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 straightforward to shim the fringe field at different distances from the superconducting 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 $\chi$ (Fig. 1), located in a magnetic (fringe) field $H_f$, can be calculated, by extending the standard passive shimming theory [2, 3], to be:

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

where $A_{n,m}$, $P_{n,m}$, and $V_{mn}$ are the magnetic field components at point P.

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%.

Conclusion: The method for passive shimming of the fringe field of a superconducting 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.

References: