

## A Fast Field-Cycling MRI system for clinical applications

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### Purpose:

Fast Field-Cycling MRI<sup>1</sup> (FFC-MRI) is a novel MRI technique in which the external magnetic field is switched during the imaging experiment. By doing this, FFC-MRI grants access to information which is invisible to conventional MRI scanners, including the variation of  $T_1$  with magnetic field. These measurements, known as  $T_1$ -dispersion, exhibit great promise as a new form of endogenous image contrast, and may have application in the early diagnosis of a range of diseases including osteoarthritis<sup>2</sup>, cancer and neurodegeneration. Furthermore,  $T_1$ -dispersion at ultra-low magnetic fields (less than 10 kHz proton Larmor frequency), measured by FFC-MRI, can offer new insight into the molecular dynamics and structure of tissues and is a largely unexplored area of study in in-vivo imaging.

The construction of an MR imaging system capable of rapidly switching magnetic fields, and reaching ultra-low fields requires novel magnets, power supplies and control electronics. Here we describe progress on a new whole-body human sized FFC imaging system and present images obtained from normal volunteers.

### Methods:

The magnet (Tesla Engineering Ltd, Storrington, UK) is of a resistive design with a length of 2 m and an inner bore diameter of 500 mm. The main magnet is comprised of three identical coils, angularly offset from each other by 120° embedded in epoxy resin. The magnet includes three conventional gradient coils and eight shim coils, which provide shimming up to 4<sup>th</sup> order. The current supplied to the shim coils is magnetic field dependent to ensure optimum shimming at all field values.

Each of the  $B_0$  coils is driven by a rack of 6 current amplifiers (IECO, Helsinki, Finland). Each amplifier rack is capable of supplying a maximum current of 600 A, so the total current supplied to the magnet is 1800 A, corresponding to a maximum field strength of 0.2 T (8.52 MHz proton Larmor frequency). The magnet power supply incorporates a zero-flux current transducer (Danfysik A/S, Denmark) in a feedback loop which is configured for a current stability of 0.1 ppm. The system can switch between zero and maximum field in 20 ms, corresponding to a maximum dB/dT of 10T/s. The scanner is also equipped with a set of three orthogonal 2-metre wide square Helmholtz coils (Figure 1) centred on the isocentre of the magnet to provide earth's field cancellation, allowing a minimum  $B_0$  of less than 1  $\mu$ T (42 Hz) to be achieved over a 30 cm DSV.

The gradients and RF system are controlled by a commercial MRI console (MR Solutions Ltd, Guildford, UK) while the main magnet coil, shim coils and earth-field cancellation coils are controlled by a dedicated computer running in-house software written in Labview (National Instruments, Austin, US). The main magnetic field is set and controlled by a 16-bit, high-precision DAC which provides a field resolution of 3  $\mu$ T. Synchronisation between the main console and the Labview-controlled PC is accomplished using TTL lines with timing accuracy on the order of 100 ns.

### Results

The system has been fully commissioned and is now capable of in-vivo imaging using its full field range. Figure 2 shows an example of an image of the head of a human volunteer obtained at an evolution field of 100 mT, while Figure 3 shows an image of a volunteer's knee obtained at 200 mT.

### Discussion

The novel system design described here will allow us to explore the unique  $T_1$  dispersion contrast made available by FFC-MRI in greater detail than was possible using our previous system<sup>3</sup> which had detection at 0.06 T. Furthermore, the use of a purely resistive magnet design allows us to access ultra-low magnetic fields

along with the associated information on slow molecular dynamics. Future work will concentrate on identifying how this newly accessible region of the  $T_1$  dispersion curve can be exploited for clinical diagnosis.

1. Lurie, D. J. *et al.* Fast field-cycling magnetic resonance imaging. *Comptes Rendus Phys.* **11**, 136–148 (2010).
2. Broche, L. M., Ashcroft, G. P. & Lurie, D. J. Detection of osteoarthritis in knee and hip joints by fast field-cycling NMR. *Magn. Reson. Med.* **68**, 358–362 (2012).
3. Lurie, D. J., Foster, M. A., Yeung, D. & Hutchison, J. M. S. Design, construction and use of a large-sample field-cycled PEDRI imager. *Phys. Med. Biol.* **43**, 1877–86 (1998).



Figure 2: Image from a volunteer's head, obtained at an evolution field of 100 mT.



Figure 1: The FFC-MRI system and earth's field cancellation coils.

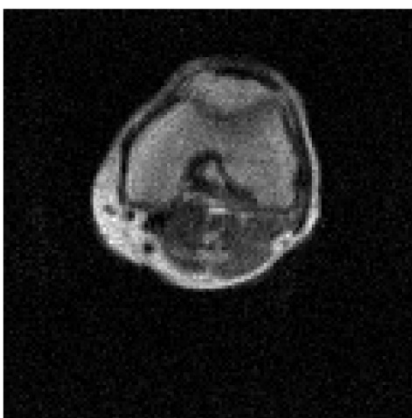


Figure 3: Image from a volunteer's knee, obtained at an evolution field of 200 mT.