Dephased MRI – separating magnetic susceptibility effects from partial volume effects

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Introduction - By applying dephasing gradients, it is possible to selectively visualize local magnetic field inhomogeneities with positive contrast, as was presented as the 'white marker phenomenon' [1]. In recent work, we developed an extended theoretical and experimental framework, which was called 'Dephased MRI' [2]. Dephased MRI improves both the visualization of sub-voxel structures by a partial volume effect, and the positive and selective visualization of paramagnetic entities (e.g. paramagnetic markers, magnetically labeled cells or clusters of magnetic particles). What remained unclear so far was the actual contribution of partial volume (PV) and magnetic susceptibility effects (χ) in creating the dephased MRI signal. In this work, we present the theory and supportive experiments of two strategies to fully separate the magnetic susceptibility effects from the partial volume effects during application of 'dephased MRI', i.e. (1) subtraction of symmetrically dephased MRI, (2) subtraction of corrected dephased MR images at different echo-times.

Theory- The 'dephased MRI signal' of a voxel with dimensions Δx, Δy, Δz at position (x_0,y_0,z_0) with uniform spin density ρ_0 for a certain dephasing δk_x by a gradient ($\delta k = \gamma \int G(t)dt$) is given by $s(\delta k_x) = \rho_0 \Delta x \Delta y \Delta z \times \mathrm{sinc}(p \delta k_x \Delta x) \times \exp(-i2\pi x_0 \delta k_x)$ [Eq.1], where the sinc function describes the modulation of the signal strength by a certain dephasing. The exponential function represents the complex nature of the dephased MRI signal. Complete dephasing occurs at the zeroes of the sinc function. Although formulas are given for x-direction, other directions are treated identically. For a non-uniform spin density distribution within a voxel, a term $\Sigma(\rho_i-\rho_0)\, \Delta x_i \Delta y \Delta z \times \mathrm{sinc}(p \delta k_x \Delta x_i) \times \exp(-i2\pi x_i \delta k_x)$ should be added to Eq. 1. In case of the presence of a magnetic susceptibility deviation (local magnetic field inhomogeneity ΔB_0), the effective dephasing δk_x is a sum of the applied dephasing $\delta k_x^{dephase}$ by an external gradient and the inherent local dephasing $\delta k_x^{\Delta Bo}$ by the magnetic field inhomogeneity. This $\delta k_x^{\Delta Bo}$ is proportional to the local distorting gradient and its effective duration (generally the echo time (TE)).When both terms cancel each other, no dephasing occurs and signal is conserved. To eliminate the contribution of the partial volume effects the following strategies are proposed: (1) by taking the modulus of the signal, the exponential function reduces to 1 and the local signal strength is determined by the sinc function (symmetric in its argument). By applying a dephasing gradient in both positive and negative direction, e.g. by using $\delta k_x^{dephase}$ and $-\delta k_x^{dephase}$ respectively, signals for both positive and negative dephasing will equal each other in regions with $\delta k_x^{\Delta Bo}=0$. Subtraction of the modulus images will then result in images with effective signal from regions with $\delta k_x^{\Delta Bo} \neq 0$ only. (2) Another strategy is to vary TE, for example acquiring two images at TE_1 and TE_2 followed by modulus subtraction. Since variation of TE will select other regions that then satisfy the condition $\delta k_x^{dephase} = \delta k_x^{\Delta Bo}$, different regions will exhibit signal conservation, whereas regions with pure partial volume effects will only experience a signal change due to transverse signal decay. After correcting this transverse decay, subtraction of both TE images only depicts regions with a varying field inhomogeneity.

Experiments – *Phantom*: A spherical phantom (∅ 10 cm) was filled with a solution of 19.2 mg/l $MnCl_2$. The spherical phantom was chosen because the magnetic field inside is constant. Three cylindrical elements (∅ 1 mm) with 2.5 cm spacing between each other were positioned in the middle of the sphere (see Fig.1), and oriented perpendicular to the main magnetic field. The middle element was a titanium needle representing a distinct magnetic susceptibility deviation. The right element was a plastic rod, creating a signal void. The left element was a thin-walled glass capillary filled with 30 mg/l $MnCl_2$ to locally vary the relaxation time. *MR imaging* – The phantom was investigated with a clinical 3T MR scanner (Achieva, Philips Medical Systems, the Netherlands). Imaging was done with spoiled gradient echo, FOV 128x128 mm^2, matrix 128^2, slice 10 mm, TE/TR/flip = 4.6,9.2/100/25 in both transverse and coronal orientation. In-plane dephasing was done in both read and phase encoding by 0, 96, and -96 stepsizes Δk which was equivalent to dephasing of $\delta k = 0$, 17.6, and -17.6 $\mu T.s.m^{-1}$. For dephased MRI analysis, an oversampled version was acquired with identical settings except for the resolution (512^2 matrix) and 8 signal averages.

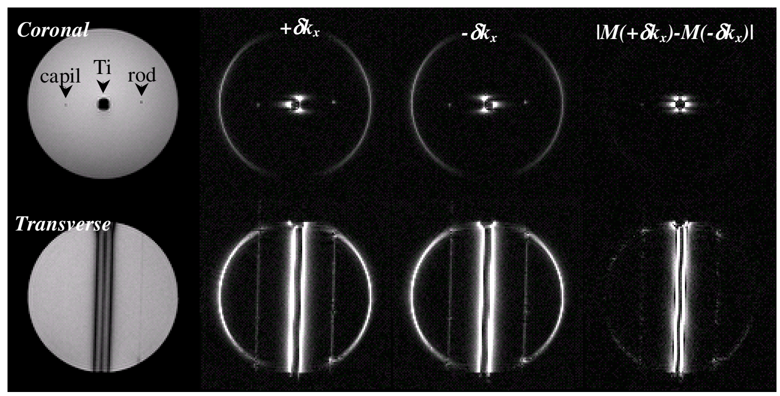

Figure 1. *Standard and 'Dephased MR images' of a spherical phantom with a titanium needle and two adjacent cylindrical elements. The left column shows the conventional imaging (TE 4.6 ms), the second column dephased images with $+\delta k_x$, the third column with $-\delta k_x$ .The right column presents the modulus of the subtraction of the dephased images, showing elimination of the partial volume effects, which are mainly observed at the edge of the phantom, but also at the rod and the capillary. Note that the rod and capillary are hardly visible in the standard images, but clearly visible in the dephased images because of PV effect, being a clear advantage of application of dephased MRI.*

Results - Application of both suggested strategies showed that pure partial volume effects -especially at the edges of the phantom- were eliminated as expected (Fig. 1 & 2). The resultant pattern in the combined images depends on the actual shape of the magnetic element and strategy followed. For spherical and cylindrical elements this is a distinct and defined shape. The results also indicated that rod and the capillary exhibited a tiny susceptibility effect.

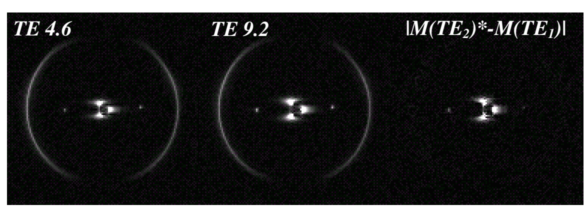

Figure 2. *Elimination of partial volume effects in the phantom with the strategy of different TE's. $M(TE_2)^*$ is the signal corrected for transverse decay.*

Discussion - This study shows that by exploiting the symmetry of the dephased MRI signal, it is possible to eliminate the partial volume effects. As a result of that, magnetic susceptibility effects can be detected in a purely selective way. This can certainly be advantageous in the detection of magnetically labeled cells or clusters of USPIO's that are generally visualized in an inhomogeneous background (e.g. the brain) that may yield 'signal' from partial volume effects during depiction with 'white marker' sequences. Eliminating the partial volume effects will then yield signal that can be attributed to the labeled cells or USPIO clusters alone. It should be mentioned that the first method is preferred in case of a background with large variation in transverse relaxation times. Finally, it is certainly an advantage that the actual strategies involve only slight additional dephasing gradients and very basic post-processing, being easy and straightforward.

References - [1] JH Seppenwoolde, MA Viergever, CJG Bakker, *Passive Tracking Exploiting Local Signal Conservation: the White Marker Phenomenon*, MRM (2003);50:p 784-90, [2] CJG Bakker, JH Seppenwoolde, KL Vincken, *Dephased MRI*, MRM (in press)