Analogy of Motion-Induced Phase in Diffusion-Weighted Steady-State Free Precession MRI with RF Spoiling

Rafael O'Halloran[1], and Roland Bammer[1]

[1]*Radiology, Stanford University, Stanford, CA, United States*

INTRODUCTION –

Diffusion-weighted steady state free precession (SSFP) imaging has received attention recently as a potential technique to enable high-resolution 3D DWI and DTI [1,2,3]. However, these techniques require many shots to cover k-space. Combining data from multiple shots to form an image leads to artifactual signal dropout because of "random", motion-induced phase that is different for each shot. Specifically, the spin phase at each point in space changes in an unpredictable fashion relative to the B_1^+ phase, which leads to the loss of essential coherences. This in turn leads to considerable signal loss, especially in regions where there are pronounced phase changes over time, such as for example in the midbrain or around the fourth ventricle. A simple and intuitive way to understand this phenomenon is by analogy to RF spoiling, in which random phase is imposed on the transverse magnetization by changing the phase of the RF excitation pulse.

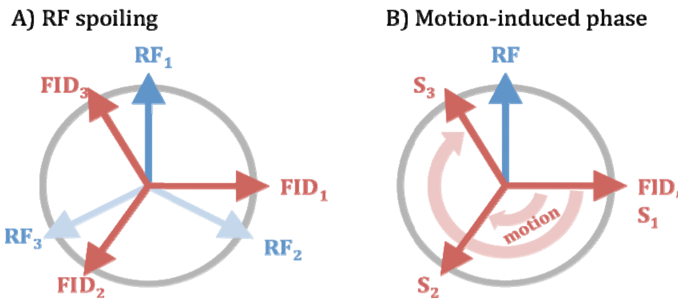

Fig. 1 – RF spoiling (a) compared to motion-induced phase (b). The position of each arrow on the circle represents the phase of the RF pulse (Blue arrows) relative to the transverse magnetization that leads to the refocused signal, FID's and S_n (red arrows).

THEORY –

RF Spoiling: RF spoiling is a way to eliminate unwanted coherences by changing the RF phase each TR. A common spoiling scheme is to linearly increment the RF phase ϕ_{RF} every shot. So for the i[th] shot the phase is:

$$\phi_{RF}(i) = \phi_{RF}(i-1) + \varphi_{spoil}, \quad [1]$$

where $\varphi_{spoil} \approx 117°$ is a typical value for the spoiling angle. This is, essentially, a simple way to generate a pseudo-random phase similar to the golden-angle ordering scheme used in some radial imaging [4] by using the spoiling angle $\varphi_{spoil} \approx 111°$. So RF spoiling can be viewed as a way to pseudo-randomize the phase of signal coherences, to disperse them around the transverse plane.

Motion-induced Phase: Motion during the diffusion gradients, G, induces a phase in the image according to [5]:

$$\phi_{motion} = \gamma \int \vec{G} \cdot \vec{r} dt, \quad [2]$$

where r is the position of the spin. The majority of this phase comes from two sources: (1) rigid head motion and (2) elastic deformation of the brain induced through varying arterial pressure over the cardiac cycle. These phase errors appear to be random when imaging is asynchronous with the heartbeat and the motion is fast relative to TR.

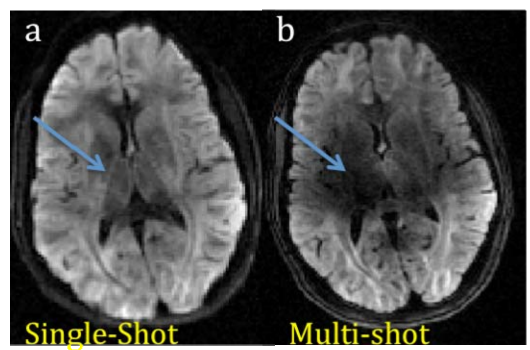

Fig. 2 – The single-shot EPI image (a) compared to the multi-shot SSFP image (b) showing the signal dropout caused by the motion-induced phase error.

Spoiling vs. Motion: Figure 1 demonstrates the analogy pictorially. The first 3 RF pulses in a spoiled RF scheme are shown (Fig 1a, blue arrows) with their respective FID signal phases (Fig 1a, red arrows). The phases of the FID signals are distributed homogeneously around the circle, providing effective spoiling. In the case of motion, even though the initial FID is in the same location for each shot, motion (see Eq [2]) will cause the transverse magnetization to acquire phase (Fig 1b, light red arrows). If this motion is random, then over many TRs the phases of the generated coherence pathways will become distributed homogeneously around the circle (Fig 2b, red arrows). Consequently, the transverse magnetization relative to the RF pulse has a similar configuration to that of RF spoiling even though the RF pulse has the same phase for every shot, **After many RF pulses, in both cases (Fig 1 a and b), the RF pulses "see" previous coherence pathways with phases that are homogeneously dispersed around the transverse plane, causing destructive interference or spoiling.**

EXAMPLE –

To illustrate the RF-spoiling-like effect of motion-induced phase cancelation, a single slice of a single-shot spin echo EPI DW scan is shown (Fig 2a) next to a slice of a 3D DW-SSFP sequence (Fig 2b). The blue arrows indicate a region near the ventricles that experiences a high amount of pulsatile motion. The pulsing causes motion that results in signal loss in the multi-shot DW-SSFP image. The signal loss is like a local RF-spoiling where the phases are random from shot to shot and therefore cancel each other out. Because the EPI scan (Fig 2a) was performed in a single shot, the phase in the image is consistent for the acquired k-space and does not cause cancelation of the signal. While a fraction of the signal lost in the SSFP image (Fig 2b, blue arrow) is recoverable by clever reconstruction [2], some is lost irrecoverably due to destructive interference. This irrecoverable signal loss, causes to main problems: **1) loss of the magnitude** of the signal, **2) loss of diffusion contras**t due to longer lived heavily diffusion weighted pathways being destroyed.

CONCLUSIONS and DISSCUSSION –

In this work the analogy of RF spoiling to motion-induced phase errors is presented. The phase cancelation due to motion in DW-SSFP is a problem that must be addressed if these rapid sequences are to be adopted into clinical use. This analogy may be useful for those designing ways to overcome these challenges to take advantage of the potential benefits of the DW-SSFP sequence for efficient 3D DWI.

REFERENCES – [1] Jung et al JMRI 2009 [2] Mcnab et al. MRM 2010. [3] O'Halloran et al. ISMRM 2011. [4] Winklemann et al. IEEE Trans Med Imag 2007. [5] Anderson and Gore MRM 1994.

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