Design and Construction of an Optimized Open-Access Human-Scale MRI Magnet for Posture Dependent Lung Studies

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Introduction: Regional heterogeneity of pulmonary ventilation and perfusion is well-known to be influenced by gravity[1], but is also affected by the lung parenchyma and surrounding organs and stroma, leading to some controversy over which effect is more physiologically relevant[2,3]. Of particular interest is the change in gas exchange dynamics when a subject is moved from a supine to an upright position. To date, all pulmonary function tests performed on upright individuals have measured global parameters sampled at the airway opening (mouth) only. MRI[4] and PET[5] imaging can resolve regional dynamics such as *V/Q*, but available imaging systems restrict subjects to decubitus positions only. We recently demonstrated *in vivo* ^{3}He MR imaging of human lungs in the supine and upright positions in an open-access prototype system at ~ 4 mT[6], exploiting both the ability to perform hyperpolarized 3He at B_0 well below that of clinical scanners, with an open-access magnet design. While this showed the feasibility of using ^{3}He MRI for posture-dependent pulmonary studies, we were hampered by low SNR, short T_2* due to B_0 inhomogeneity, and gradient coil heating which limited imaging speed.

Methods: We have built an optimized second-generation open-access MRI system specifically designed for orientation-dependent pulmonary ^{3}He human imaging. The B_0 coils are based on a bi-planar, four-coil design[7] that can provide a magnetic field up to 10 mT (at 65 A) with a theoretical homogeneity better than 100 ppm across a 40 cm diameter spherical volume (DSV). An aluminum framing system allowed for high-precision mounting of the coils as well as translational and rotational adjustments. Three planar gradient sets provide magnetic field gradients up to 0.18 G/cm with a linearity suitable for 256^2-pixel imaging across a 40 cm FOV. The inter-coil spacing is 78 cm, providing ample room for the subject. Heat dissipation has been optimized through active liquid and forced-air cooling. The RF enclosure provides >100 dB attenuation within our operating frequencies of ~ 200-300 kHz.

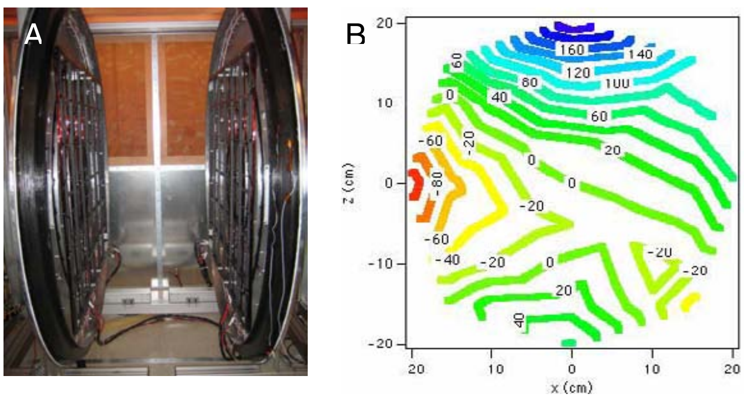

Figure 1 Low-Field MRI system and initial field map. **A)** Photograph of the open-access low-field imager showing the subject space as well as the B_0 and gradient coils. **B)** ^{1}H ω_o map (Hz), with zero at the center frequency of 210 kHz, obtained at 5 mT across a horizontal imaging plane spanning ~40 cm.

Results: Small B_1 coils and water samples have been used for NMR testing of B_0 field homogeneity and field gradient linearity. After initial installation of the magnet (Figure 1A) we shimmed the field to produce a B_0 homogeneity of ~200 ppm at 5 mT across a 35 cm DSV. A field plot showing ^{1}H ω_o variation is given in Figure 1B. It should be noted that while fractional homogeneity is high in comparison to high-field scanners, the absolute field variation and resulting $\Delta\omega_o$ remains small, comparable to a homogeneity of a few ppm on a 1.5 T system. Such B_0 homogeneity, combined with effective environmental noise filtering provided by the RF shielding enclosure, allow high sensitivity ^{1}H and ^{3}He MRS and MRI at 5 mT. A 50 cm^3 sample of water in a high-filling-factor solenoidal coil tuned to 210 kHz (5 mT) has yielded a response with T_2* > 80 ms, SNR ~ 900. ^{3}He SNR is at least a factor of 10 greater at the same frequency. Gradient fields deviate ~ ± 50 Hz from perfect linearity, within the required limit for 256^2-pixel imaging.

Discussion: The optimized imaging system has realized improvements of ~ an order of magnitude in both homogeneity and environmental noise suppression over that seen with the prototype open-access imager[6]. Such advances will allow for eventual posture-dependent ^{3}He lung MRI with a resolution of 2 x 2 x 20 mm. We note that although operation at 5-10 mT is well within the coil-noise-dominated regime, thereby reducing hyperpolarized ^{3}He SNR from the optimal value obtained at the coil-noise/sample-noise threshold, the SNR expected at 10 mT is only ~ a factor of two lower than that realized at 1.5 T[8]. Hyperpolarized ^{3}He therefore will allow high-resolution, human lung imaging, with high SNR, at very low magnetic field strengths, where magnet designs can be specifically tailored to allow for orientation-dependent studies.

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