Static Magnetic Field Instability and Its Inhomogeneity Distribution Mapping in NMR

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Abstract. *Instability of the static magnetic field of an NMR scanner can distort measured maps of its inhomogeneity distribution. The research described in the paper was aimed at finding a method of correction influences of the instability. Measured maps of the static magnetic field inhomogeneity distribution were processed using an optimization method and recalculated to the initial value of the static magnetic field. The resulting inhomogeneity maps were measured using two methods and compared with very good results.*

Keywords: Static Magnetic Field, Inhomogeneity, Optimization, Phase of NMR Data, Spectral Line Position of Water

1. Introduction

Mapping inhomogeneity distribution of the static magnetic field of an NMR scanner can be used for setting the magnet. Intentionally caused inhomogeneity can be an initial value for calculation of some physical parameter. There are many methods of mapping the static magnetic field distribution in NMR. The research described in the paper is a continuation of the research described in Ref. [1]. The maps of the static magnetic field are distorted by drifting the magnetic field frequently and the ratio processing can not give proper results. Purpose of the paper is to present a new method of processing such maps. Phases of the both NMR data matrices are modified using addition of the phase values which serve as variables for the subsequent optimization of the magnetic field level. The values acquired after the optimization recalculates the both source matrices to the initial same magnetic field. It ensures reliable unwrapping the resulting phase as a source for the magnetic field distribution calculation. It is assumed that the optimized matrices are determined for the ratio processing and the magnetic field drift has not caused a more complex distortion.

2. Subject and Methods

Static magnetic field distribution can be measured in more ways. Measuring from the phase of the NMR data is quick and simple. Nevertheless for accurate results some rules must be adhered. In the previous work [1] there was showed that double measurement using an NMR measuring sequence sensitive to inhomogeneities e.g. the gradient echo (GRE) with different values of the time echo (TE) can remove most of significant distortions. Nevertheless if the initial phases do not have suitable values (e.g. due to parasitic phase shifts caused by drifting the field during the measurement) unwrapping of the resulting phase need not be perfect. Therefore the new method was developed to correct the parasitic phase shifts. Each of the both initial matrices measured with different TE after the Fourier transform is multiplied by exponential term with variables φ_{1shift} and φ_{2shift} representing correcting phase shift. Then an object function is created depending on the both variables. Possible object function can be derived from the root mean square as

$$f(\varphi_{1shift},\varphi_{2shift})=\sqrt{\frac{1}{k}\cdot\sum_{\mathbf{r}_j\in ROI}(\Delta B(\mathbf{r}_j))^2}\ , \tag{1}$$

where $\mathbf{r}_j$ are position vectors of voxels from the region of interest (ROI), $j\in\langle 1,k\rangle$.

Magnetic field distribution is given by

$$\Delta B(\mathbf{r})=\frac{\varphi_1-\varphi_2+\varphi_{1sh}-\varphi_{2sh}+\varphi_{1shift}-\varphi_{2shift}}{\gamma\Delta TE}=\frac{1}{\gamma\Delta TE}\cdot Arg\left(\frac{\mathbf{I}_1}{\mathbf{I}_2}\right)+\frac{\varphi_{1shift}-\varphi_{2shift}}{\gamma\Delta TE}\ , \tag{2}$$

where γ is the gyromagnetic ratio and $\mathbf{I}_1$, $\mathbf{I}_2$ are complex matrices of measured and Fourier transformed NMR data. ΔTE is difference between the both echo times. Magnetic field distribution can also be measured and calculated from the position of the spectral line of water [2]. The considered method is based on repeated measurements with increasing TE. Voxel signal of such measurement can be considered as sampled FID signal with sampling interval ΔTE. Spectrum of FID signal is a line one (if not distorted) corresponding to the static magnetic field inhomogeneity in the considered voxel. In the conditions of the drifting static magnetic field all measured matrices of NMR data first must be recalculated to the same magnetic field. The matrices are again multiplied by exponential terms realizing phase shifting variables. The ratio processing of 5 measured and Fourier transformed matrices yields 4 matrices for optimization. They should be equal. Therefore the object function is given by

$$\begin{aligned}
&f(\varphi_{1shift},\varphi_{2shift},\varphi_{3shift},\varphi_{4shift},\varphi_{5shift})=\\
&\sqrt{\frac{1}{k}\cdot\sum_{\mathbf{r}_j\in ROI}(\Delta B_1(\mathbf{r}_j)-\Delta B_2(\mathbf{r}_j))^2}+\sqrt{\frac{1}{k}\cdot\sum_{\mathbf{r}_j\in ROI}(\Delta B_1(\mathbf{r}_j)-\Delta B_3(\mathbf{r}_j))^2}+\\
&+\sqrt{\frac{1}{k}\cdot\sum_{\mathbf{r}_j\in ROI}(\Delta B_1(\mathbf{r}_j)-\Delta B_4(\mathbf{r}_j))^2}+\sqrt{\frac{1}{k}\cdot\sum_{\mathbf{r}_j\in ROI}(\Delta B_2(\mathbf{r}_j)-\Delta B_3(\mathbf{r}_j))^2}+\\
&+\sqrt{\frac{1}{k}\cdot\sum_{\mathbf{r}_j\in ROI}(\Delta B_2(\mathbf{r}_j)-\Delta B_4(\mathbf{r}_j))^2}+\sqrt{\frac{1}{k}\cdot\sum_{\mathbf{r}_j\in ROI}(\Delta B_3(\mathbf{r}_j)-\Delta B_4(\mathbf{r}_j))^2}\ .
\end{aligned} \tag{3}$$

Magnetic field distributions can be calculated using the ratio processing as

$$\begin{aligned}
\Delta B_1(\mathbf{r})&=\frac{\varphi_1-\varphi_2+\varphi_{1sh}-\varphi_{2sh}+\varphi_{1shift}-\varphi_{2shift}}{\gamma\Delta TE}=\frac{1}{\gamma\Delta TE}\cdot Arg(\frac{\mathbf{I}_1}{\mathbf{I}_2})+\frac{\varphi_{1shift}-\varphi_{2shift}}{\gamma\Delta TE},\\
\Delta B_2(\mathbf{r})&=\frac{\varphi_2-\varphi_3+\varphi_{2sh}-\varphi_{3sh}+\varphi_{2shift}-\varphi_{3shift}}{\gamma\Delta TE}=\frac{1}{\gamma\Delta TE}\cdot Arg(\frac{\mathbf{I}_2}{\mathbf{I}_3})+\frac{\varphi_{2shift}-\varphi_{3shift}}{\gamma\Delta TE},\\
\Delta B_3(\mathbf{r})&=\frac{\varphi_3-\varphi_4+\varphi_{3sh}-\varphi_{4sh}+\varphi_{3shift}-\varphi_{4shift}}{\gamma\Delta TE}=\frac{1}{\gamma\Delta TE}\cdot Arg(\frac{\mathbf{I}_3}{\mathbf{I}_4})+\frac{\varphi_{3shift}-\varphi_{4shift}}{\gamma\Delta TE},\\
\Delta B_4(\mathbf{r})&=\frac{\varphi_4-\varphi_5+\varphi_{4sh}-\varphi_{5sh}+\varphi_{4shift}-\varphi_{5shift}}{\gamma\Delta TE}=\frac{1}{\gamma\Delta TE}\cdot Arg(\frac{\mathbf{I}_4}{\mathbf{I}_5})+\frac{\varphi_{4shift}-\varphi_{5shift}}{\gamma\Delta TE}\ .
\end{aligned} \tag{4}$$

3. Results

Verification experiments were performed on the Opera NMR scanner with permanent magnet of 0.18 T (Esaote Group, Genova, Italy). The GRE sequence was applied to ball-shaped phantom filled with the water solution of 5 mM of $NiCl_2$ and 55 mM of NaCl. Diameter of the phantom was 140 mm. During the first experiment transversal slice was depicted two times with two values of TE, ΔTE = 2 ms. Parameters of the measurement: the slice thickness 5 mm, FOV = 200 mm × 200 mm, the resolution was 256 pixels × 256 pixels, number of averages 6, the repetition time TR = 500 ms. The both matrices of measured data were processed using the equations (1), (2). The processing yielded magnetic fields map depicted in Fig. 1. The map acquired without optimization is also depicted in Fig. 1.

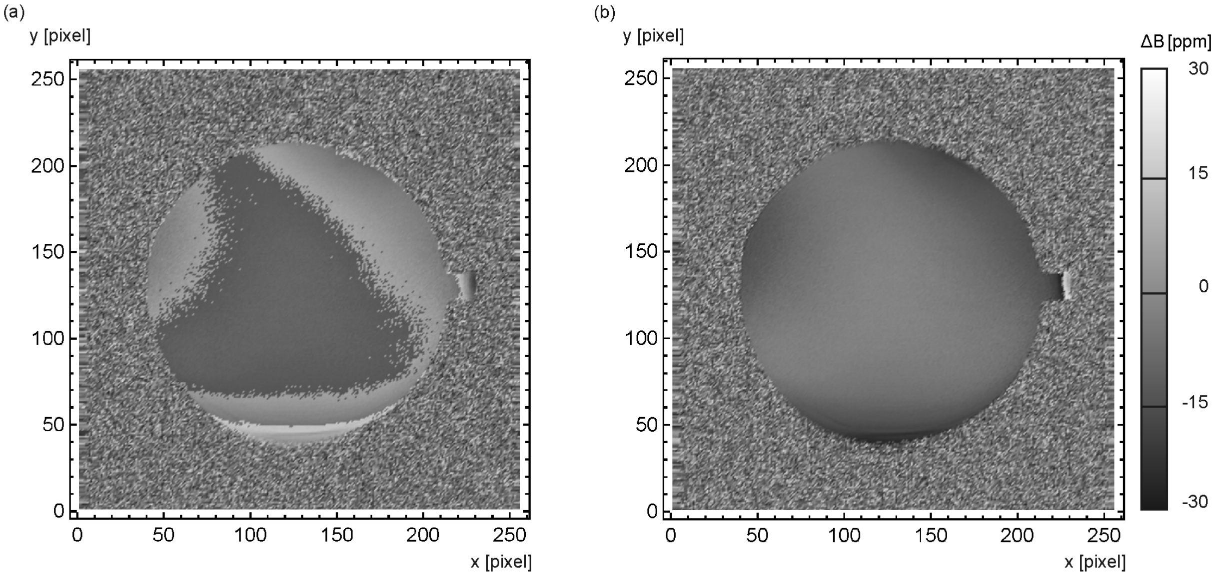

Fig. 1. Figure of the static magnetic field map (a) without the optimization and (b) after the optimization. Improving the unwrapping thanks to the optimization is evident.

During the second experiment the same phantom was measured under the same conditions 5 times with increasing TE, ΔTE = 2 ms.

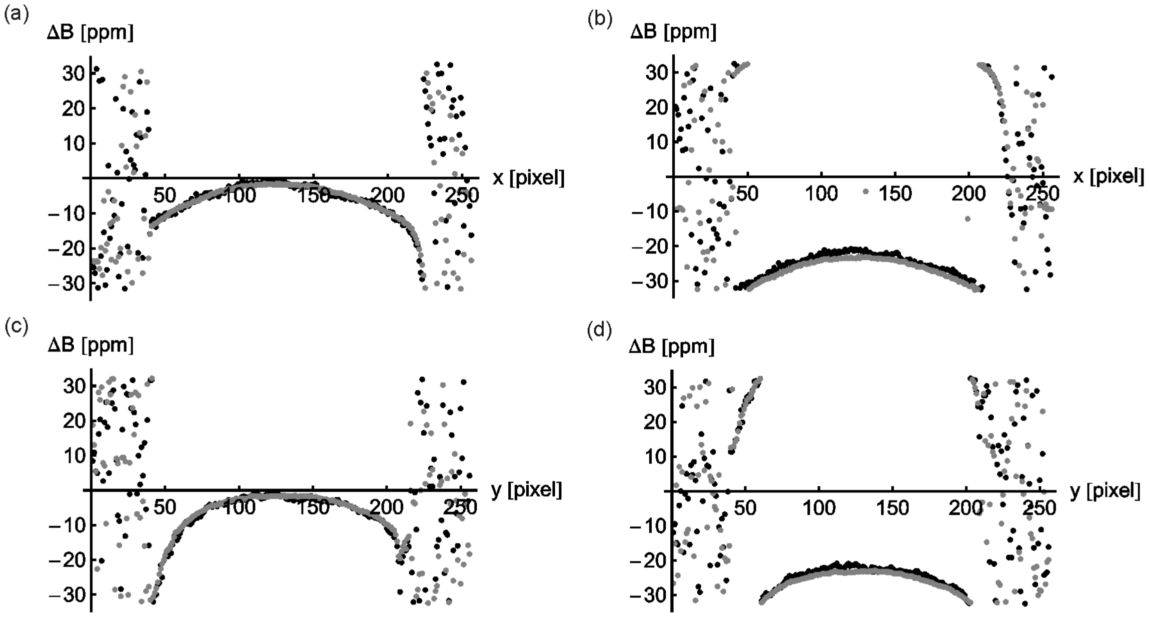

Fig. 2. Verification of the results from the optimized measurement with five matrices. The row (a) and the column (c) from the middle of the sample phantom prove the total agreement between the both manners of measurements. The black points were calculated from the phases and the grey points from the spectral lines of water positions. Figures (b) and (d) depict the same situation before optimization. The unwrapping is correct but the level of the magnetic field is too low therefore aliasing distorted the data. The whole maps of the magnetic field distribution are very similar to those in the figure 1.

The data were optimized using the equations (3), (4) and the static magnetic field map was calculated from the phase using the ratio processing and from the position of the spectral line of water. The FID signal for the position of the spectral line calculation was determined by 5 samples. It is not sufficient for successful processing therefore an interpolation using the zero filling method was used. The both results were compared in the Fig. 2. Figures (b) and (d) depict comparison of the middle row and column for the both methods without the optimization. The black points were calculated from the phase, the grey points were determined from the position of the spectral line of water using the zero filling interpolation. Imperfect unwrapping is evident again. Figures (a) and (c) compare the same row and column after the optimization. The improvement is evident.

4. Discussion

The map of the magnetic field acquired from the position of the spectral line of water was calculated only from 5 samples. To improve resolution the technique of zero filling was used. The whole number of the data matrices was increased by adding 301 zero matrices to get interpolated resolution of 0.2 ppm. The position was then determined as a simple maximum of the spectral curve. Spectral curves should be of line shape but more frequently they are in many ways distorted. Therefore more sophisticated manners of determining the position of the spectral line are used, e.g. average of the both values at the half-level of the spectral curve. Such results have also features of interpolation and the zero filling is not necessary or can be reduced to less number of zero matrices. All calculations were performed using the program package Mathematica (Wolfram Research Inc., Champain IL).

5. Conclusions

The described method is intended for scanners with lower stability of the static magnetic field or for more long-time measurements. Important component of the method is proper object function. Object function for a specific experiment can have also a specific form therefore this is more a group of methods. Looking for more sophisticated techniques of determining the position of the spectral line of water and interpolations are problems for possible future works. More details on the described method can be found in Ref. [3].

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