Toward Microtesla MRI of Hyperpolarized Carbon-13 for Real-Time Metabolic Imaging

V. S. Zotev[1], T. Owens[1], I. M. Savukov[1], A. N. Matlashov[1], J. J. Gomez[1], and M. A. Espy[1]
[1]Applied Modern Physics Group, Los Alamos National Laboratory, Los Alamos, NM, United States

INTRODUCTION: Metabolic imaging by MRI spectroscopy of ^{13}C provides important information about metabolic pathways and allows in vivo detection of changes in cell metabolism, caused by cancer and other diseases. The method for hyperpolarization of ^{13}C [1], based on dynamic nuclear polarization (DNP), enables enhancement of ^{13}C polarization in solution by >10,000 times [1] over polarization levels achieved in conventional MRI. Injection of a hyperpolarized substance labeled with ^{13}C allows an unprecedented increase in imaging SNR and makes it possible to perform metabolic imaging in real time [2]. Because hyperpolarization of ^{13}C is performed outside an MRI scanner, high magnetic fields of conventional MRI instruments offer little advantage. Moreover, imaging of hyperpolarized substances can be naturally performed using ultralow-field (ULF) MRI [3]. This method combines the pre-polarization technique and broadband signal reception by superconducting quantum interference device (SQUID) sensors to enable MRI at microtesla fields. Recently, we demonstrated the first ULF MRI of the human brain [4], as well as accelerated parallel imaging at ULF [5]. Hyperpolarization of ^{13}C makes the pre-polarization step in ULF MRI unnecessary, and allows imaging using only microtesla-range fields. It has been suggested that DNP mechanisms "promise to form a perfect complement to microtesla MRI" [6].

METHODS: Here we demonstrate feasibility of microtesla NMR/MRI of dynamically polarized ^{13}C. We modified our ULF MRI system [4,5] to enable imaging with in situ DNP (Overhauser enhancement) [7]. The experiments were performed at B_m=96 μT measurement field (f_H~4090 Hz, f_C~1030 Hz). The samples were doped with TEMPO free radicals and subjected to RF irradiation at 120 MHz simultaneously with pre-polarization at B_p=3.5 – 5.7 mT. Surface-coil antennas [8] were used for RF irradiation.

RESULTS: The first image acquired by ULF MRI with DNP (i.e. the first Overhauser-enhanced MRI with SQUID signal detection) is exhibited in Fig. 1. It shows ^{1}H polarization enhancement by factor $|E|$ as high as 60, corresponding to equivalent polarization field of 0.2 T. The first NMR spectra of ^{13}C at microtesla fields are exhibited in Fig. 2. They are characterized by $|E|$ as high as 200, so the equivalent field is >1 T. ^{13}C pyruvate is widely used for metabolic imaging [2]. Its *J*-coupling quartet is clearly observed in Fig. 2.

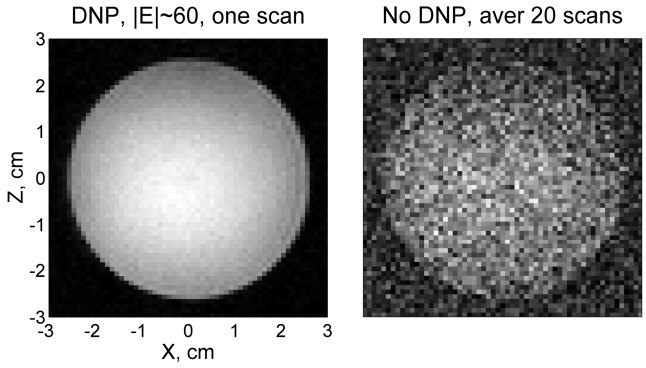

Fig. 1. The first ULF MRI with DNP. *Left*: phantom image (2 mM water solution of TEMPO) acquired at B_m=96 μT and B_p=3.5 mT using DNP. *Right*: image of the same phantom without DNP.

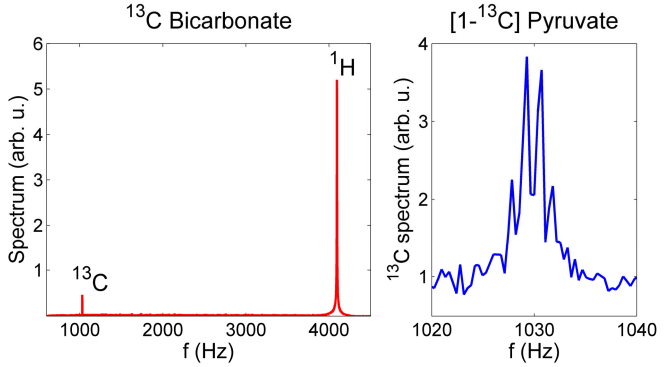

Fig. 2. The first ULF NMR of ^{13}C. Spectra were acquired at B_m=96 μT and B_p=5.7 mT with DNP. *Left*: ^{13}C sodium bicarbonate 1M, TEMPO 16 mM. *Right*: [1-^{13}C] sodium pyruvate 1 M, TEMPO 4 mM.

CONCLUSION: Our results demonstrate feasibility and potential of microtesla NMR/MRI of ^{13}C. The typical metabolites can be distinguished by means of *J*-coupling spectroscopy [9] or magnetic relaxometry of ^{13}C at ULF instead of chemical shift spectroscopy. Real-time metabolic imaging with hyperpolarized ^{13}C can be performed using a novel type of MRI scanner depicted in Fig. 3.

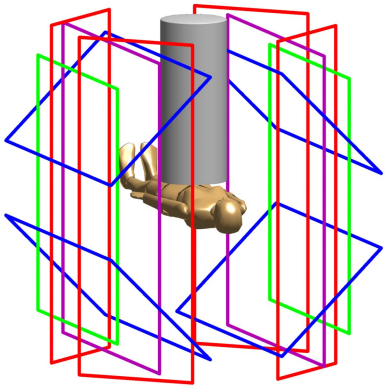

Fig. 3. Open, portable, and inexpensive MRI scanner for imaging hyperpolarized ^{13}C. It uses only microtesla-range magnetic fields.

REFERENCES:

[1] J.H. Ardenkjaer-Larsen et al. *PNAS* **100**, 10158 (2003).
[2] K. Golman et al. *Acad. Radiol*. **13**, 932 (2006).
[3] R. McDermott et al. *PNAS* **101**, 7857 (2004).
[4] V.S. Zotev et al. *J. Magn. Reson*. **194**, 115 (2008).
[5] V.S. Zotev et al. *J. Magn. Reson*. **192**, 197 (2008).
[6] K.P. Pruessmann, *Nature* **455**, 43 (2008).
[7] D.J. Lurie et al. *J. Magn. Reson*. **84**, 431 (1989).
[8] S. Matsumoto et al. *Magn. Reson. Med*. **57**, 806 (2007).
[9] Y.S. Levin et al. *Magn. Reson. Med*. **58**, 245 (2007).