Quadrupole-Dip Measurement in Humans by Whole-Body Field-Cycling NMR Relaxometry and Imaging

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Introduction

It is well known that proton relaxation in proteins and other bio-polymers can be strongly affected by interactions with the quadrupolar nucleus ^{14}N, with ^{14}N-^{1}H groups acting as "relaxation sinks". This gives rise to the so-called "quadrupole dips", which are reductions in the proton spin-lattice relaxation time at those NMR frequencies which correspond to the ^{14}N nuclear quadrupole transitions. This effect was studied extensively in the early to mid 1980s, and quadrupole dips were measured in hydrated proteins and various biological samples [1]. The first *in vivo* demonstration of the phenomenon was carried out by Kimmich *et al.*, who studied living leeches [2,3]. (Leeches are robust, and can fit inside a standard NMR sample tube.) In this work, quadrupole dips have been measured for the first time in human muscle *in vivo* using a whole-body sized field-cycling relaxometry system. Field-cycled inversion recovery images have also been obtained of the human forearm, enabling indirect NQR imaging via the quadrupole dip effect.

Methods

Experiments were carried out using a whole-body field-cycling MRI system, originally developed for free radical imaging using the Overhauser effect [4]. The imager uses a whole-body permanent magnet with a vertical 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 field of the permanent magnet. A field change of 30 mT can be achieved in 10 ms. Field gradient coils are integrated into the structure of the permanent magnet, and the useable bore of the secondary magnet coil is 52 cm in diameter, sufficient for human subjects. In this work, a split-solenoid coil with i/d 14 cm was used for NMR transmit and receive at 2.5 MHz. The imager is controlled by a commercial NMR console (SMIS, UK). A field-cycled, interleaved inversion recovery - saturation recovery pulse sequence was used to measure T_1 values by a two-point method; the pulse sequence is shown in Fig 1. During the polarisation period (length T^{pol}) the magnetisation equilibrates at the measurement field. A 10 ms adiabatic fast passage (AFP) inversion is applied and the field is returned to the measurement value where the magnetisation recovers with the spin-lattice relaxation time. The saturation recovery part of the sequence is identical, except

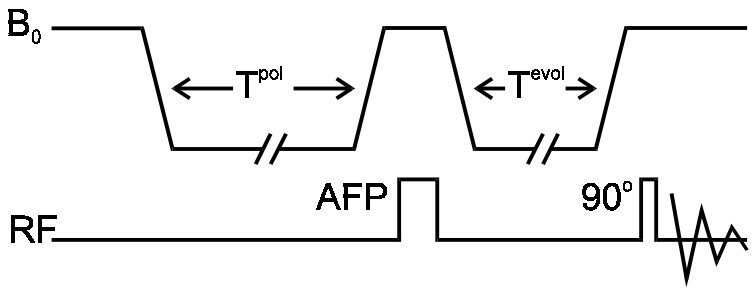

Figure 1: Field-cycled inversion-recovery pulse sequence.

that the AFP is not applied. T_1 data was collected over the range 30 mT to 80 mT, at intervals of 1 mT. An interleaved field-cycled inversion recovery imaging pulse sequence was also implemented, collecting images at 57.5 mT and 65 mT using an adapted version of the sequence shown in Fig. 1.

Results

Fig. 2 shows a T_1 dispersion plot of the author's forearm; two quadrupole dips at 2.1 MHz (49 mT) and 2.8 MHz (65 mT) can clearly be seen. The timing parameters were: T^{pol}=600 ms, T^{evol}=150 ms, TR=1500 ms. A copper sulphate solution with similar T_1 was also measured, and showed a roughly linear variation of T_1 with field. Inversion recovery images collected at 57.5 mT (between the dips) and 65 mT (high-field dip) with the same timing parameters showed considerable differences in the intensity of muscle; subtracting the images yielded an image which highlighted the regions where ^{14}N-^{1}H relaxation is most effective.

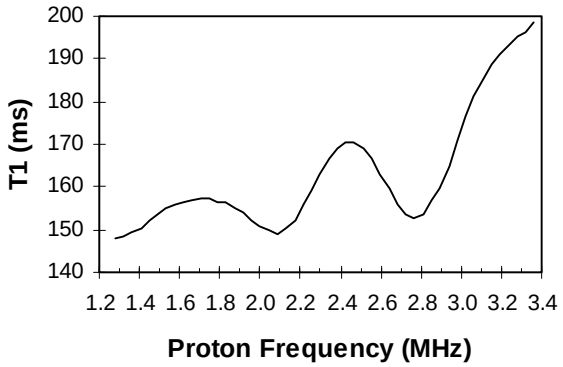

Figure 2: T_1 dispersion plot of human arm.

Conclusions

The use of a whole-body field-cycling NMR/MRI system has allowed quadrupole dips to be measured *in vivo* in the human for the first time. Field-cycled inversion recovery imaging allows indirect NQR imaging to be carried out, via the quadrupole dip effect. Work is underway to optimise the imaging pulse sequences and image analysis protocols. These techniques offer the possibility of studying relaxation mechanisms *in vivo*, and of NQR detection with the spatial resolution and versatility of MRI.

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