Comparative Magnetic Field Measurements for Homogeneity Adjustment of Magnetic Resonance Imaging Equipments

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Abstract. *The goal of this paper is to demonstrate three methods for static magnetic field measurement on a whole body magnetic resonance imager. The measured data are serving for computation of feeding currents of correcting coils for the static magnetic field used in NMR imaging. The methods suggest to measure the magnetic field in selected points twice: 1. correcting coils are switched off and 2. measurement of magnetic field changes caused by switching on the feeding current of particular correcting coil in each of selected measuring points. Measurements are realized using: magnetometer based on Hall effect, NMR point magnetometer and gradient echo imaging method applied to circular test tubes. All three measurements measure magnetic field on a circle (12 measuring points) and one point in the center. A set of linear equations, determination of a target function and optimization computations are procedures that provide optimal values of currents for correcting coils. Results of all three methods are compared and discussed. The proposed method is suitable for periodic testing and magnet inhomogeneities correction for MRI magnets.*

Keywords: Magnetic Field Measurement, Magnetic Field Homogeneity Calculation, Nuclear Magnetic Resonance Imaging.

1. Introduction

Measurement and imaging methods based on magnetic resonance principles need a static homogeneous magnetic field with the highest homogeneity in all the measurement object volume [1]. No magnet (permanent or electromagnet) generates an ideal homogeneous magnetic field and therefore a sophisticated coil system construction fed by separate currents power supplies for compensation (shimming) of particular magnetic inhomogeneous components (x, y, xy, yz, xz, x^2-y^2, xz^2, yz^2, z, z^2, z^3 z^4, ...) is needed, Fig.1.

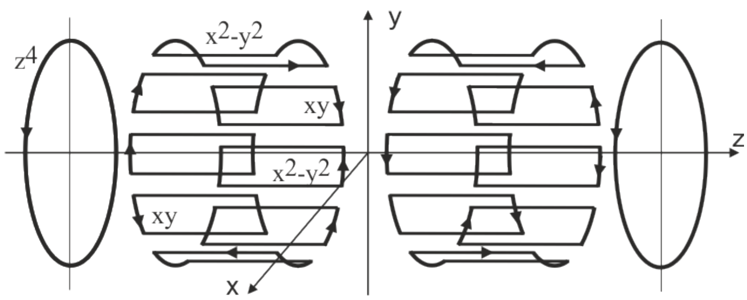


Fig.1. Image of selected shimming coils of the whole-body MRI imager.

A complex measurement method and mathematical computation for individual shim current setting are needed, for commercial imagers performed by the magnet producer [2]. Final shim currents are set directly on site after real magnetic field inhomogeneities measurements using NMR magnetometers or directly by imaging [3]. Periodical basic magnet homogeneity testing during its operation, especially in situations when ferromagnetic objects distribution near the magnet is changed and when the magnet is not equipped with magnetic shielding, is needed.

Several methods for magnetic field correction and shim coils current calculation have been developed generally based on the spherical harmonic expansions and their derivatives. By computation of the coefficients for every component of the expansion using minimization methods [1, 2], least squares method [4], or rapid spherical harmonic calculation method [5] it is possible to correct the magnetic field to achieve the highest homogeneity.

In the paper, we have described new, simple and fast methods for shim coil currents computation based on magnetic field values measured without shim coils (currents for shim coils are switched off) and magnetic field values after switching on the shim coils testing currents.

2. Subject and Methods

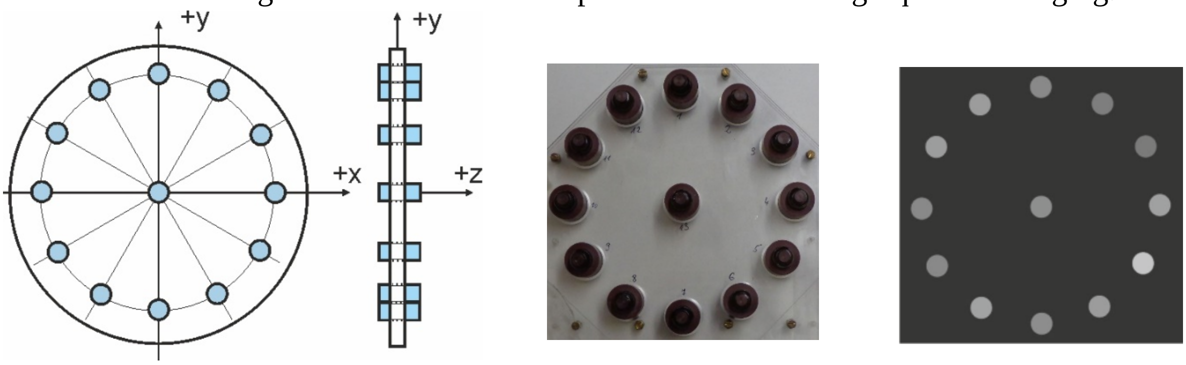
For calculation of driving currents in n correction coils it was necessary to measure magnetic flux density of pure original uncorrected basal field $\vec{B}_j^{0,uc}$, as well as magnetic flux density contribution of each correction coil separately with the same initial driving current, e.g. $I_0 =$ 1A, in m probe points ($\vec{B}_{i,j}^{c}$, for $i \in \{1, \dots, n\}$, $j \in \{1, .., m\}$).

Optimization, by self, assumes linear contribution (in driving currents) of each correction coil to the basal field. Therefore, resultant field is a superposition of all correction fields and basal field. This could be mathematically expressed as a system of linear equations

$$\vec{B}_j^{0,c} = \vec{B}_j^{0,uc} + \sum_{i,j=1}^{n,m} I_i \vec{B}_{i,j}^{c} \qquad (1)$$

where $\vec{B}_j^{0,c} = \vec{B}_0$, for $j \in \{1, .., m\}$, is desired corrected field $\vec{B}_0$ in j-th probe point, and I_i is unknown current of i-th correction coil. System of linear equations (1) is soluble by simple linear decomposition.

For measurements, a circular disc with 13 measuring holes was constructed, Fig.2. The holes served for measuring sensors insertion or ampoules with measuring liquid for imaging.



a) b) c)

Fig. 2. a) Circular module equipped with 13 ampoules (measuring transducers) placed in a holder in x, y plane. The diameter of the ampoules circle is 200 mm. b) The real positioning of measuring transducers. c) MR image of 13 ampoules.

For magnetic field measurements and optimal shim coil currents calculation, 3 methods - instrumentations were used. The measurement was repeated in 3 positions of the circular module, in the center of the basic magnet and moved: -100 mm (left) and +100 mm (right) in z - direction.

The calculation procedures were formally performed by the following algorithm:

- Magnetic field measurement in 3 planes, received 3 data files.

- Calculation of the mean values and deviations from the mean value.
- Calculation of inhomogeneity values = max. - min. values.
- Testing of 14 shim coils magnetic field contributions. Coils are fed by currents 1, 5 or 10 A.
- List of contributions to the magnetic field in 3 planes in the z-direction, 39 values.
- Writing of basic equations, calculation of the minimal and maximal values.
- Calculation of shim currents using the algorithms of linear decomposition.

a) Hall effect measurement

For magnetic field measurements the Tesla Meter based on Hall effect, type: MODEL 7010, (SYPRIS) was used, measured: x, y, z components. Resultant values were in digital form. Measurement of magnetic field contributions from particular shim coils was performed without the basic magnetic field of the tomograph switched on. The resultant values were compared with magnetic field values measured in 3 parallel planes using NMR magnetometer.

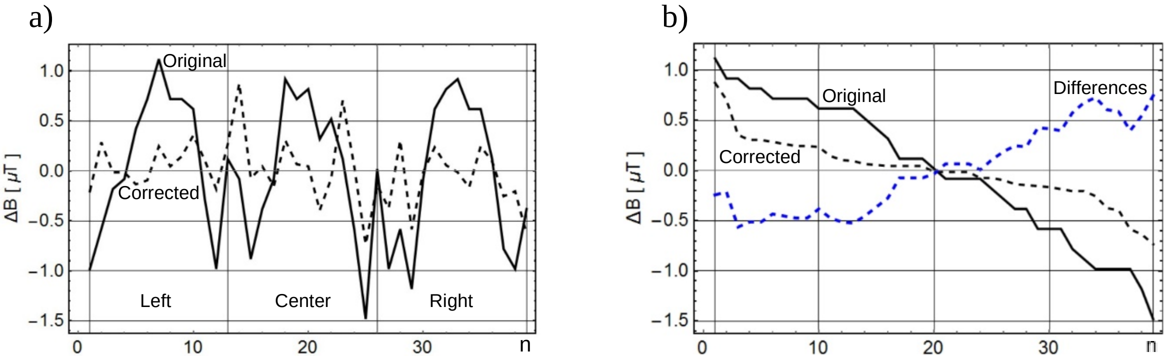


Fig. 3. a) Graphical display of n=39 values of the magnetic field contributions (3 planes in z-direction, left, center and right) measured by Tesla Meter based on Hall effect. b) Values sorted according to size and differences.

b) NMR Magnetometer measurement

For magnetic field measurements a magnetometer based on magnetic resonance principles Bruker NMR Gaussmeter ER035M was used. The measurement was performed with basic magnetic field 0.1 Tesla of the tomograph switched on.

First attempts to measure the magnetic field of a whole body imager, using NMR Gaussmeter and a least square method for the homogeneity optimization, was published in [4].

A magnetometer based on magnetic resonance principles measures the *z* component. Measuring transducer was placed into the holes in the plastic holder, Fig.2. The "normal" value $B_0 = B_z$ was measured in the center of the holder. In every measuring position of the circular module, 13 magnetic field values were measured, switching on and off 10 ampers current to the shim coils.

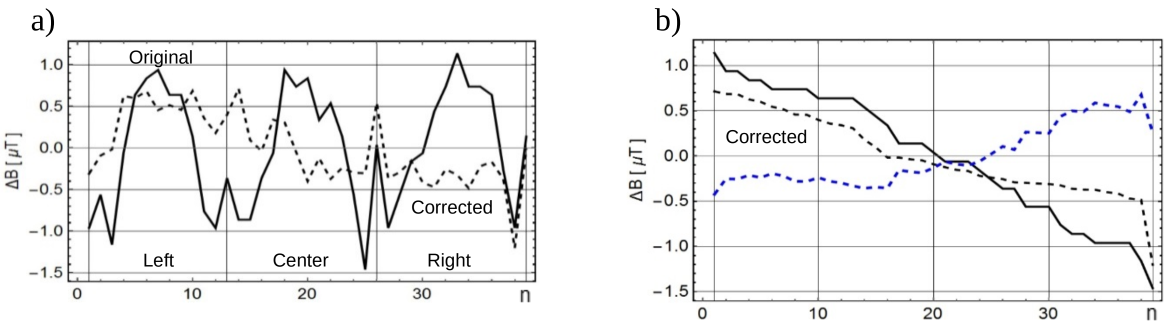


Fig. 4. a) Graphical display of n=39 values of the magnetic field contributions, (3 planes in the z-direction, left, center and right) measured by Bruker NMR Gaussmeter. b) Values sorted according to size and differences.

c) Imaging measurement method

Magnetic field measurement method using Gradient Echo imaging sequence of 13 ampoules, cylindrical vessels, was applied. Basic magnetic field 0.1 Tesla of the tomograph was switched on. Measurement of *z* components was adjusted. Resultant values were proportional to the contrast levels of circular images calculated as average values of the imaging data.

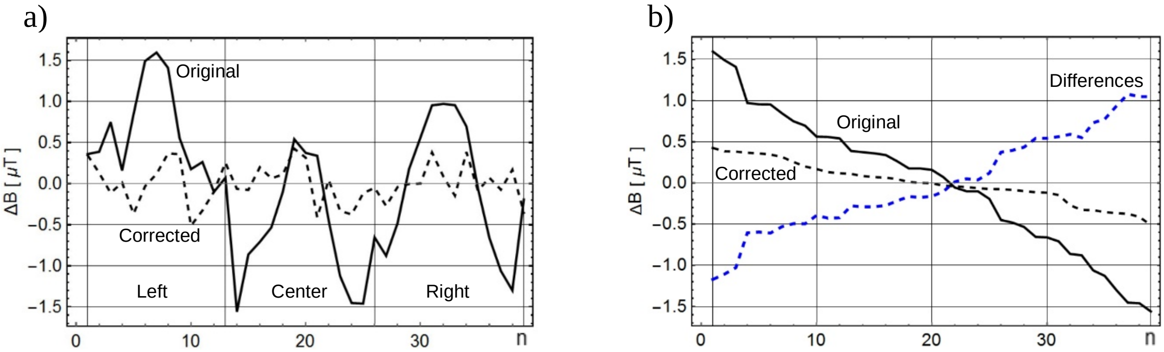


Fig. 5. a) Graphical display of n=39 values of the magnetic field contributions, (3 planes in z-direction, left, center and right) measured by NMR method using Gradient Echo imaging sequence. b) Values sorted according to size and differences.

Results and Conclusions

The goal of this study was comparative magnetic field measurements for homogeneity adjustment of magnetic resonance imager 0.1 Tesla. Three measurement methods were used: Hall effect, NMR Magnetometer, and imaging. The experimental results were in good correlation with the mathematical simulations. Comparison of 3 methods showed little differences of measured results. The differences are given by different principles of measuring probes. The best results were achieves using “imaging measurement method”, Fig.5. The maximal differences were reduced. Results of measurements and calculations provided concrete currents for shim coils adjustment.

Acknowledgements

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