Passive Shimming of the Fringe Field of a Superconducting Magnet for Ultra-low Field Imaging of Hyperpolarized ^{129}Xe Gas

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Introduction: Laser polarization methods make it feasible to obtain images of xenon gas in the lungs at ultra-low field strengths (~10 mT) [1]. The magnetic field outside the bore of conventional superconducting magnets used in MR imaging systems potentially provides an inexpensive and extremely stable magnetic field for this purpose. However, the extremely strong field gradients associated with the fringe field, for which correction using standard active shimming techniques requires impractically high shim currents, present a major obstacle.

In this work a simple passive shimming method is described and used to reduce inhomogeneities of the fringe field of a superconducting magnet to a level that can be corrected with standard active shims. This approach makes it straight forward to shim the fringe field at different distances from the superconductive magnet. In this way, it is possible to perform MR imaging experiments at several field intensities using a single magnetic field source. Unlike the standard method [2, 3], the proposed method explicitly takes into account the strong variations of the fringe field intensity over the volume of the shim elements and the lack of cylindrical symmetry. In the implementation described, sets of steel rods parallel to the Z axis are used to produce volumes of homogeneity sufficient to obtaining images from HXe gas samples at ultra-low field intensities of 8.5 mT and 20 mT.

Theory and Methods: The magnetic field at point P produced by a shim element of susceptibility χ (Fig. 1), located in a magnetic (fringe) field H_Z, can be calculated, by extending the standard passive shimming theory [2, 3], to be:

$$H_Z(r,\theta,\phi) = -\frac{\chi}{4\pi}\sum_{n=0}^{\infty}\sum_{m=0}^{n} A_{n,m} r^n P_{n,m}(\cos\theta)\left[\cos m\phi\, H_{n,m} + \sin m\phi\, K_{n,m}\right] \qquad (1)$$

$$A_{n,m} = -\varepsilon_m \frac{(n-m+2)!}{(n+m)!} \qquad \varepsilon_m = 1 \quad for \;\; m=0\,;\; otherwise\;,\; \varepsilon_m = 2\,.$$

$$H_{n,m} = \int_{Velem} \frac{H_Z(r')}{r'^{\,n+3}} P_{n+2,m}(\cos\alpha)\cos m\psi \; dV$$

$$K_{n,m} = \int_{Velem} \frac{H_Z(r')}{r'^{\,n+3}} P_{n+2,m}(\cos\alpha)\sin m\psi \; dV$$

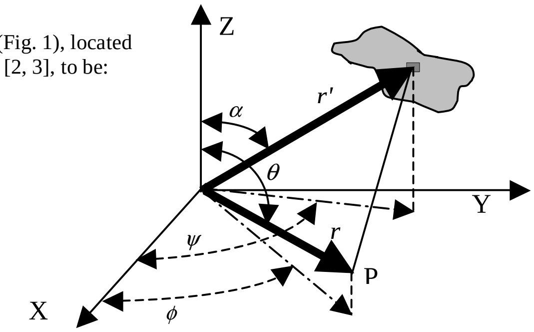

Fig. 1. Coordinate system used in this work.

where: $P_{n,m}$ are the associate Legendre functions and V_{elem} is the volume of the shim element. This explicitly takes the spatial variation of H_Z within the integral, which is usually taken to be a constant in the conventional method.

The home-built ultra-low field MR imaging system uses the fringe field of a 30 cm bore superconductive magnet (1.89 T) which permitted field intensities up to 20 mT. Imaging was accomplished using a 26 cm diameter gradient and shim set (Bruker B-GS 30/C-19) powered by the gradient and shim power supplies of the high field system and controlled by an MRRS (formerly SMIS) MR5000 console. The NMR electronics and the continuous-flow polarization system used has been previously described [1, 4]. Initial field mapping was performed using a Hall-effect gaussmeter. Once the field homogeneity was passively shimmed as described bellow to a level that permitted HXe signals to be obtained, field mapping was performed more rigorously using HXe signals directly. Steel rods were used as shim elements. The optimum arrangement of shim elements was obtained by iteratively adjusting their parameters from an initial estimate [3], and numerically calculating the field using Eqn. 1, and the measured field maps. The shimming procedure was used at two different positions, located at 120 cm and 85cm from the centre of the superconducting magnet, such that after shimming, field intensities of 8.5 mT and 20 mT, respectively, were obtained. After correcting most of the field inhomogeneities by passive shimming, the field homogeneity was improved further using standard active shims. Imaging of a 10 mm diameter open glass cell was performed using a gradient-echo pulse sequence with variable flip angle.

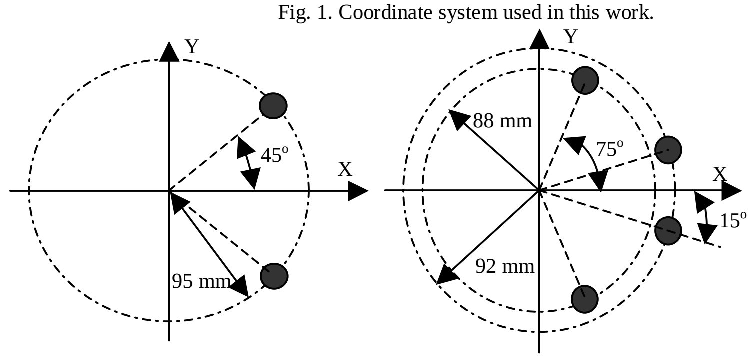

Fig. 2. Diagram of the shim sets for the 8.5 mT (left) and 20 mT (right) positions.

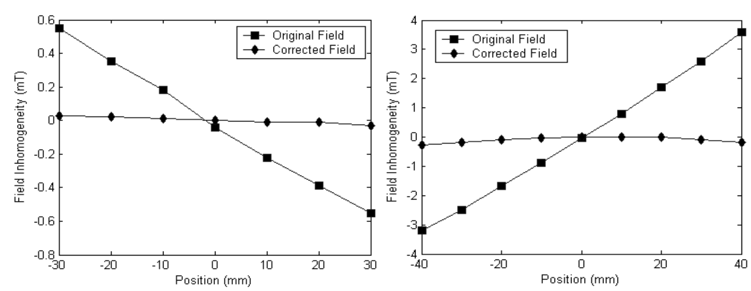

Fig. 3. Field maps (X direction) before and after passive shimming at the 8.5 mT (left) and 20 mT (right) positions. These positions were at opposite sides of the magnet.

Results: The practical implementation (Fig. 2) of the shimming procedure produced the desired volumes of homogeneity (Fig. 3) at 8.5 mT (2 cm DSV) and 20 mT (8 cm DSV). At the 8.5 mT position, the field gradient (0.30 mT/cm) was effectively corrected, improving the field homogeneity to 0.5% from the initial 7.2%. At the 20 mT position, the very strong field gradient (0.92 mT/cm) was corrected, improving the field homogeneity from 25% to 0.2 %.

At the 8.5 mT position, the field homogeneity was further improved by active shimming. The final field homogeneity (0.03%) allowed HXe spectra to be obtained with linewidth of 27 ± 5 Hz as well as images of small HXe samples (Fig. 4). It is anticipated that rat lung imaging will be performed in the larger volume of homogeneity obtained at 20 mT.

Conclusion: The method for passive shimming of the fringe field of a superconductive magnet reduced field inhomogeneities to permit the detection of HXe signals that can be used with standard active shimming procedures to further improve the field homogeneity up to the level needed to obtain MR images. The simplicity of the method and the possibility of using most of the hardware of the high field system make this approach an inexpensive and a convenient way of expanding the low field capabilities of existing or new MRI facilities for hyperpolarized gas imaging.

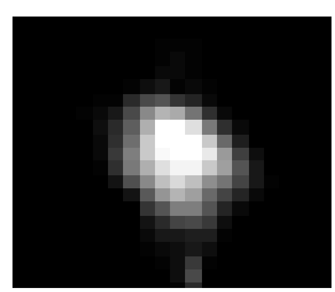
Fig. 4. HXe gradient-echo image at 8.5 mT.

References

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