Optimal contrast for ^{23}Na MRI

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Introduction ^{23}Na MRI has been used for a variety of tissue and organ imaging, including the brain, cartilage, the disc, breast, and kidneys. With the advent of high-field MRI scanners, high-resolution images can be obtained within clinically acceptable scan times. The sodium ions bound to tissues and organs can provide us with an invaluable information on the onset of disorder, such as osteoarthristis (OA) and degenerative disc diseases (DDD), through their concentration and quadrupolar interaction/relaxation. Slow motion of sodium ions may occur in cells, and its altered relaxation properties further provide important insights into cell viability, such as in the case of tumor tissue, or in the monitoring of muscle activity. In this paper, we are presenting two ^{23}Na MRI constrast schemes, one selecting sodium ions with quadrupolar interation [1] and the other with quadrupolar relaxation. An optimization algorithm based on optimal control theory is used to achieve a maximum of the contrast.

Method Optimal control theory gave a particularly simple solution for a sequence which maximizes the differentiation between anisotropic and isotropic sodium: (1) The quadrupolar jump-and-return (QJR) sequence can be useful to seprate ordered sodium ions from free sodium ions (Fig. 1(a)). The QJR sequence suppresses the signal from free sodium ions and the satellite transitions of ordered sodium ions. At the same time, the intensity of the central transition of ordered sodium ions is increased by 50% from its thermal equilibrium intensity. (2) Pulse sequences to differentiate bound and free sodium ions through quarupolar relaxation have been obtained by numerical optimization based on optimal control theory. One of the pulse sequences is shown in Fig. 1(b), which suppresses the z magnetizations of free sodium ions and keeps 41% of the z magnetization of bound sodium ions at the end.

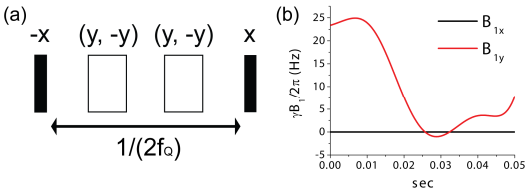

Fig. 1 *(a) QJR sequence. Thin black and wide white rectangles represent 54.7° and 180° pulses, respectively. (b) Optimal pulse sequence differentiating slow and fast sodium through quadrupolar relaxation.*

Results and Discussion (1) The QJR sequence was tested on a 2D phantom consisting of filamentous Pf1 bacteriophage ([Na^+] ~ 70mM) and 50mM NaCl aqueous solution. Sodium ions in the bacteriophage are quarupolar coupled (f_Q ~ 205 Hz). Fig. 2(a) is the image when the signal is excited by a hard 90° pulse, which reveals both the inner and outer sample regions. Fig. 2(b) is the image when the signal is excited by the QJR sequence with the delay of 2.5 ms, which shows only the inner tube filled with the bacteriophage solution. For both the experiments, TE = 5ms.
(2) The optimal shaped pulse shown in Fig. 1(b) was tested on a 1D phantom consisting of 3% Agarose gel and 200mM NaCl aqueous solution and compared with a conventional image and inversion recovery (IR) method. The 1D images with the relative intensities of the individual regions excited by different excation methods are shown in Fig. 3.

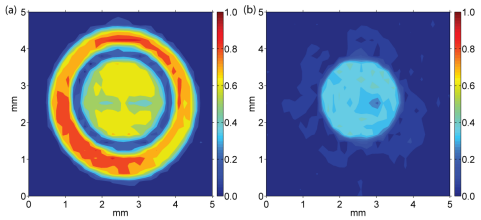

Fig. 2 *2D ^{23}Na images obtained with the signal excited by (a) a hard 90° pulse and (b) the QJR sequence shown in Fig. 1(a) on a 2D phantom consisting of an inner tube (o.d.=3mm) filled with filamentous Pf1 bacteriophage and an outer tube (o.d.=5mm) filled with 50 mM NaCl solution. Reproduced from Ref. [1].*

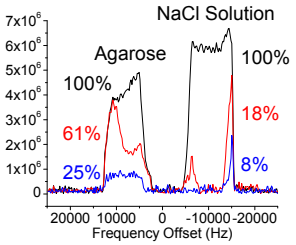

Fig. 3 *1D ^{23}Na images excited by (black) a hard 90° pulse excitation, (blue) the inversion recovery, and (red) an optimal pulse sequence shown in Fig. 1(b) on a 1D phantom consisting of Agarose (left) and 200 mM NaCl solution (right).*

Conclusion We designed pulse sequences seperating ordered and bound sodium ions from free sodium ions and demonstrated their feasibility on phantoms. As a result we show that quadrupolar contrast can be improved, from a hard 90° pulse excitation, by a factor of 3.4 for the QJR sequence and 3.9 for the optimal shaped pulse in Fig. 1(b). The development of pulse sequences robust againt a distribution of quadrupolar couplings, variations in relaxation parameters, and B_0 and B_1 field inhomogeneity is under way.

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References 1. J.-S. Lee, R. R. Regatte, A. Jerschow, JMR **2009**, 200, 126-12