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MRI with Continuously Flowing Laser-Polarized ^{3}He

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Abstract : MRI of laser-polarized ^{129}Xe under continuous flow conditions has recently been used for imaging of porous materials, however, any attempts at using a continuously circulating flow of laser-polarized ^{3}He have not been made until now, presumably due to its extremely long spin exchange time (5-10 hrs). Since the inherent NMR sensitivity of ^{3}He is 80 times greater than that of ^{129}Xe when considering the natural abundance, ^{3}He can be expected to be a better nucleus for imaging than ^{129}Xe even under continuous flow conditions. In this report, the first MRI with continuously flowing laser-polarized ^{3}He is shown for a phantom of Teflon tubing, demonstrating the feasibility of ^{3}He imaging under continuous flow.

INTRODUCTION

Laser-polarized noble gases such as ^{3}He and ^{129}Xe have proven to be a high sensitivity source of magnetic resonance,[1,2] and attracted special attention in MRI of human and animal lungs.[3,4] The sensitivity enhancement of noble gases is achieved by spin exchange optical pumping technique,[5-8] which can be conceptualized as a two step processes: in the first step the hyperfine sublevels of an alkali metal vapor such as rubidium are polarized by repeated absorption of circularly polarized photons, while in the second step spin exchange collisions between the alkali and noble gas atoms lead to the accumulation of an enhanced nuclear polarization of the latter. The enhancement by this optical pumping process is as much as 10^5 compared with the thermal equilibrium in ^{3}He and ^{129}Xe NMR, which is more than enough to overcome the inherently low spin density of gases (about 1/1000 that of liquids).

In porous materials, it is sometimes difficult to fill the void spaces uniformly with liquids, especially when the void space is small, making the high-sensitivity liquid MRI unreliable. Thus, gas is better suited for the MRI of porous materials with its high permeability, and laser-polarized noble gases can be useful for this purpose. However, many

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porous materials of interest possess paramagnetic centers that have a profound depolarizing effect. Once the laser-polarized gas is brought into contact with the material, all polarization may be lost in a very short time through the mechanisms of spin-lattice relaxation. This is mainly a limitation of experiments that use laser-polarized gas produced in a batch mode. With the use of a continuous flow apparatus,[9,10] this drawback can be less important, and several attempts have been made to image materials by using a continuously circulating flow of laser-polarized ^{129}Xe.[11-13]

Some of porous materials have large heterogeneity in magnetic susceptibilities, making the use of conventional MRI techniques such as gradient or spin echo very difficult. This heterogeneous magnetic susceptibility necessitates the use of SPI (single point imaging) method,[14] a pure phase-encoding MRI technique, which requires very long data acquisition times. In such cases, ^{3}He could be a better nucleus for imaging, since its inherent NMR sensitivity is 80 times greater than that of ^{129}Xe when considering the natural abundance. However, any attempts at using a continuously circulating flow of laser-polarized ^{3}He for imaging have not been made until now, presumably due to its extremely long spin exchange time (5-10 hours). In this paper, we demonstrate, by using a phantom of Teflon tubing, that the imaging of porous materials can be performed within a reasonably short time with the use of laser-polarized ^{3}He produced in a continuous flow. To the best of our knowledge, this is the first MRI with a continuously circulating flow of laser-polarized ^{3}He.

EXPERIMENTAL PROCEDURES

Rubidium (99.7%) was purchased from Aldrich and used without further purification. ^{3}He gas (99.9995%) was purchased from Cambridge Isotope Laboratories, Inc.

Imaging experiments were performed using a Bruker super-widebore 300 MHz NMR equipped with micro-imaging accessories, which is operating at ^{3}He resonance frequency of 228.65047 MHz. The homebuilt ^{3}He NMR probe with a coil diameter of 5 mm was used for the experiments. SPI (single point imaging) method was applied in the ^{3}He MRI measurement with the excitation pulse length of 2.7 μsec, the dephasing time of 117 μsec, and the repetition time of 10 msec. The field of view (FOV) was 6 x 6 x 12 mm. The matrix size was 32 x 32 x 16, and the number of scans was 4 for each point. The applied magnetic field gradient was 70 Gauss/cm, 70 Gauss/cm, and 70 Gauss/cm in X, Y, and Z axes, respectively. The 3D image was obtained by zero-filling to 64, 64, 32 points.

RESULTS AND DISCUSSION

Fig. 1 shows a schematic diagram of the continuous flow system used for production of laser-polarized ^{3}He. The optical pumping cells were made of standard borosilicate glass (Pyrex). The cell body is spherical (~4.5 cm o.d.) and has a volume of approximately 50 cm^3. In order to remove impurities adsorbed to the surface of the glass, the cell was baked at elevated temperatures (500-550 K) under vacuum using a high-vacuum diffusion pump. The adsorbed paramagnetic impurities are known to be a major source of wall relaxation, which dictates the polarization efficiency. The laser-polarized ^{3}He can also relax in the presence of the local magnetic field gradients caused by ferromagnetic impurities in the walls of tubing and connections, which is far more damaging to polarization than the paramagnetic impurities. Thus, the materials for tubing and connections were carefully chosen to avoid the destruction of ^{3}He polarization. Teflon and brass were used for tubing (1/8 in.) and connections, respectively. Opening or closing of the gas flow was controlled by brass Swagelok valve. Helmholz coil pair of 60 cm in diameter produces a maximum magnetic field of 80 Gauss when driven in parallel with 30 V at 3 A. The laser diode array (Coherent, 795 nm) produces a maximum power of 60 W with a full width at half maximum linewidth of about 2 nm. The linearly and randomly polarized laser light is transferred to the circularly polarizing unit (Coherent) and converted to circularly polarized light in the unit. The laser-polarized ^{3}He gas was circulated through the closed circulation system using a pressure- and vacuum-resistant gas circulation pump (GCP, Brey).

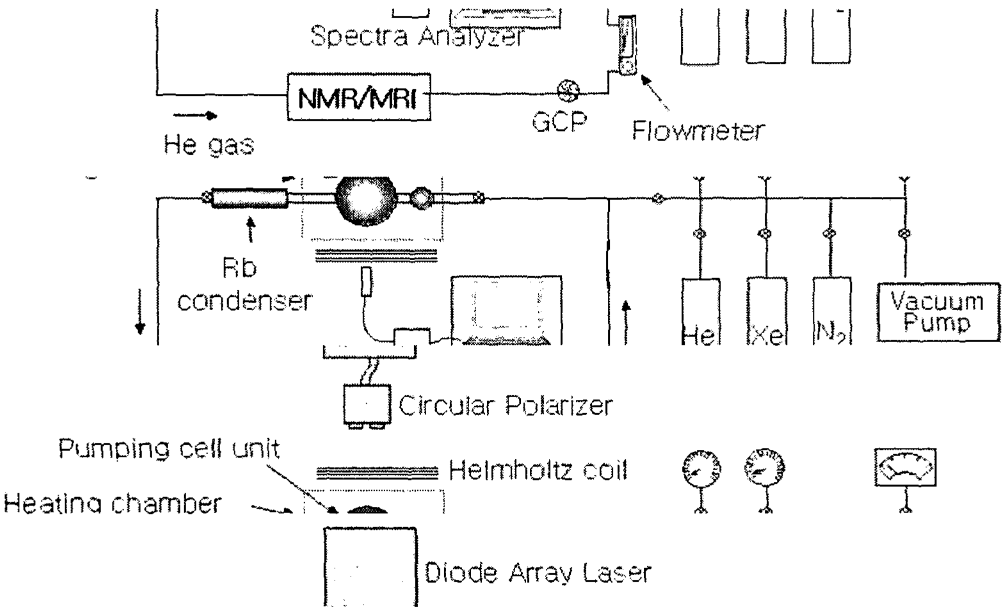

Fig.1. A schematic diagram of the continuous flow polarization system

To obtain the laser-polarized ^3He gas, rubidium of 1g and ^3He gas of 7 atm mixed with 10% N_2 were placed in the pumping cell and irradiated by the laser at the wavelength of 795 nm (Rb D_1 transition) in 70 Gauss magnetic field. The rubidium was consequently excited to a hyperpolarized state of electron spin, where the electron in S orbit was pumped to P orbit. Cohabitation of ^3He gas with the hyperpolarized rubidium leads to spin polarization of ^3He gas. The laser-polarized ^3He gas was then continuously supplied to the probe for imaging at a rate of 10 ml/min by using the gas circulation pump. Based on the flow rate of 10 ml/min., the contact time between the hyperpolarized rubidium and ^3He in the cell is approximately 5 min., which is far less than the spin exchange time of 5-10 hrs for ^3He. Nevertheless, the overall NMR sensitivity of laser-polarized ^3He was much better than that of ^{129}Xe (data not shown), and was good enough for imaging within a reasonably short time. The reason for poor sensitivity of ^{129}Xe is that it has a very fast depolarization rate through Xe-Xe collisions when using high partial pressures, even though it has a very short spin exchange time (~30 sec).

Fig. 2 shows the 3D image of Teflon tubing (2 mm i.d.) with a continuously circulating flow of laser-polarized ^3He. The white region represents the ^3He image of the inner space in the tubing. The raw data were acquired as a 32 x 32 x 16 matrix, using SPI (single point imaging) method, a pure phase-encoding technique. A repetition time of 10 msec was used during the accumulation of 4 scans for each point, and the pulse length of 2.7 μsec used in

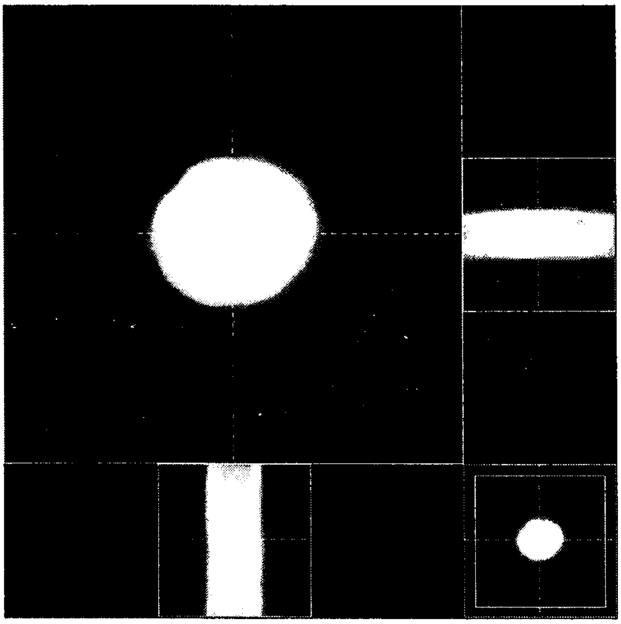

Fig. 2. 3D image of Teflon tubing with continuously flowing laser-polarized ^3He.

the experiments corresponds to approximately 15° pulse. The field of view (FOV) is 6 x 6 x 12 mm, resulting in-a resolution of 188 x 188 x 750 μm. The 3D image was obtained by zero-filling to 64, 64, 32 points. As can be seen from the image, the inner space of the tubing is clearly seen, demonstrating the feasibility of ^{3}He imaging under continuous flow. Furthermore, the total experiment time is only 10 min., indicating that the ^{3}He image of real porous materials could be obtained in a reasonably short time. Since the-continuous flow system has the advantage of long experiment time with stable ^{3}He polarization, the resolution can be further improved with a long signal accumulation. Alternatively, the resolution can be improved if the polarization efficiency is enhanced with increased contact time of ^{3}He through the use of large-volume pumping cell and high-power laser.

Acknowledgements

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[CORRECTIONS]

Fig. 4 in the article published in Vol. 6. No. 2, on page 100 appears incorrectly.
The correct version of this figure appears below.

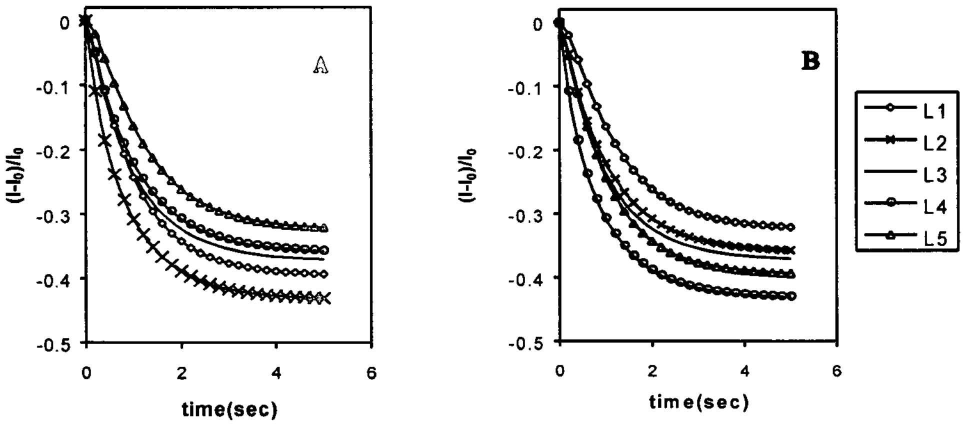

Fig.4. Same as in Figure 3 (A), but with P2' and P2 protons saturated (A) and with P4' and P4 protons saturated (B).