Increasing Spoiling Efficiency in RF-Spoiled Gradient Echo Sequences by Averaging of Phase-Cycle Adapted k-Spaces

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Introduction RF-spoiled [1,2] gradient echo sequences (FLASH, SPGR, T1-FFE) set up a pseudo steady state of the voxel magnetization [3,4]. The integral over all isochromats (created by the spoiler gradient) in the voxel leads to elimination of ghost artefacts if the moment of the spoiler gradient is sufficiently high [5]. Here we show that the necessary moment of the spoiler gradient can be halved if two k-spaces with dedicated adaptation of the phase encoding gradients to the RF-pulse phase cycle are averaged. The reordering of the two k-spaces is performed such that the periodic nature of the PSS makes the sum of two integrals (each one covering one half of the necessary range of isochromats) equal to one integral that covers the full range of isochromats.

Theory The time table of the events in one cycle of a FLASH sequence is depicted in Fig. 1. Essential for RF-spoiling [1,2] is stepping the pulse phase φ_n with pulse number n according to $\varphi_n = n(n-1)\psi/2$, wherein ψ is the "spoiling increment" and is usually chosen to be 50° or 117° in order to give T1-contrast. Magnetization is built up that is 2π-periodic in the total precession angle θ which a certain isochromat accumulates during TR. After a number of sequence cycles the magnetization vectors (which depend on ψ) after the RF excitation follow the simple shift [3,4]

$$\mathbf{M}^+_{n+x}(\theta) = \mathbf{M}^+_n(\theta + x\psi) \quad (1)$$

for sequence cycles that are x cycles apart. This means, the integral $\int_{-\pi}^{\pi} \mathbf{M}^+_n(\theta)d\theta = \text{const.}$ (2)

is constant for all n, and a constant signal can be measured after each pulse [4]. The magnetization that follows Eqs. 1 and 2 is denoted as "pseudo steady state" (PSS). The range of isochromats from −π to π is set up by the spoiler gradient, its total moment m_{sp} is given by the range of isochromats existing in one voxel (i.e. $m_{sp} = 2\pi$ for the range from −π to π). The spoiler gradient is assumed to be switched in readout direction only, without loss of generality [5].

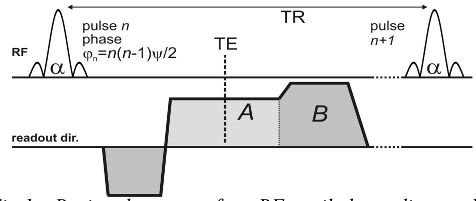

Fig.1: Basic elements of a RF-spoiled gradient echo sequence. Signal is acquired during gradient pulse A is switched, B is an additional spoiler gradient. Not depicted are gradients in slice and phase encoding direction.

Now, if $\psi = (K/P)*360°$, with integer K and P, then $\mathbf{M}_n^+(\theta)$ is periodic with period P, i.e. $\mathbf{M}^+_{n+P}(\theta) = \mathbf{M}_n^+(\theta)$. Thus, it is

$$\mathbf{M}^+_{n+P/2}(\theta) = \mathbf{M}^+_n(\theta + \pi) \quad (3)$$

Now we suppose to acquire two 2D k-spaces with a FLASH sequence and one continuous pulse train, each one with a number of phase encodes equal to $r*P/2$ (r is an odd integer), then $\mathbf{M}^+_{k2}(\theta) = \mathbf{M}^+_{k1}(\theta + \pi)$ (4)

holds; $k1$ and $k2$ are identical k values in phase encoding direction for the first and second k-space, respectively.

For both k-spaces we assume $m_{sp} = \pi$. Subsequent averaging of $k1$ and $k2$ leads now to

$$\int_{-\pi/2}^{\pi/2} \mathbf{M}^+_{k1}(\theta)d\theta + \int_{-\pi/2}^{\pi/2} \mathbf{M}^+_{k1}(\theta + \pi)d\theta = \int_{-\pi}^{\pi} \mathbf{M}^+_n(\theta)d\theta$$

(5)

Thus, averaging of the two k-spaces acquired in the described manner leads to sufficient spoiling even if the spoiler gradient sets up only half of the range of isochromats (indicated by the integral borders -π/2 to π/2) necessary to make the integral (2) constant, see Fig.2.

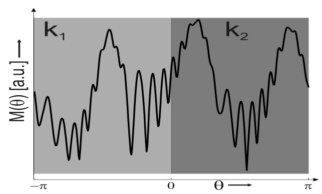

Fig.2: 2π-periodic magnetization for an arbitrary n and ψ=117°. If the spoiling moment is 2π, the voxel signal is an integration over the whole depicted profile, while for a spoiling moment of π two k-spaces are organized such that the averaging of the lines k1 (covering the light shaded area in one voxel) and k2 (covering the dark shaded area) results in a sum over the whole profile, too.

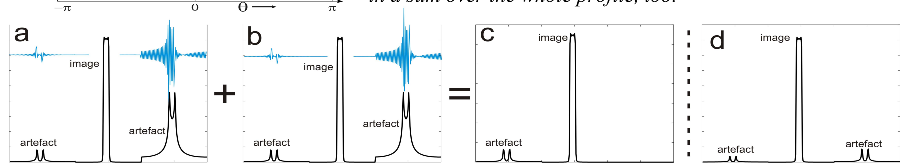

Fig.3: Simulation of image and artefacts from 2 k-spaces with $m_{sp}=\pi$ (a,b). Complex summation leads to c. A single acquisition with $m_{sp}=2\pi$ is shown in d. Black lines: magnitude, blue lines: real part of the two artefacts.

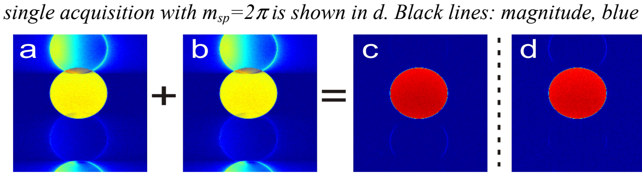

Fig.4: Phantom experiments. a,b: two images with $m_{sp}=\pi$. Summation leads to c. d: Single acquisition with $m_{sp}=2\pi$. Magnitude is depicted, but sum is complex.

Method Simulations and Experiments were performed in order to confirm the "spoiling amplification" of the averaging method described in "Theory".

1. Simulations: Imaging with the FLASH sequence (Fig.1) of a 1D object covering 9 voxels in readout direction was simulated. Thus, every signal appearing in the image in phase encoding direction is an artefact. The spoiling increment was $\psi=117°$, i.e. P=40. Two k-spaces covering six periods of the magnetization cycle (giving 240 phase encodes) and with $m_{sp} = \pi$ were simulated and are shifted by P/2=20 periods against each other, thus fulfilling Eq. 5 after averaging. Other parameters used for simulation (also for Fig.2): T1=T2=150ms, flip angle = 20°, TR/TE=10ms/5ms, 100 readout sample points, 240 lines.

2. Experiments: A cylinder phantom (diameter=9cm) containing Gd-doped water was imaged on a 1.5T system with a 2D FLASH sequence. A number of dummy cycles were traversed to establish the PSS. Two k-spaces were acquired, the necessary shift of the second k-space by 20 pulses was simply established by a difference in the number of dummy cycles, these were 200 cycles for k-space one and 220 cycles for k-space two. Both k-spaces were averaged before the final image was reconstructed. Parameters: T1=T2=150ms, flip angle = 25°, TR/TE=10ms/2.29ms, 512 readout sample points, 240 lines.

Results Simulation results are shown in Fig. 3. Figs. 3a and 3b show selected lines of both magnitude images: The 1D image and two artefacts. The real part of the artefacts is shown in blue as well. Complex averaging of them lead to the final image 3c. The elimination of the main artefact is obvious. For comparison, a single image with with $m_{sp} = 2\pi$ is shown in Fig. 3d. Results of the experiments are shown in Fig. 4. Magnitude images of the individual acquisitions are shown (4a and 4b), which lead to image 4c after averaging. Fig. 4d is a single image with with $m_{sp} = 2\pi$.

Discussion By means of the described averaging of P/2-shifted k-spaces, the moment of the spoiler gradient can be reduced by a factor of two in comparison with a common FLASH acquisition. This is beneficial to gradient duty cycle and shortens potential dead times. In its plain form, the acquisition of two k-spaces doubles total acquisition time - which can be reduced by parallel imaging, though. Besides, the method is promising for applications making averaging anyway necessary due to low SNR, e.g. imaging at very low field systems. Motion sensitivity of the method has still to be examined. From Figs. 3 and 4 it is obvious that not all artefacts are reduced by the described method. Especially artefacts from image edges remain. However, they originate from signal oscillations at time points during readout for which Eq. 2 is not valid [5], and they are also visible in acquisitions with $m_{sp} = 2\pi$. A means of further artefact reduction would be resorting of the k-space (and not only a shift as presented) such that the oscillations are more benign in terms of artefact behaviour, either for a single k-space acquisition or for an averaging procedure as presented. This approach is currently under verification in our group.

References [1]Zur et al. Proc. SMRM 1987,p.440 [2]Zur et al. MRM 1991,21:251-263 [3]Crawley et al. MRM 1988,8:248-260 [4]Denolin et al. MRM 2005,54:937-954 [5]Leupold et al. MRM 2008,60:119-127