes and mass with FLASH and SSFP cine sequences at 1.5 vs. 3 Tesla: a validation study. J Magn Reson Imaging 2006;24(2):312-318.
3. Snyder CJ, Delabarre L, Metzger GJ, van de Moortele PF, Akgun C, Ugurbil K, Vaughan JT. Initial results of cardiac imaging at 7 tesla. Magn Reson Med 2008.
4. Vaughan JT, Snyder CJ, DelaBarre LJ, Bolan PJ, Tian J, Bolinger L, Adriany G, Andersen P, Strupp J, Ugurbil K. Whole-body imaging at 7T: preliminary results. Magn Reson Med 2009;61(1):244-248.
5. Cheng ASH, Pegg TJ, Karamitsos TD, Robson MD, Serle N, Jerosch-Herlod M, Choudhury RP, Banning AP, Neubauer S, Selvanayagam JB. Cardiovascular Magnetic Resonance Perfusion Imaging at 3 Tesla for the Detection of Coronary Artery Disease: A Comparison with 1.5 Tesla. JACC 2007;49(25):2440-2449.