On the spoiler gradient in RF-spoiled gradient echo sequences

J. Leupold[1], J. Hennig[1], and K. Scheffler[2]

[1]University Hospital Freiburg, Dept. of Diagnostic Radiology, Medical Physics, Freiburg, Germany, [2]MR Physics, Department of Medical Radiology, University Hospital of Basel, Basel, Switzerland

Introduction RF-spoiled gradient Echo sequences (FLASH, SPGR, T1-FFE) are widely used in clinical MRI. However, the theoretical description of the measured signal is not trivial, as a pseudo steady state (PSS) according to [1] is built up. We demonstrate that the occurrence of ghost artifacts [2] is a direct consequence of the existence of the PSS, and that there is no rigid rule for the needed moment of the spoiler gradient of an RF spoiled gradient echo sequence.

Theory The time table of the events in one cycle of a FLASH sequence is depicted in Fig. 1. Essential for RF-spoiling [3,4] is stepping the pulse phase with pulse Number *n* according to

$$\varphi_n = n(n-1)\psi / 2 , \quad (1)$$

wherein ψ is the "spoiling increment" and is usually chosen to be 50° or 117°. A 2π–periodic pseudo steady state of the magnetisation is built up after a number of sequence cycles such that the magnetisation vectors (which depend on ψ) after the RF excitation follow the simple shift

$$\mathbf{M}_{n+1}^{+}(\theta) = \mathbf{M}_{n}^{+}(\theta + \psi) \qquad (2)$$

for consecutive sequence cycles, with θ being the total precession angle a certain isochromat accumulates during TR. This means, the integral

$$\int_{-\pi}^{\pi} \mathbf{M}_{n}^{+}(\theta) d\theta \qquad (3)$$

is constant for all *n*, and a constant signal can be measured after each pulse [1]. Also mandatory for the FLASH sequence is a spoiler gradient switched in one or more encoding directions, such that it sets up a distribution of phase angles θ within one voxel according to its spoiling moment m_{sp} with

$$-m_{sp} / 2 \le \theta \le m_{sp} / 2 . \qquad (4)$$

For simplicity, we assume the spoiler gradient being switched in readout direction. With m_{sp}=2π and homogenous voxel filling, Eq. 3 reflects the voxel signal. The description up to this point is well known and the composition of the pseudo steady state is analysed in several publications [1,3-8]. However, to our knowledge, the evolution of the PSS under the intrinsically unavoidable readout gradient has not yet been described. The voxel signal under the influence of the readout gradient B after applying the prephasing gradient A (see Fig 1.) is written as

$$s_n(t) = \int_{-\pi}^{\pi} \mathrm{M}_{n}^{+}(\theta) \exp(i\theta t) \mathrm{d}\theta \text{ , with } t \in [-1/2, 1/2] . \qquad (5)$$

For $t = 0$ (reached at echo time TE) the steady state integral (Eq. 3) is obtained, while for any other *t* no simple connection between $s_n(t)$ and $s_{n+1}(t)$ exists. This translates into signal oscillations for the voxel signal along n-direction in k-space, which result in ghost artifacts in the image. These oscillations occur despite a distribution of the phase angles θ over 2π, which is usually assumed to be the necessary moment of the spoiler gradient.

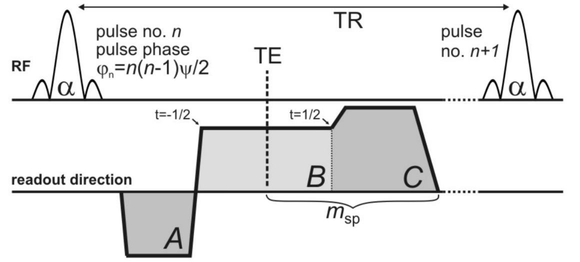

Figure 1: Events in a FLASH sequence. A - readout prephasing gradient. B - readout gradient. C - spoiler gradient. The spoiling moment m_{sp} results from the spoiler gradient and the unbalanced part of the readout gradient. Gradients in slice direction and phase encoding direction are not depicted.

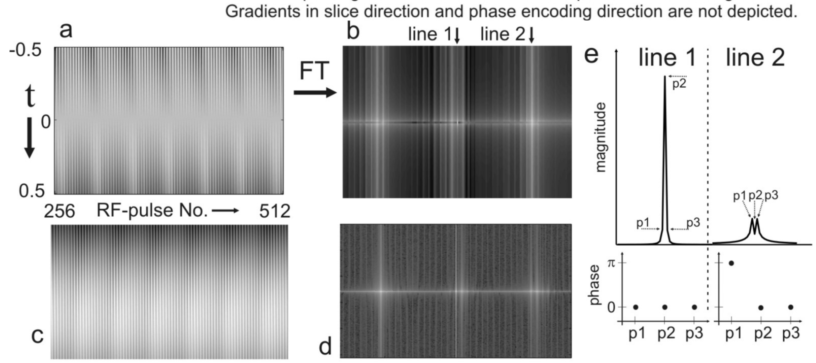

Figure 2: k-space (a,c) and image w/o phase encoding in logarithmic scaling (b,d) of a one voxel object in simulation (a,b) and experiment (c,d). Clearly visible are the k-space oscillations and the artifacts in the image. e) intensity and phase of two selected lines from the simulated image from b).

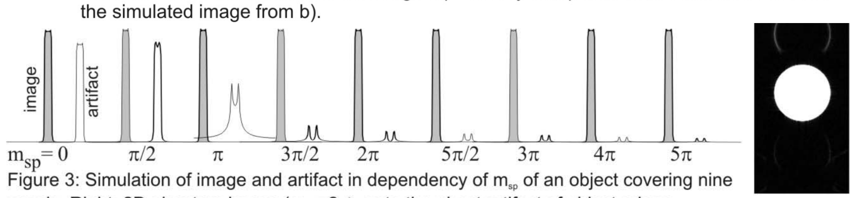

Figure 3: Simulation of image and artifact in dependency of m_{sp} of an object covering nine voxels. Right: 2D phantom image (m_{sp}=2π), note the ghost artifact of object edges.

Method Simulations and experiments were performed to examine the predicted signal oscillations and the resulting ghost artifacts (Parameters for simulation and experiment: ψ=117°, TR/TE=10ms/5ms, flip angle = 20°, matrix 256*256, 256 dummy cycles to reach the PSS, T1=T2=150ms. Slice thickness was 10mm for the 2D experiment, Phantom T1=T2=150ms). Signal simulations of 1D objects extending over a selectable number of voxel were performed with selectable strength of the spoiler gradient. Phase encoding (PE) was not simulated, so each k-space line gives a projection of the object. Thus, every signal that appears in the image perpendicular to the read direction is an artifact. 2D Experiments were performed with selectable spoiling moment on phantoms without and with PE and on the head of a volunteer (with PE).

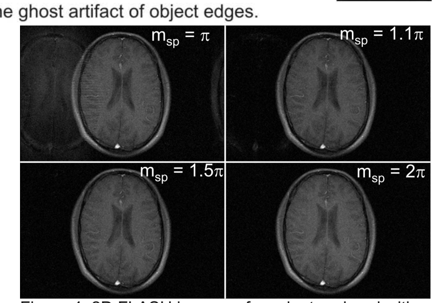

Figure 4: 2D FLASH images of a volunteer head with different spoiling moments m_{sp}.

Results Fig. 2 shows simulation and experiments of a one voxel object, based on a 2D FLASH sequence without PE and m_{sp} = 2π. Signal oscillations are obvious in the k-spaces in 2a and 2c, which translate into artifacts in the images 2b and 2d. Note there would be only a single point in the centre of the image if artifacts were absent. The voxel size in the experiment was 59 mm, which is the height of the examined cylinder phantom. Fig. 2e shows selected lines from 2b, line 1 is the image and line 2 a ghost artifact. Note the phase jump between p1 and p2 for line 2. Fig. 3 shows a simulation of an object covering nine voxels, with ghost artifacts of the edges and the decrease of the ghost intensity with the spoiling moment. The intensity of the image remains independent of the spoiling moment. On the right in Fig. 3, a 2D phantom image with PE and m_{sp}=2π is presented, where the edge artifact is obvious. Fig. 4 shows 2D images of a volunteer head with varying spoiling moment. The ghost disappears nearly completely with m_{sp}=1.5π.

Discussion Ghost artifacts appear in RF-spoiled gradient echo images even if the spoiling moment is exactly 2π. The origin of this phenomenon has not yet been properly described. The presented work demonstrates that the origin of this phenomenon lies in the signal oscillations that result from the fact that there is no steady state integral when the voxel magnetisation underlies a phase factor from the readout gradient. Consequently, there is no certain value which minimum spoiling moment has to be chosen for efficient artifact suppression. The ghost artifact shows enhancement of edges, which can be understood as the ghost artifact from a single voxel extends over more than one voxel and shows a phase that leads to cancellation of ghosts from adjacent voxels. This cancellation is incomplete at image edges. The artifacts can be damped down by increasing the spoiling moment and switching the spoiler gradient in slice direction as well, as shown in [2].

References: [1]Denolin et al. MRM 2005,54:937-954 [2]Mugler III, Proc. ISMRM 1994,p.486 [3]Zur et al. Proc. SMRM 1987,p.440 [4]Zur et al. MRM 1991,21:251-263 [5]Crawley et al. MRM 1988,8:248-260 [6]Sobol and Gauntt, JMRI 1996,6:384-398 [7]Duyn MRM 1997,37;559-568 [8]Ganter, MRM 2006, 55:98-107