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Field-Cycled Magnetic Resonance Imaging - Techniques and Applications

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Introduction

A small number of research groups are using field-cycling in conjunction with magnetic resonance imaging (MRI). One use of field cycling in MRI is to produce images in the Earth's magnetic field [1]. Field-cycling is used to pre-polarise the spins in a relatively high, inhomogeneous field, before allowing them to precess in the very low, but very homogeneous Earth's field, with field gradients being used in the usual manner to form an image. "Prepolarised MRI" is also being developed to produce a low-cost, high-sensitivity MRI system [2]. In Aberdeen we have used field-cycling in conjunction with proton electron double resonance imaging (PEDRI) of free radicals [3], and we have constructed a whole-body sized field-cycling imager for this purpose. More recently, the field-cycling imager has been used to measure quadrupole dips in human subjects. The latter two applications will now be discussed in more detail.

Field-Cycled PEDRI

PEDRI is a method for imaging the distribution of free radicals in biological samples or in animals. It is based on the Overhauser effect: an NMR signal is measured while, or after, the EPR resonance of a free radical in solution is irradiated. Under the correct conditions a transfer of polarisation can occur from the electrons to the nuclei, and the NMR signal is enhanced. In PEDRI, proton NMR images are obtained with and without EPR irradiation, and the difference yields an image showing only the free radical distribution. PEDRI produces images with superior resolution to EPR imaging (EPRI), because in EPRI the resolution is degraded by the very broad (~5 MHz) EPR lines of most free radicals. The main difficulty with PEDRI is that it must be performed at very low field (~10 mT) in order to bring the EPR frequency below 300 MHz, for studying biological samples or animals. Even so, excessive RF power deposition is problematical, since the EPR line must be partially saturated. Field-cycled PEDRI (FC-PEDRI) addresses these problems; the basic pulse sequence is shown in Figure 1. The EPR irradiation is applied during the evolution period at field strength B_0^E (~3 mT) at correspondingly low frequency (~50 MHz). The field is then increased for the detection period at field strength B_0^D, where the NMR detection pulse(s) and imaging gradients are applied. The length of the EPR irradiation, T^{EPR} should be of the order of the NMR T_1, to allow the Overhauser enhancement to build up, and the time to ramp the field up to B_0^D should be shorter than T_1, in order not to lose enhancement. Since the EPR irradiation is applied at low frequency, its power deposition is low and it will penetrate easily into biological samples. The signal-to-noise ratio, and hence the sensitivity is improved by detecting at a higher magnetic field. We have used FC-PEDRI to study the exogenous free radical proxyl carboxylic acid (PCA) injected into the bloodstream of living, anaesthetised rabbits [4].

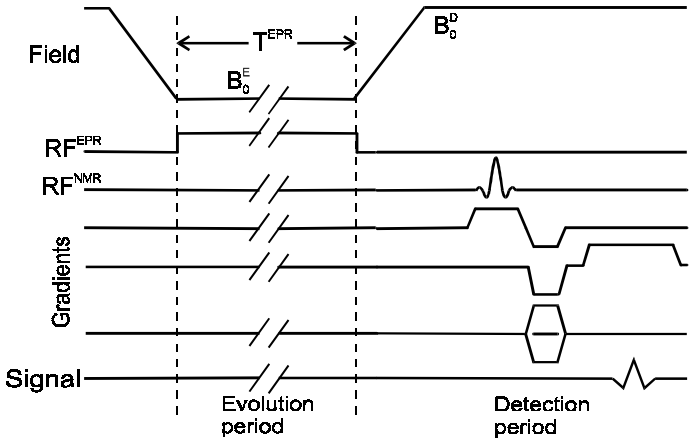

Figure 1: Field-Cycled PEDRI pulse sequence.

Quadrupole Dip Relaxometry and Imaging

It has been known for some time that proton relaxation in proteins and other bio-polymers can be affected by interactions with quadrupolar ^{14}N nuclei, giving rise to "quadrupole dips", which are reductions in the proton spin-lattice relaxation time at NMR frequencies which correspond to the ^{14}N nuclear quadrupole resonance transitions. This effect was studied extensively by

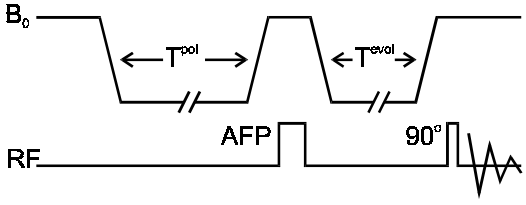

Figure 2: Field-Cycled IR pulse sequence.

Kimmich and co-workers, who measured quadrupole dips in hydrated proteins, and various biological samples including living leeches [5]. Our whole-body field-cycling imager has recently been used to measure quadrupole dips in human muscle and brain. In order to measure T_1 at a range of field strengths, a field-cycled inversion recovery pulse sequence was used, as shown in Figure 2. A polarisation field, identical to the T_1-measurement field, is applied for T^{pol} to bring the spins into equilibrium. A 10 ms adiabatic fast passage (AFP) inverts the magnetisation, and the spins then evolve for T^{evol} at the T_1-measurement field. An interleaved method was used, an identical pulse sequence being applied without AFP at each field strength, to allow T_1 to be calculated by a two-point method. T_1 dispersion spectra were obtained of the author's head and forearm (Figure 3). The timing parameters were T^{pol}=600 ms, T^{evol}=250 ms (head) and T^{evol}=150 ms (arm). T_1 data were collected over the range 30 mT to 80 mT, at intervals of 1 mT. Quadrupole dips at 2.1 MHz (49 mT) and 2.8 MHz (65 mT) can clearly be seen, in good agreement with previous work on muscle [5]. An imaging version of this pulse sequence has also been used, which allows inversion recovery images to be obtained at 57.5 mT (between the dips) and 65 mT (high-field dip). Images of the author's thighs showed considerable differences between the images, most apparent in areas of muscle as shown in Figure 4.

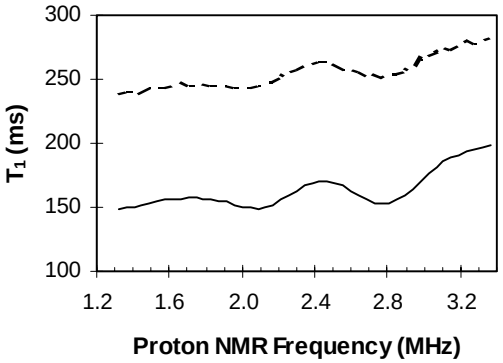

Figure 3: T_1 dispersion plots of human head (dashed) and forearm (solid).

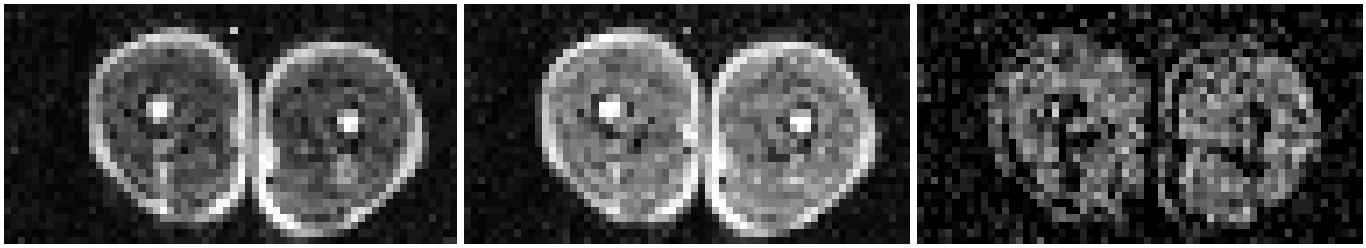

Figure 4: Field-cycling IR images of human thighs. Left: 57.5 mT; middle: 65 mT; right: difference.

Hardware

Experiments were carried out using a whole-body sized field-cycling MRI system [4]. The imager uses a whole-body, ferrite permanent magnet with a vertically-oriented field of 59 mT (Field Effects, USA); this provides the detection magnetic field. Field cycling is accomplished by the field-compensation method: a resistive, saddle-shaped magnet (Magnex Scientific Ltd., UK) is fitted into the bore of the permanent magnet. The field from this secondary magnet can add to or subtract from the permanent magnet's field. A switch-mode power supply amplifier (Copley Controls Inc., USA) is used to drive the secondary magnet; a field change of 59 mT can be achieved in 40 ms, or 30 mT in 10 ms. Eddy currents do not pose a problem with this system, as the structure of the permanent magnet is non-conducting. Field gradient coils are integrated into the structure of the permanent magnet, and the internal bore of the secondary magnet coil is 52 cm in diameter. In the FC-PEDRI work, a split-solenoid coil with i/d 14 cm was used for NMR transmit and receive at 2.5 MHz, and a birdcage resonator (diameter 20 cm) was used for EPR irradiation at 51 MHz. The imager is controlled by a commercial MRI console (SMIS Ltd., UK). A split-solenoid transmit/receive NMR coil with i/d 30 cm was used for the quadrupole dip experiments.

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