Quantitative Mapping of Susceptibility Gradients from Regular Gradient Echo Images and First Application at 7T

H. Dahnke[1], T. Schaeffter[2], S. Winkelmann[1], R. Bowtell[3], and P. Börnert[1]

[1]Philips Research Europe, Hamburg, Germany, [2]King's College, London, United Kingdom, [3]University of Nottingham, Nottingham, United Kingdom

Introduction Changes in local susceptibility induce signal loss in T2* weighted images. In the context of blood oxygen imaging or the detection of ion oxide based contrast agents, there is a high interest in selectively turning this dark signal into a positive contrast as well as to quantify the susceptibility effect. Several MR sequences have been proposed to image these field distributions selectively with a positive contrast [1-3]. The different approaches show bright positive contrast images, but prior knowledge about the strength of the field disturbance is required to optimize positive image contrast. We developed a method for positive contrast imaging by means of susceptibility gradient mapping (SGM) that calculates the susceptibility gradient vector for each voxel [4]. The SGM technique can be performed without the use of special sequences, i.e. via a conventional single gradient echo 3D scan. We demonstrate that this method allows the quantitative determination of susceptibility gradients and show first applications to BOLD induced susceptibility gradients in phantoms at 3T and volunteer neuro images at 7T.

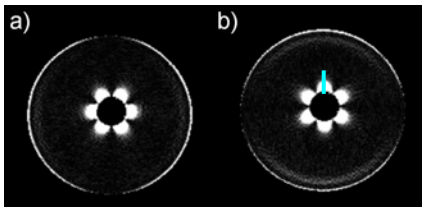

Fig. 1 Susceptibility gradient map of air filled cylinder, a) x-component, b) y-component

Theory An object with a magnetic susceptibility that deviates from the surrounding creates a local inhomogeneous magnetic field. During the acquisition of a gradient echo based image, these susceptibility gradients locally alter the imaging gradients that are applied. In addition to the well-known geometric distortion, this leads to a shift of the affected echo in k-space [5]. The SGM method determines this echo shift for every voxel in all spatial dimensions by means of local one-dimensional FFTs, that generate a coarsely resolved k-space, which can be used to measure the shift of the echo [4]. The local susceptibility gradient strength G^{suscep} is proportional to this shift in k-space M and the echo time TE: $G_i^{suscep} \approx -M_i \cdot G_i^{imaging} \cdot \tau_i \cdot TE^{-1}$ with i=x,y,z, whereas τ_i represents the gradient duration. A three dimensional vector is obtained for each voxel that contains the strength of the susceptibility gradient for all spatial dimensions.

Materials and Methods To quantify the strength of the susceptibility gradient, phantom experiments were carried out by placing an air filled glass cylinder, diameter 2.8 cm, perpendicular with respect to B_0 into a water filled bowl, diameter 15cm. 3D gradient echo imaging was performed on a 1.5T whole-body scanner (Philips Achieva) using a T/R head coil at: TR=12.5ms, TE=10ms, flip angle: 30°, FOV: 180x180x48, Matrix: 256×256×24, NEX=1.
To explore the influence of the different susceptibilities of oxygenated and deoxygenated blood, a cylindrical glass bowl, diameter 15 cm, filled with 6% gelatin was used. It contained two holes (1cm ∅), which were directly filled with venous blood from a volunteer to avoid any disturbing susceptibility artifacts from glass or plastic tubes. One blood sample was saturated with oxygen by bubbling with air for 5 min. Imaging was performed on a 3T whole-body scanner (Philips Achieva) using a T/R head coil at: TR=27ms, TE=24ms, flip angle: 20°, FOV: 200×200×45, Matrix: 400×400×30, NEX=4. In-vivo imaging was performed on a 7T whole-body scanner (Philips Achieva) using a T/R head coil at: TR=18.8ms, TE=10.9ms, flip angle: 15°, FOV: 230×230×49, Matrix: 384×384×70, NEX=1.

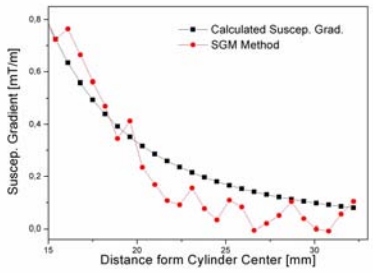

Fig. 2 Strength of the susceptibility gradient in y-direction (parallel to B_0).

Results and Discussion By using a 3D data set measured for the air filled cylinder, a parameter map of the x- and y-components (R-L and F-H direction) of the susceptibility gradient was obtained (Fig. 1a and b). In the case of the air filled cylinder, the measured value of the susceptibility gradient can be verified quantitatively, since an analytical expression for the field distribution f outside the cylinder is e.g. given in [6]. To simplify matters, we only look at one line of voxels that points in the direction of B_0 as indicated by the line in Fig. 1b. The induced susceptibility gradient is described by the first derivative of the known field distribution with respect to r:

$$\frac{\partial \Delta f(r)}{\partial r} = -\Delta\chi \cdot \frac{a^2}{r^3} \cdot B_0$$

Where $\Delta\chi$ is the susceptibility difference between the cylinder and surroundings, r is the distance from the cylinder center. In a first order approximation, we ignored the influence of the glass walls and used the susceptibility difference of air/water $\Delta\chi$=9.04 ppm (SI units) to calculate the susceptibility gradient as it is plotted in Fig 2 (filled squares). The filled circles show the result of the SGM derived results. A good agreement of both curves can be observed, which shows that the SGM method leads to quantitatively correct results.

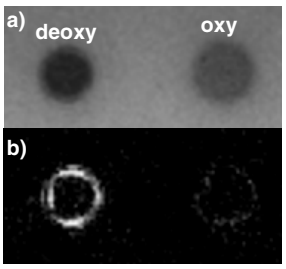

Fig. 3 Deoxygenated and oxygenated blood in gelatin phantom a) gradient echo image, b) susceptibility gradient map calculated from gradient echo image.

Fig. 3a shows the gradient echo image of the blood samples, from which a map of the susceptibility gradients was calculated, that is shown in Fig. 3b. A bright contrast around the deoxygenated blood is found indicating the susceptibility gradients that are induced by the susceptibility difference between deoxygenated blood and water, a much smaller effect is observed for the oxygenated blood. Assuming a susceptibility difference of venous blood (60% oxygenation) to water of $\Delta\chi$=0.026 ppm [7] a susceptibility gradient of 0.012 mT/m can be calculated at 5.5 mm form the center of the blood filled hole. The SGM derived value of 0.02 mT/m shows that even for small susceptibility differences quantitative values are available.

Fig 4a shows the gradient echo image of a sagittal brain slice, and Fig. 4b depicts the corresponding susceptibility gradient map. It can be seen that venous structures appear brighter in the positive contrast image due to the higher susceptibility gradients that surround them. In further studies this will also be verified quantitatively.

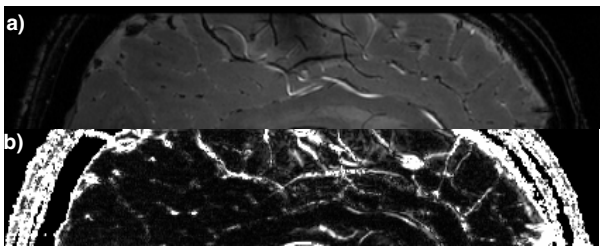

Fig. 4: Sagittal brain slide, a) gradient echo image, b) map of susceptibility gradients showing bright positive contrast for venous structures.

Conclusion We demonstrate a method to generate positive contrast images from regular gradient echo images by means of susceptibility gradient mapping. Furthermore, this method allows the quantitative determination of susceptibility gradient values as shown in phantom experiments. The susceptibility effect of venous blood was quantified, and the strong positive contrast of venous structures in 7T neuro images is demonstrated. This can be applied in further studies for discriminating arteries form veins, to improve oxygen mapping, and to explore the susceptibility effect of contrast agents.

References [1] JH Seppenwoolde et al, MRM 2003;50:784–790. [3]CH Cunningham et al, MRM 2005;53:999–1005. [3] M Stuber e al. ISMRM 2005, #2608. [4] H Dahnke et al. ISMRM 2006, #361 [5] JR Reichenbach et al, JMRI 1997;7:266-279. [6] EM Haacke et al Magnetic Resonance Imaging, Willey-Liss 1999. [7] EM Haacke, 1997 Human Brain Mapping 5, 341, 346.