Design and test of a magnet and gradient system for hyperpolarised gas lung MRI at ultra-low field

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Introduction Using hyperpolarised gases, high and nearly field-independent NMR signal-to-noise ratios (SNRs) are obtained over a wide range of field values. At very low fields (a few mT), the SNR loss is not prohibitive and important benefits are gained, such as very long T_2* and T_2 even in porous materials[1] or lung alveoli[2,3] and negligible RF power deposition. So far, very low field human lung MRI has been demonstrated using inappropriate systems[3,4]. Recently, an improved magnet designed for orientational lung MRI study has been reported[5]. Here, the innovative design of a compact MRI system is described, that provides good field and gradient homogeneity and high power efficiency. To validate the concept, a 1:4-scale model of the whole-body magnet and 3-axis gradient set has been built and characterized.

Methods All coil sets are designed using homemade optimisation software, based on a downhill simplex method. Given specific constraints (number and shape of coils, overall size), other parameters (coil positions, dimensions and currents) are set to minimize the standard deviation (s.d.) of the field or gradient values over a specified volume (s.d. of *relative* variations are indeed scale-independent when computed over properly scaled volumes). Only insulating materials are used to build the 1:4-scale test system (fig.1) to avoid eddy currents during gradient switching. Pulsed NMR measurements are performed on a cylindrical sealed cell (radius R=2.5cm, length L=5cm), filled with 1.38mbar of He3 gas optically pumped in situ, using B_1 and detection coils (also at 1:4 scale) described elsewhere[2]. Field and gradients are mapped from Larmor frequencies and FID lifetimes measured at different cell locations. FID decay is exponential for a moderate applied gradient G, due to motional averaging at low pressure[6] ($D=0.138\,m^2/s$ in this cell[2]). G induces an additional relaxation rate $1/T_2' = k\gamma^2 G^2/D$, where $k=L^4/120$ (cell axis along G), and $k=7R^4/96$ (cell axis perpendicular to G)[6].

Results For the whole-body system, satisfactory field and gradient maps are obtained with a 5-coil field magnet, a set of four coils for the longitudinal gradient (Gz), and two sets of eight planar rectangular coils for the transverse (Gx and Gy) gradients (fig.2). Optimised dimensions are specified in the captions.

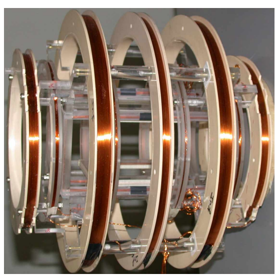

Fig.1: Picture of the 15-cm bore, 1:4-scale test system, without Gx and Gy coils. For the whole-body system, magnet coil dimensions are: diameter d=1.1m, spacing s=0.26m for the three inner coils (224, 144 and 224 turns); d=0.75m, s=1.03m for the two end coils (165 turns each).

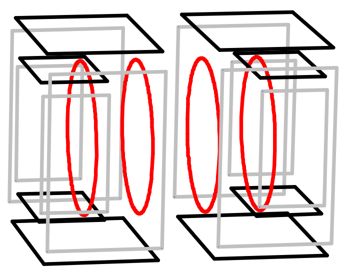

Fig.2: Sketch of the gradient coils. Gz: four coaxial coils, d=0.7m; two with 5 turns and s=0.3m, two with 37 turns and s=0.82m. Gx and Gy: overall set size $0.9\times0.9\times1.3\,m^3$; small coils ($0.3\times0.54\,m^2$, s=0.6m) have 12 turns, large coils ($0.52\times0.81\,m^2$, s=0.9m) have 20 turns.

For the 1:4-scale test system, the computed field strength (2.6mT/A) and gradient amplitudes (3.2mT/m/A for Gz, 1.1mT/m/A for Gx and Gy) are 4 and 16 times higher than in the whole-body system, respectively. The computed s.d. over a 10-cm diameter sphere is 15ppm for the static field, 0.3% for Gz, and 2.5% for Gx and Gy. NMR measurements at 99kHz (3.1mT, 70W of power dissipation) provide T_2*=2.8s at magnet centre, after first order shimming. Imperfections in coil sizes and positions account for residual field inhomogeneities over the cell size, that are ~17 times higher than expected (expansion of the computed field map over the gas diffusion modes in the cell yields T_2*=780s). Gradient calibrations, inferred from T_2' measurements, agree with computations within a few percents.

Discussion Better magnet construction is required to reach the expected performances. The present test system is operational for MRI at 1 bar pressure over ~100cm^3 volumes, and magnet barely requires air cooling up to 5mT. The high efficiency of the gradient coils allows driving by a linear bipolar amplifier with negligible RF noise. Imaging with 10-kHz sampling rate (matched to detection bandwidth) and 10-cm FOV requires a 3mT/m Gz (resp. Gx,y) gradient that only dissipates 6W (resp. 50W) and has 30µs (resp. 90µs) rise time. Gradient calibration at very low fields, where conventional NMR techniques cannot be used, is most conveniently performed using a low pressure optically pumped cell. With a fully characterised reference cell, accuracy easily reaches 1% under usual experimental conditions. Otherwise, ratios of gradient intensities can still be accurately determined from T_2' measurements performed using different cell orientations.

[1] Tastevin G. and Nacher P.-J., *J. Chem. Phys.* **123** (2005) 064506
[2] Bidinosti C.P. et al., *J. Magn. Reson*. **162** (2003) 122
[3] Bidinosti C.P. et al., *MAGMA* **16** (2004) 255
[4] Ruset C. et al., *Concepts Magn. Reson. (M.R. Engin.)* **29B** (2006) 210
[5] Tsai L.L. et al., *Proc. Intl. Soc. Mag. Reson. Med. 14* (2006) 1380
[6] Hayden M. et al., *J. Magn. Reson* **169** (2004) 313