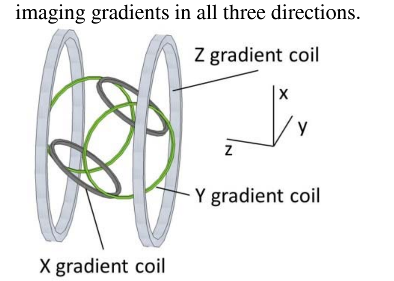
Very low field imaging of laser-polarized noble gases

Yuan Zheng[1], Gordon D Cates[2], John P Mugler[2], William A. Tobias[2], and G Wilson Miller[2]
[1]University of Virginia, Charlottesville, VA, United States, [2]University of Virginia, VA, United States

Introduction: Since the magnetization of a hyperpolarized sample is independent of the holding field strength, it is possible to image hyperpolarized noble gases at very low B_0 [1]. Here we describe a completely home built, inexpensive, and simple MRI system for imaging laser polarized noble gases at B_0 = 2 mT. Our apparatus incorporates a novel approach to produce transverse magnetic field gradients, which provides a simple alternative to Golay-type gradient coils typically used in commercial MRI scanners. We demonstrate the use of this apparatus to generate relatively high resolution images of both hyperpolarized He-3 and Xe-129 phantoms. We also discuss the potential of using this apparatus for small-animal imaging.

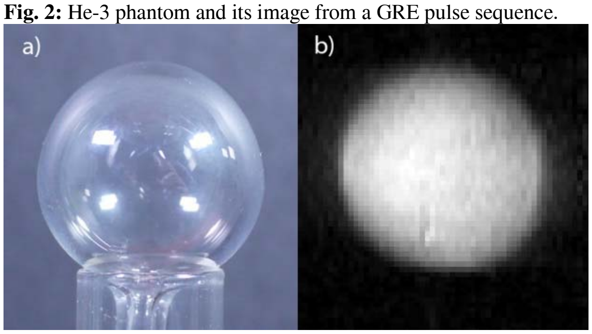
Methods: In our low-field imaging apparatus, the B_0 and B_1 fields are generated by pairs of Helmholtz coils, and the NMR signal is detected by a third pair of coils placed close to the sample. These three coil pairs are mutually orthogonal. Imaging gradients are produced along all three physical axes by three pairs of Maxwell coils (two identical coils with opposite current directions placed along a common axis) arranged as shown in Fig. 1. The z-axis gradient is produced by a Maxwell pair oriented in the familiar longitudinal configuration, whereas the x-axis and y-axis gradients are produced by two sets of Maxwell pairs oriented at the so-called "magic angle" of $\theta = \cos^{-1}(1/\sqrt{3})$ with respect to the longitudinal axis. At this angle, the z-axis gradient produced by a Maxwell coil pair vanishes, leaving only a transverse magnetic field gradient. The gradient coils are driven by programmable bipolar power supplies (Kepco BOP 72-6M and 36-12M), the B_0 coils are driven by a current regulated power supply, (Walker HA-1365-3SS), and the B_1 coils are driven by a programmable function generator (Agilent 33250A) and low-frequency RF amplifier (ENI1040L). A National Instruments Data Acquisition (DAQ) card programmed in LabView is used to generate gradient and RF waveforms and record the NMR signal data.

Fig. 1: Maxwell coil pairs used to generate imaging gradients in all three directions.



Our initial test subjects for this system were two sealed glass phantoms. The helium phantom was a 25-mm diameter spherical cell, shown in Fig. 2a, containing 2.8 atm of He-3 and a small amount of rubidium and nitrogen. The xenon phantom was an "X" shaped cell, shown in Fig. 3a and 3b, containing 2.8 atm of isotopically enriched (86.2%) Xe-129 and a small amount of rubidium and nitrogen. The width of the "X" is about 15 mm and the height is about 25 mm. He-3 and Xe-129 were polarized using the technique of spin-exchange optical pumping (SEOP) [2], and the saturation polarization reached 40% and 7% respectively. A SEOP setup was incorporated into this MRI system so that we can repolarize the noble gases without moving the phantoms.

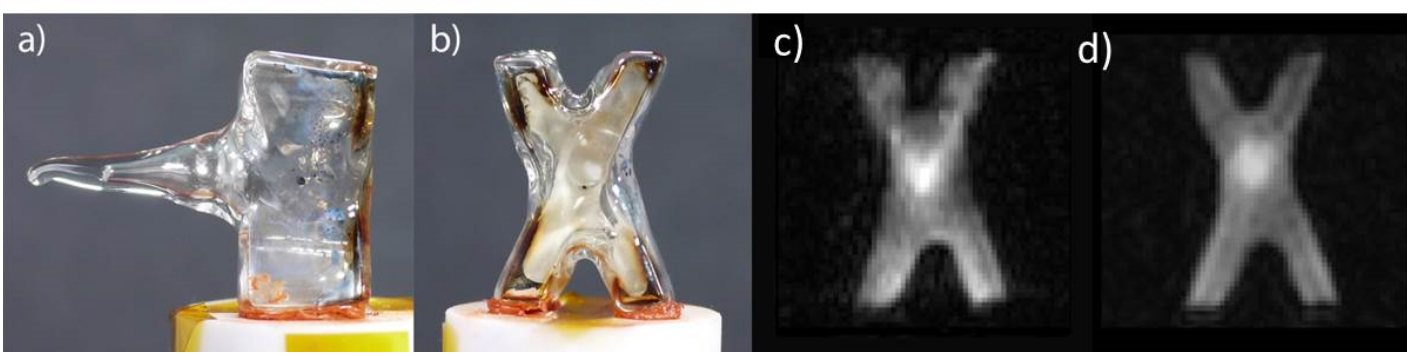
Fig. 2: He-3 phantom and its image from a GRE pulse sequence.



The phantoms were imaged at B_0 ~ 2 mT using nonselective excitation RF pulses. A Cartesian gradient-echo (GRE) pulse sequence was used to image the He-3 phantom (TR=2 s, TE=14 ms, FA=14°). 32 lines of k space were collected and the spatial resolution was 1 mm. We note that the choice of TR doesn't matter as long as it is much shorter than T1, which is tens of hours in the glass cell. We used two different pulse sequences to image the Xe-129 phantom. It was first imaged with a similar gradient-echo pulse sequence (TR=4 min, TE=50 ms, FA=90°, 32 lines, 1mm resolution) with 8 averages. We chose a 90° tip angle since the magnetization of the Xe phantom was much smaller due to the smaller gyromagnetic ratio and lower polarization of Xe-129. Therefore, we needed to re-polarize the Xe-129 after each excitation. We typically spent 4 min to repolarize the xenon to close to saturation polarization before the next excitation. We also imaged the Xe-129 phantom using a "single point" (fully phase encoded) pulse sequence on a 64×64 matrix to achieve 0.5 mm pixel resolution. For this pulse sequence, the Xe-129 was also repolarized after each measurement. Since the spins were excited so many times, we chose TR=15s, FA=35° as a compromise to get a reasonable signal size while keeping the whole MRI procedure short enough to be practical.

Results/Discussion: The MR image of the He-3 phantom is shown in Fig. 2b, and the images of the Xe-129 phantom are shown in Fig. 3c and 3d. The GRE image of the He-3 phantom demonstrates the potential of our system to be used for very low field in-vivo imaging. Since only one bolus of hyperpolarized gas was involved, all data can be collected fairly quickly. Although our choice of TR for in-vitro MRI was 2 s, it can be shortened to within 100 ms for in-vivo MRI and the whole procedure will only take several seconds. To our knowledge, the xenon images shown here are the first obtained at this low a B_0 field. Interestingly, the xenon image acquired with the single-point (fully phase encoded) pulse sequence has both better resolution and SNR than the one acquired with conventional phase encoding with 8 averages, even though the total imaging time (17 hours) was the same. We believe that the paradoxical SNR and resolution advantages result from considerations associated with gas diffusion. In the single-point technique, the encoding gradient is only applied before ADC opens, and therefore gas diffusion during data acquisition causes neither incorrect spatial phase encoding nor diffusion-induced signal attenuation that would degrade the image quality. Although the single-point technique is clearly unsuitable for single-breath-hold imaging, it may lend itself to multi-breath/multi-bolus acquisitions that are commonly used for rodent imaging. With a ready supply of well-polarized gas, the imaging time would be much shorter then the 17 hours required for continuous re-polarization.

Fig. 3: Xe-129 phantom and its images. The center bright area in the images is the projection of the phantom pull-off as shown in the side view (a).



References: [1] C.H. Tseng et al. Physical Review Letters 81 (1998). [2] S. Appelt et al. Phys. Rev. A 58 (1998).
Acknowledgments: Supported in part by research funding from Siemens Healthcare.