Super-resolution MRI using microscopic spatial modulation of magnetization (microSPAMM)

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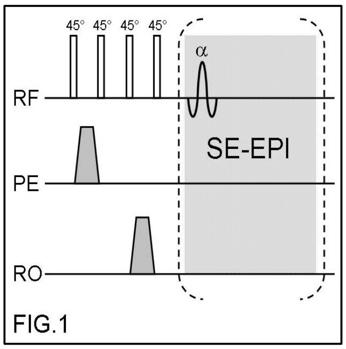
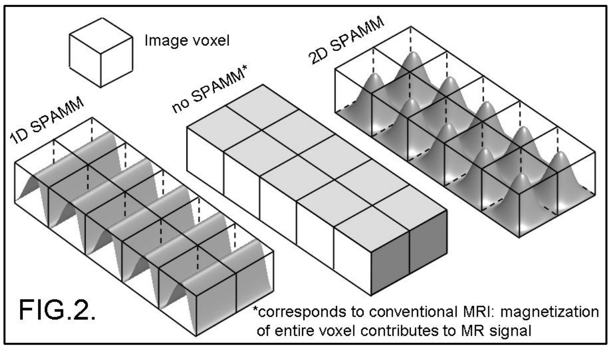
Introduction:
In this work a new super-resolution (SR) method for MRI is introduced. SR refers to an image processing method that incorporates multiple low-resolution images – related by known spatial shifts – into a single high resolution image. In MRI, SR has been proposed for increasing the image resolution in the slice selection direction (1) and in the phase or frequency encoding direction (2,3). It was argued, however, that no new information beyond the first image can be acquired with such an approach, because a FOV shift corresponds only to a phase shift in *k*-space (4). To obtain real new and independent *k*-space data with each FOV shift, we propose to spatially modulate the magnetization in addition to the FOV shift. Sub-voxel excitation is possible with a microscopic spatial modulation of the magnetization (microSPAMM). We here demonstrate the feasibility of this new approach and explain how it can be employed to break current resolution limits in MRI.

Material and Methods:
All experiments and measurements were done on a 3T Tim Trio system (Siemens Medical Systems, Erlangen). One-dimensional and two-dimensional microSPAMM was implemented as a preparation of a single shot spin echo EPI sequence (Fig.1). The parameters for the EPI sequence were: FOV=256x256mm, matrix=128x128, THK = 4mm, TR = 3000 ms, TE = 70 ms. SPAMM preparation was done for each dimension with a binomial 1$\underline{1}$ block pulse and a modulation gradient between, where the flip angle of the block pulse was 45° to generate only positive longitudinal magnetization (5). The wavelength of the modulation function ($2\pi/(\gamma^* \int G_{mod}(t)dt)$) was set to the width of one voxel (= 2 mm), therefore the modulation was not visible in the MR image (="microscopic" SPAMM). Additionally, the phase of the block pulses was adjusted such that the peak of the modulation function was centred in the middle of a voxel (Figure 2). A typical SR measurement consisted of 2 to 4 sub-voxel shifts either in one or in both dimensions, whereas the modulation function was shifted in parallel such that the peak of the modulation function remained always in the centre of the voxels. Portions of the single shifted images then were merged to a single high resolution image by interleaving their voxels. An example for increasing the resolution by a factor of two is given in Figure 3. The new approach was evaluated in a geometric phantom and in brain tissue of two healthy volunteers.





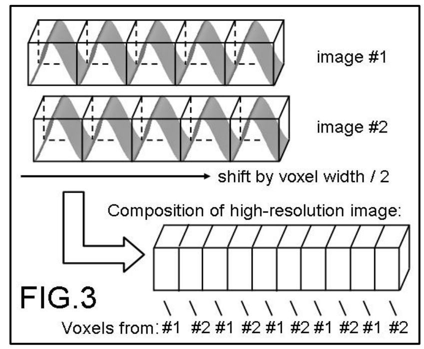


FIG.4. Single shot EPI images of the geometric phantom. Left: entire reference image. Middle: magnified inset (interpolated to 512x512). Right: SR image with 512 x 512 matrix (corresponds to 500 µm x 500 µm in-plane resolution).

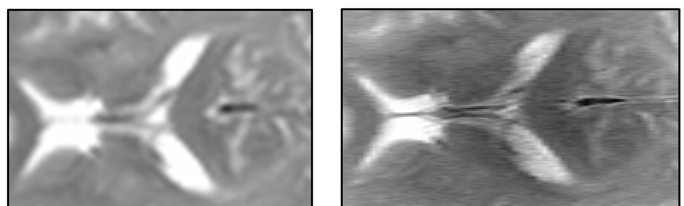


FIG.5. Single shot EPI at the level of the lateral ventricles. Left: reference image (matrix 128x128 interpolated to 512x128). Right: SR image as a result of four shifts in the LR direction (matrix 512x128).

Results:
The application of the SR method resulted in a significant improvement of the resolution compared to the reference image without SPAMM preparation. This could be demonstrated for both, phantom and in vivo measurements (Figure 4 and 5). The total measurement time scaled with the resolution improvement factor, i.e. the number of FOV shifts. The signal to noise ratio in the SR images was lowered by approximately 30% independent of the resolution improvement factor.

Discussion:
The proposed SR method can be combined with any pulse sequence and any image encoding technique including spiral and radial imaging. For instance, it allows to acquire single shot EPI images with a matrix of 512x512 or even higher which may be of high interest for high resolution DTI and fibre tracking. It is important to note, that the final image resolution is independent of the sampling bandwidth; therefore high resolution imaging with short echo times becomes feasible. Image fusion is done in the image domain, it is fast and simple, and does not need any reference scan or navigator such as segmented EPI. Deconvolution by the SPAMM profile is expected to further improve image quality. Alternatively, binomial pulses of higher order can be employed to produce a more rectangular modulation function.

References:
[1] Greenspan H. et al. Magn Reson Imaging 2002;20:437. [2] Peled S and Yeshurun Y. Magn Reson Med 2001;45:29. [3] Carmi E et al. Magn Reson Imaging 2006;24:133. [4] Scheffler K. Magn Reson Med 2002;48:408. [5] Axel L and Dougherty L. Radiology 1989;171:841.