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A SIMPLE METHOD OF PHASE UNWRAPPING FOR NMR IMAGES

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The goal of the paper is a new method for smoothing of nuclear magnetic resonance (NMR) phase images measured by the gradient echo (GE) sequence method. The magnetic filed inhomogeneity is coded in a phase image that is outwardly demonstrated by phase jumps. For a practical study and detection of the magnetic field inhomogeneity, the unwrapping of absolute phase jumps greater than 2π must be processed in the first instance.

Keywords: phase jump smoothing, NMR imaging, image phase processing, signal filtering

1 INTRODUCTION

Homogeneity of the stationary magnetic field B_0 generated by electromagnets or permanent magnets is a basic condition for high quality imaging using magnetic resonance methods. Inhomogeneity requirements are in the range of from 10^{-4} to 10^{-6} relative to the basic magnetic field strengths. Gradient-echo sequence [1] (see basic diagram on Fig. 1) is used for basic magnetic field inhomogeneity measurement, where the phase of the measured signal is responsible for magnetic field differences ΔB calculation.

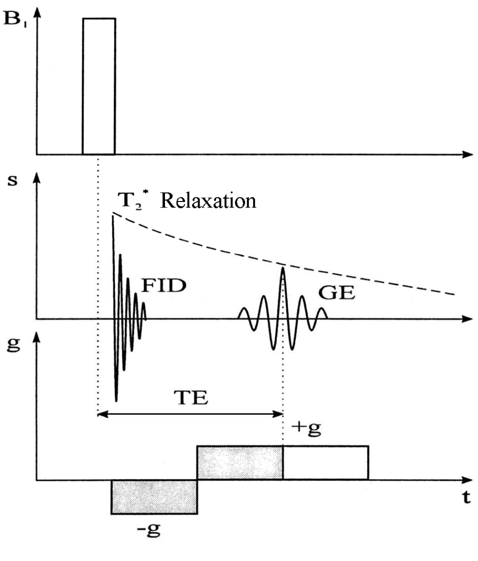

Fig. 1. Gradient – echo pulse sequence.

From the basic physical principles of the magnetic resonance imaging (MRI) follows that a phase signal is comparable with the *GE* time. After the application of the a small-flip-angle pulse, a negative gradient is turned on to dephase the spins. Then the spins are rephased by a successive positive gradient pulse. In the presence of B_0 inhomogeneities the spins will not be completely rephased by the gradient reverse. As a result the amplitude of the gradient echo marked by a T_2^* - weighting. This property is used for magnetic field inhomogeneity measurement and imaging.

Scanned NMR data in a matrix $M(x,y)$ after applying complex Fourier Transform can be described by the imaginary exponential function

$$M(x,y) = \rho \cdot e^{-j\gamma \Delta B(x,y) TE}, \quad (1)$$

where ρ is proton density, γ = 42.58 MHz/T, *TE* is Echo Time, and $\Delta B(x,y)$ is the inhomogeneity of magnetic field which is coded in phase [2]

$$\varphi = \gamma \int_0^{TE} \Delta B(x,y)\ dt. \quad (2)$$

The 2π phase jump is caused by the magnetic field inhomogeneity defined as

$$\Delta B_0(x,y) = \frac{1}{\gamma\, TE}, \quad (3)$$

and the general angle $\Delta\theta$ of phase jump is given by

$$\Delta B_0(x,y) = \frac{\Delta\theta \,.\, \Delta B_0(x,y)_{2\pi}}{2\pi\gamma}. \quad (4)$$

The absolute 2π phase jumps must be unwrapped to practical detection of the magnetic field inhomogeneity from the NMR phase images. However, there exists also another approach coming out from the physical principles of MRI and originating from the fact that the choice of time *TE* has significant influence to the range of $\Delta B_0(x,y)_{2\pi}$. It means the phase jumps when the time *TE* is shorter then corresponding maximum of magnetic field inhomogeneity does not need to unwrap. But in praxis this condition often cannot be fulfilled. Therefore some method for smoothing NMR phase images and unwrapping phase jumps is needed to apply. In the program system MatLab there is also UNWRAP function [3] implemented, but it works only as 1-D and cannot be used for processing of 2-D image matrix. This is the reason why

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we started the development of new complex unwrapping procedure and smoothing algorithm.

2 SUBJECT AND METHODS

For description of the designed NMR phase image-smoothing technique a demonstration example is shown. In our NMR scan experiments a glass tube filled with solution of $CuSO_4$ in distillated water (applied for *TE* time shortening) was used – see Fig. 2. Imagining parameters: *GE* sequence, 128x128 samples, FOV = 270mm, eight accumulations, *TE* = 27ms, Tr = 300ms, slice = 10mm.
The complete unwrapping and smoothing algorithm consists of five steps:

- image pre-processing – selecting the region of interest (ROI),
- estimation of phase jumps unwrapping direction,
- basic unwrapping of phase jumps,
- filtering and smoothing of unwrapped signal on slices,
- image finalising.

2.1 Image pre-processing

The binary zero/one mask obtained from module image for masking the input phase image is used. By this operation we create selected ROI on the phase image, the rest of image (usually the noise) is equal to zero.

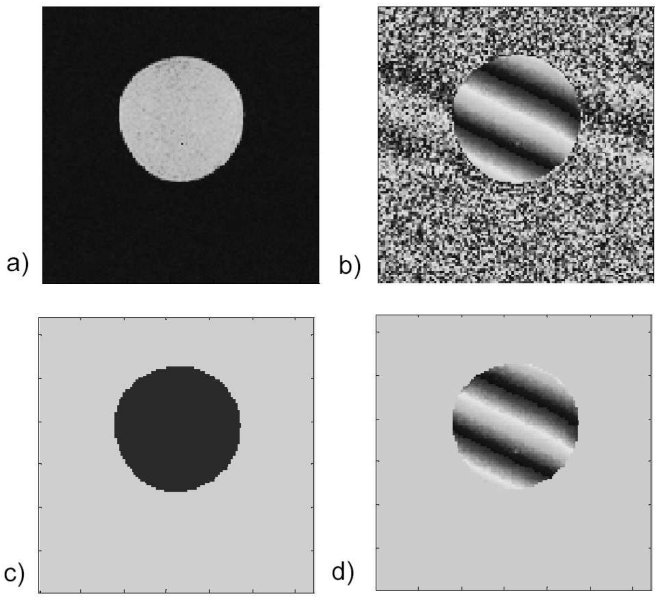


Fig. 2. Phase image pre-processing: original module image (a), original phase image (b), mask of module image corresponding to the selected ROI (c), masked phase image by zero/one mask from module image(d).

2.2 Estimation of phase jumps unwrapping direction

The second phase of the algorithm realizes the automatic choice of the direction for phase jumps unwrapping (or can be set manually). The central point (CP) of ROI in the masked phase image is firstly identified. Through this point the cuttings are led on X and Y-axis and on two diagonal directions (see Fig. 3). From data vector on cutting the difference signal and sum of absolute differential signal is calculated.

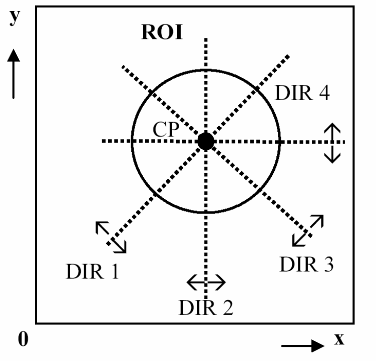


Fig.3. Principle of unwrapping direction determination.

For phase unwrapping procedure the direction with the biggest differential sum of the cutting is used. This selection approach brings the maximum across direction to the border lines between 2π phase jumps in image (see Fig. 4)

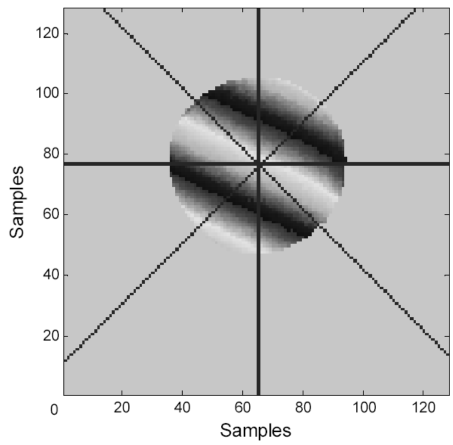


Fig. 4. Estimation of phase jumps unwrapping direction by CP=[77,65]: DIR=[51, 18, 26, 26], the DIR=1 (with maximum of 51) is chosen.

2.3 Basic unwrapping of phase jumps

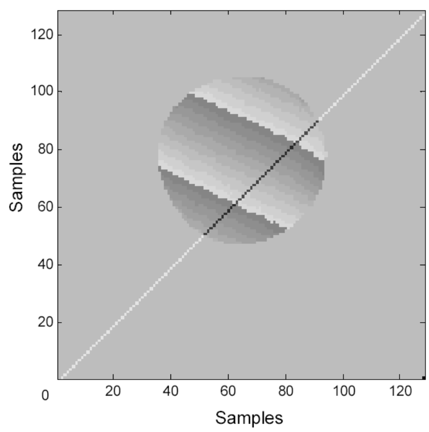


Fig. 5. Processed phase image for unwrapping on the cutting line – slice, the unwrapping direction DIR = 1.

The main procedure of phase jumps unwrapping is processing the cuttings through the CP and follows on the right and left by the selected direction. Masked object in the RIO is highlighted according to CP position (see Fig. 5).

The phase signal on cutting is unwrapped at points of local maxima defined by computed gradient signal. This signal has maximum in the place of the ROI object edges (with a range more than ±10 – these vales are overridden for next processing) and in the places of the phase jumps into the ROI object. Phase unwrapping is applied only in the ROI object area, resulting course of the slice is next calibrated.

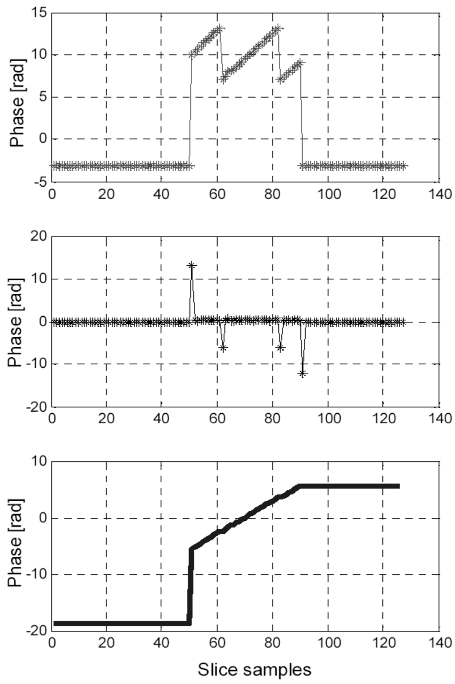
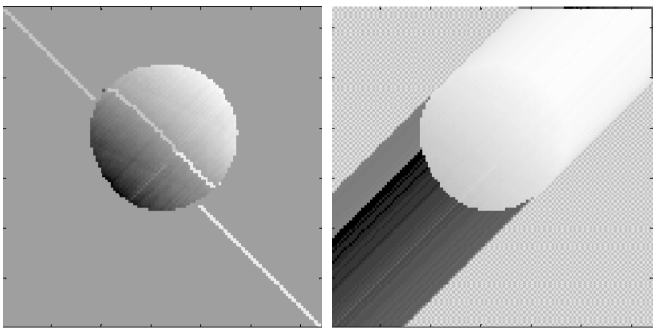


Fig. 6. Demonstration of used sequential phase unwrapping method by cuttings: input vector of phase data values on slice (a), 1-D gradient signal (b), resulting slice after unwrapping and calibrating (c).

2.4 Filtering and smoothing of unwrapped signal on slices

From unwrapped signal on cutting the inner value and position (IVP) are evaluated, which is used for filtration and smoothing the level differences of all processed cuttings.



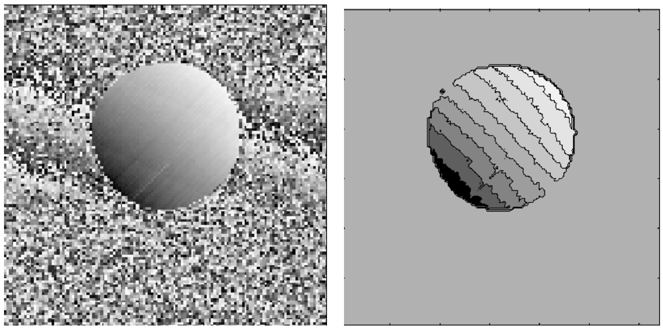
a) **b)**

Fig. 7. Phase image after unwrapping by slices on the direction DIR=1 (a), masked phase image after smoothing by IVP trajectory (b).

By this method the smoothing trajectory for whole image is determined. Smoothed phase image is again masked by a mask generated from the module image and normalized to 2π range.

2.4 Image finalising

Finally, at the smoothed and normalized phase image in ROI, the original noise background image by the inverse module mask is superimposed. For better deduction of relative phase values at unwrapped image the 8 or 16 line contours are added (see Fig. 8).



a) **b)**

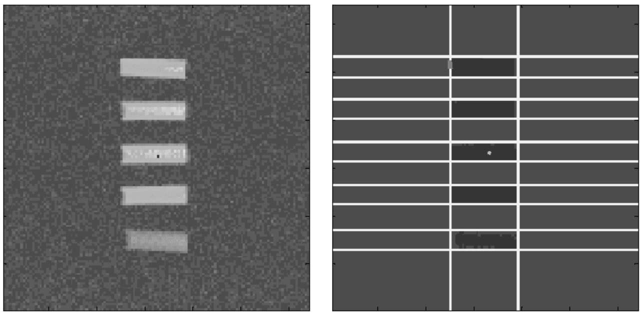
Fig. 8. Finalized phase image: finally smoothed phase image with superimposed original noise background (a), smoothed object in ROI of phase image with added contour N_{col} =8 (b).

4 EXPERIMENTS AND RESULTS

The smoothing method has been tested on the NMR phase images generated by the 0.1 Tesla experimental whole-body NMR imager controlled by S.M.I.S. console including MRI software package [4]. Tested NMR phase images were reconstructed from symmetric 2D matrix with dimension of 64, 128 and 256 samples.

The described algorithm give best results in the case of images with single object (in ROI). Some worse result we can obtain of image with more objects. In this case the ROI is taken area over of all objects, the CP point is also determined from the whole area (and generally doesn't need lie into the one of objects) – see Fig. 9. This fact brings problem with the accuracy definition of unwrapping and smoothing trajectory. Another problem looked ahead in the NMR data processing where the object in module image is “corroded” and in this manner given mask hence is not correct – see Fig. 10. Further, it must be taken into consideration, that unwrapped and smoothed phase images by this approach produce only relative values of phases. It means this method brigs only relative values and visual effect and cannot be directly used for measuring or deduction of the absolute magnetic field inhomogeneities.

However acquired images can be effectively used for magnetic field homogeneity improvement using shim coils. Interactive (after some training) or exactly using mathematical calculation [5] it is possible to modify the preset shim coil currents to get the minimal basic magnetic field inhomogeneities.



a) **b)**

Fig. 9. NMR module images with more objects (image of five proofs): original module image (a), ROI definition from the mask – CP = [64,64] (b).

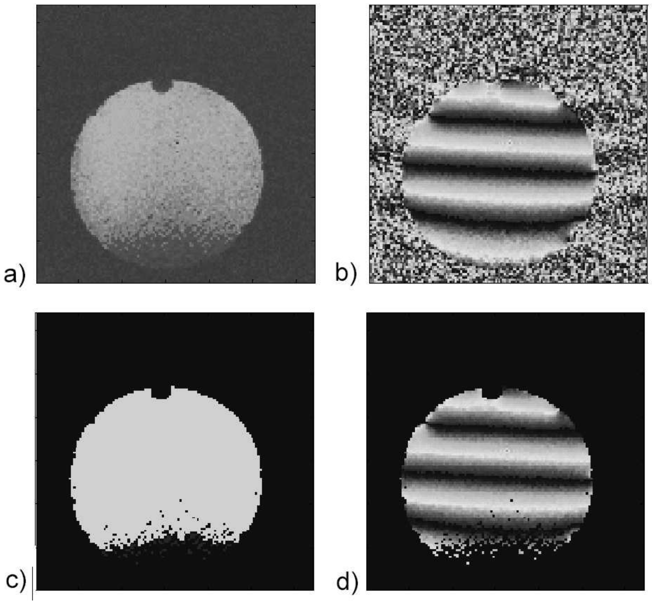


Fig. 10. NMR module and phase images with "corrosion" effect: original module image (a), original phase image (b), mask of module image (c), masked phase image (d).

5 CONCLUSIONS

Presented smoothing algorithm was implemented and tested in Matlab programming environment. The implementation in the form as the standard Windows application or as the plug-in filter for image processing application is our goal for a near feature. The file I/O management (support for S.M.I.S. NMR file formats [4]) is also needed to solve.

Acknowledgment

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