Design of an optimized open-access human-scale MRI magnet for orientational lung study

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Introduction

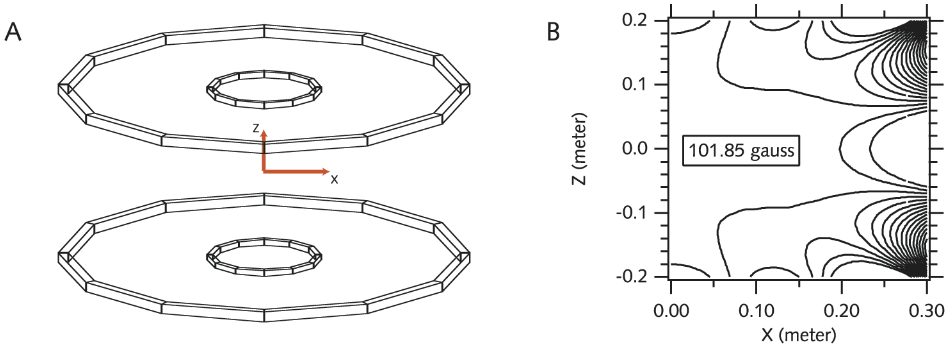
A current subject of much debate in the lung physiology community concerns the role of gravitational effects on lung inhalation and function [1]. The recent advances in spin-exchange optical pumping [2] have made laser-polarized ^{3}He MRI practical as a powerful method for studying lung structure and function. Unfortunately, conventional MRI systems restrict patients to a horizontal position in a high field superconductive magnet, severely limiting the types of orientational studies that can be performed. We avoid this limitation by exploiting a key feature of the non-equilibrium ^{3}He magnetization: the nuclear polarization attained via spin-exchange optical pumping is independent of the strength of the applied magnetic field. We therefore benefit from a novel magnet design, practical at low magnetic fields, that does not restrict the subject, while still permitting high-quality laser-polarized gas MRI. We have previously reported the design and testing of a prototype open-access human-scale imaging system that operated at ~ 4 mT (40 G) [3]. While this first-generation system demonstrated the feasibility of lung imaging at multiple orientations, the SNR was limited and many of the benefits expected from very low field operation (such as low susceptibility artifact) were not realized due to the poor magnet homogeneity. We have now designed and built a second generation low-field magnet optimized for orientation-dependent human inhalation MR imaging.

Methods

The main Bo coil design was optimized using magnetic field simulations run on the Biot-Savart software package. A four-coil common-current biplanar design based on [4] allows for magnetic field homogeneities better than 50 ppm at field strengths up to 100 gauss. The open structure of the system is maintained with biplanar gradients based on [5], allowing the generation of gradient fields up to 1 gauss/cm. The entire system is mounted within an adjustable aluminum framework which allows positioning of the coils with a translational precision of 1 mm in all three axes and angular adjustments better than one milliradian. A water-cooled Alpha current supply provides up to 100 amperes, which runs in series through all four coils with a stability better than 10 ppm. The magnet is housed in an RF-shielded enclosure that provides noise attenuation better than 80 db at the 50-150 kHz range. A combination of liquid and air cooling provides temperature control of the coils and the room. The geometry of the imaging system allows for an unobstructed volume within the magnet that measures approximately 90 centimeters in width and 2 meters in height and depth, with a homogeneous imaging volume that approximates a sphere with diameter of 40 cm located at the center.

Results

Figure 1 details some aspects of the biplanar B_0 configuration: the geometry of the design is shown in **(A)**. The outer diameter of the large coil is 210 cm, and the gap between planes is nearly 90 cm. A calculation of the magnetic field in the X-Z half-plane is shown in **(B)**. The contour lines indicate field variations in steps 50 ppm. The B_0 current is 65 A, and the field at the isocenter of the magnet is 101.85 gauss.



Discussion

The present biplanar design has a larger coil separation (~ 90 cm) than previous 8th order designs which employ four coils located on a sphere. In addition, the present design has a homogeneity that is far less sensitive to misalignment of the individual coils than other 8th order designs. This, in combination with the stable kinematic method of mounting and shimming the coil locations, gives an improvement of homogeneity nearly 200 times better than our first generation system. The biplanar coil arrangement has the same footprint as our previous system, but with an access area that is nearly twice as large. This has greatly improved the planning and implementation of experimental protocols by increasing subject comfort, allowing better subject positioning, and increasing operator access to the subject. Another significant improvement involves the temperature management of the coils. The RF shield in this second-generation design is constructed of copper mesh for the entire upper half, allowing for a greatly enhanced forced-air ventilation scheme that carries the majority of heat dissipated from the main field coils. In addition, an active liquid cooling loop is run to further dissipate heat and control the temperature of the coils. These improvements allow us to triple the magnitude of the main field compared to the first generation system.

Acknowledgements

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