K-Space Analysis and Correction of a Coherence-induced Artifact in 3D Fast-Large-Angle Spin Echo (FLASE)

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INTRODUCTION

High-resolution imaging of trabecular bone aimed at analyzing the bone's microarchitecture is preferably performed with spin-echo-type pulse sequences. Unlike gradient-echo sequences, the former are immune to artifactual broadening of trabeculae caused by local static field gradients near the bone-bone marrow interface and signal loss from chemical shift dephasing at k-space center. 3D FLASE [1], shown in Fig.1a) is a large-flip-angle, steady-state, spin-echo sequence with a short TR (T_R=80ms) that is particularly well suited for this purpose. To minimize the echo time a fractional echo is acquired. However, as a consequence of the refocusing pulse imperfection, the previously practiced 3D FLASE pulse sequence was found to be prone to a banding artifact in both the readout (*x*) and slice (*z*) direction. The imperfect refocusing pulse of flip angle $180^o+\Delta\phi$, stores a fraction of the phase-encoded transverse magnetization as longitudinal magnetization that recurs as transverse magnetization in the subsequent pulse sequence cycle, forming a spurious echo. Here we provide a k-space analysis of the artifact and show how to remedy the problem.

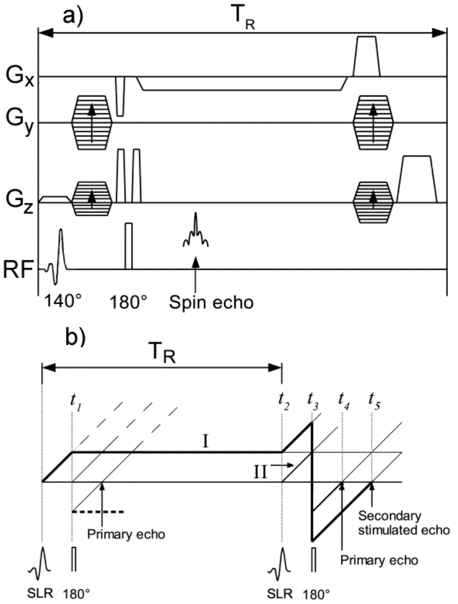

Fig.1 a) Diagram of the 3D FLASE sequence.
b) Phase diagram corresponding to the 3D FLASE sequence. The coherence pathway marked by I produces an artifactual echo. The main echo is formed by coherence pathway II.

THEORY AND METHODS

While the imperfections of the refocusing pulse are generally small, they can produce noticeable artifacts, caused by a portion of the transverse magnetization that is phase-encoded before the refocusing pulse, being converted to longitudinal magnetization. Because of the short repetition time relative to the longitudinal relaxation time (T_1 =300ms in fatty bone marrow), the longitudinal magnetization created in this manner, has not significantly decayed by the end of the repetition period and is rotated back into the transverse plane by the excitation pulse of the subsequent pulse sequence cycle. It is then again phase encoded and refocused by the refocusing pulse at time $T_E/2$ after the main echo. This unwanted and phase encoded echo is the source of the described banding artifact.

The magnitude of the artifactual echo can be calculated [2] by following the magnetization in coherence pathway I (Fig. 1b). It is noted that the gradients are only balanced if one considers all zeroth moments within a T_R period which is not the case in the periods between the excitation and the refocusing pulse. However, since the consequences of this effect are of higher order than the one presently considered we shall assume that the difference in the initial longitudinal magnetization for two adjacent repetitions is negligible. Under these assumptions it can be shown that the magnetization following coherence pathway I (Fig. 1b) produces the artifactual echo with an amplitude of $\varepsilon=0.2151|\sin(\Delta\phi)|$ relative to the amplitude of the main echo produced by coherence pathway II. The artifactual magnetization experiences the phase encoding and dephasing gradients twice. It is also phase encoded by Δk_z along the slice direction by the crusher gradient applied before time t_1 (Fig. 1b)). This phase is not unwound by the trailing crusher gradient since the artifactual magnetization is longitudinal while this gradient is played out. Taking these factors into account the artifactual signal, $s_A(k_x, k_y, k_z)$, can be expressed as $s_A(k_x, k_y, k_z)=\varepsilon s(k_x+k_{PRE}, 2k_y, 2k_z+\Delta k_z)$, where k_{PRE} is the partial readout dephasing and $s(k_x, k_y, k_z)$ is the signal of the primary echo. The magnitude image obtained from the total signal, $s_{TOTAL}=s+s_A$, is then $|\rho_{TOTAL}(x,y,z)|=[\rho^2(x,y,z)+2\varepsilon\cos(k_{PRE}x-(\Delta k_z z)/2)\rho(x,y/2,z/2)+\varepsilon\rho^2(x,y/2,z/2)]^{1/2}$. The first term represents the uncorrupted image, the second term produces the banding artifact in the readout and slice directions while the last term produces a higher order effect usually not observable in clinical scans. The expression for s_{TOTAL} was used to produce synthetic images of a cylindrical phantom that were found to be in good agreement with scans of a physical cylindrical phantom. A comparison is shown on Fig. 2.

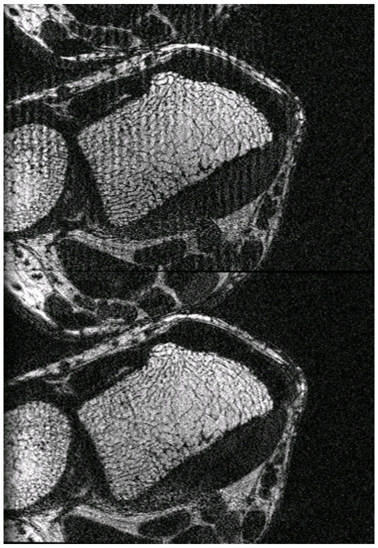

Fig. 3 a) image obtained using the 3D FLASE sequence with an imperfect refocusing pulse produced by intentionally misadjusting the rf transmitter gain; b) image acquired using the proposed modification of the 3D FLASE with the same transmitter gain.

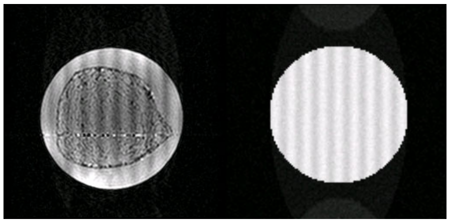

Fig 2. On the left is a phantom scan with pronounced banding . On the right is a synthetic image generated using the expression for s_{TOTAL} given in the text.

RESULTS AND DISCUSSION

We propose a modification of the 3D FLASE sequence in which all phase encodings are placed after the refocusing pulse, thus eliminating the phase encoding of the spurious magnetization that occurs before the first refocusing pulse. In this case the spurious magnetization is phase encoded only once, after having been exposed to the second refocusing pulse. Since the magnetizations giving rise to the main and artifactual echo artifact experience the same applied gradients, the resulting gradient echoes coincide. Placement of all phase encodings after the refocusing pulse also allows the spins to reach true steady state since all gradients between *every two rf pulses* are now rewound.

We have implemented a variant of this sequence in which only the readout dephasing is played out after the refocusing pulse in order to keep T_E short. In this case the artifactual magnetization is phase encoded as before but acquires phase from the readout gradient only after time t_3 in Fig.1b). This phase accrued by the artifactual magnetization, stemming from the readout gradient, is rewound coincident with the spin and gradient echo of the main signal at t_4 (the artifactual and main **gradient** echo coincide). This completely removes the banding in the readout direction. Even though there is still some artifactual signal left, displaced by Δk_z along k_z, the banding in the slice direction is negligible for the following reason. Since background gradients produced by field inhomogeneites are **always** present, the artifactual magnetization acquires unwanted phase from $t=0$ to t_1 and from t_2 to t_4. This phase is nulled at t_5, the time of the **stimulated** echo, $T_E/2$ **later than the gradient echo**. For the artifactual magnetization the T_2* dephasing is thus not reversed at time t_4 and the amplitude of the artifactual signal so dimished that it is effectively removed. Figure 3. shows a comparison between the original 3D FLASE and the just described variant.

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[2] Hennig J. Concepts in Magnetic Resonance. 1991; 3:125-143.