Ultra-low Field Magnetic Resonance Imaging Detection with Gradient Tensor Compensation in Urban Unshielded Environment

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April 25, 2013 (HP58). Per our invitation, this New Paper Highlight was submitted by the first author of the highlighted paper which recently appeared in Appl. Phys. Lett. [1]. We believe the paper deserves special interest (Editors' comment).

Several groups have reported on advantages of SQUID-based ultra-low field (ULF) magnetic resonance imaging (MRI) with systems set up in magnetically shielded rooms. However, such systems face the problems of high cost and enclosed space.

We set up an inexpensive and open ULF MRI system at an urban laboratory without magnetic shielding. In this case, other problems arise. For example, the measurement field (B_m) includes the environmental magnetic field superposed onto the static field (B_0) applied by a Helmholtz coil pair. The spatial inhomogeneity of the environmental magnetic field thus becomes one of the major challenges.The subject of this paper is to introduce a gradient tensor detection and compensation system that we developed for unshielded ULF MRI experiments. For simplicity, we assume that in the gradient fields of our laboratory environment only the first-order components influence significantly the MRI detection.

The first-order gradient field tensor comprises nine components, five of which are independent. Three three-axis fluxgate pairs placed along the respective Cartesian coordinate axes were utilized to record the gradient components along these axes (*e.g.* $G_{xx} = \partial B_x/\partial x$, $G_{yx} = \partial B_y/\partial x$ and $G_{yx} = \partial B_z/\partial x$ along the x-axis). The typical measured values of the gradient components reached several μT/m, which undoubtedly influenced the MRI detection and caused the image distortion. Note that the measured gradient tensor remained almost constant during a quite long time (*e.g.*, about one week), which made the static gradient tensor compensation expedient.

Due to the geometrical constrictions imposed by the cryostat as well as the compactness and simplicity of the ULF MRI system, only six sets of gradient field coil pairs were used for the environmental gradient tensor compensation. These six coil pairs included 3D imaging gradient coils, G_{xx}, G_{xy}, and G_{xz}, two planar gradient coil pairs, G_{yx} and G_{yz}, as well as a pair of oppositely connected square Helmholtz coils, G_{yy}, all shown schematically in Fig. 1. After applying the six gradient fields, all nine components of the final gradient tensor at the sample position were suppressed to below the order of one μT/m thanks to the concomitant gradient fields.

To demonstrate the feasibility of the gradient field compensation method, NMR and MRI signals were recorded using helium-cooled SQUIDs connected to second-order gradient pickup coils. The sample was polarized by 0.65 T NdFeB permanent magnet pair placed 1.5 m away from the cryostat, and then automatically transported to the measurement position by a commercial electric actuator. By applying gradient fields with the six gradient coil pairs, the free induction decay (FID) signal duration of water sample was extended from 0.3 s to more than 2.5 s. The envelope of the compensated FID touched that of the Carr-Purcell-Meiboom-Grill (CPMG) echo train, which meant that the compensation result already approached to the optimal situation. The corresponding linewidth of 0.76 Hz meets the requirement for MRI experiments.

2D MRI images of the winter melon, an Asian vegetable, were then acquired using filtered back-projection method to test the effect of the gradient compensation. The sample was carved into an O-shape with the outer diameter of 4 cm and inner diameter of 2 cm. The gradient field of 23.5 μT/m was rotated from 0° to 180° in 12 steps. A 25-times averaged image, presented in Fig. 2, took 100 min to record, nearly 60% of which was the prepolarizing time.

Another advantage of gradient compensation is that it may also compensate the leakage of magnetic field lines of the permanent magnet. Therefore, the sample transporting time can be decreased from 1.42 s to 0.8 s when shortening the magnet-SQUID distance from 1.5 m to only 0.5 m. This suggests that the permanent magnet polarization method and gradient tensor compensation should be suitable for samples with a short transverse relaxation time T_2.

In conclusion, the gradient tensor detecting and compensating system can be effectively applied in ULF NMR/MRI without magnetic shielding. As a result, an inexpensive and open ULF MRI system can be realized for biological samples.

[11] Hui Dong *et al*., Appl. Phys. Lett. 102, 102602 (2013); doi: 10.1063/1.4795516.

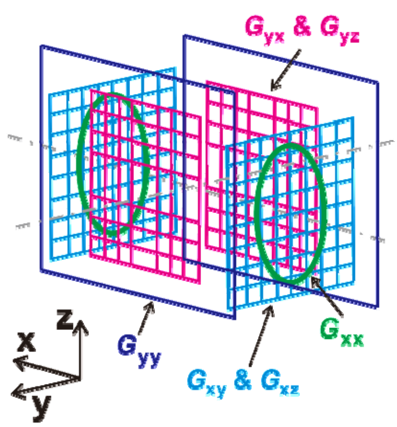

Fig. 1. The gradient compensation coil system consisting of six sets of coil pairs.

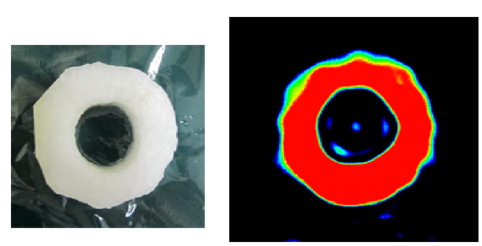

Fig. 2. The photo of O-shape winter melon and its 25-times averaged MRI image