Improved Accuracy in T₁ mapping and Flip Angle Correction with Random Spoiling in Radial Gradient Echo Imaging

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Introduction

Due to its high imaging speed and SNR efficiency, spoiled gradient echo imaging plays an important role in many quantitative MR methods. For example, a variable flip angle (VFA) method [1] is now widely used for in vivo T₁ mapping due to its time efficiency and large 3D anatomical coverage. Recently, an actual flip-angle imaging (AFI) technique [2], which utilizes two interleaved spoiled gradient echo acquisitions with different TRs, has been proposed for rapid mapping of transmitted radiofrequency field B₁. B₁ mapping has become increasingly important due to the growing availability of high-field clinical and research scanners operating at 3T and higher.

Critical to the accuracy of these quantitative methods based on spoiled gradient echo imaging is the complete spoiling of the transverse magnetization at the end of each TR. However, it was recently recognized that conventional RF spoiling yields non-ideal steady state signal intensities, particularly at larger flip angles and T₁/TR ratios, leading to significant quantification errors [3-4]. The purpose of this work is to propose an alternative spoiling scheme based on random gradient moment and RF phase, and to compare the performance of the proposed spoiling scheme with conventional RF spoiling for T₁ mapping and flip angle correction.

Theory

In conventional RF spoiling, the RF phase is often set to be a quadratic function of TR number. A constant gradient moment is also applied at the end of each TR period to create a range of resonance offset angles within each imaging voxel. This scheme leads to a steady state that is generally different from the ideal spoiling condition (Fig. 1a). In the proposed random spoiling scheme, both the RF phase and the gradient moments at the end of each TR are randomized (with intra-voxel phase dispersion in the range of [20π, 40π]). Although this leads to slight TR-to-TR variations of the signal in each voxel, the average voxel signal intensity matches the ideally spoiled condition at a wide range of T₁/TR ratios and flip-angles (Fig. 1b). As the signal variations can cause ghosting artifacts in conventional Cartesian imaging, radial acquisition could be utilized to suppress these artifacts, taking advantage of the averaging effect of oversampling in central k-space. It was found that using either random RF phase or random gradient moment alone results in higher deviation of the average signal from ideal levels.

Methods

Phantom experiments were conducted on a 1.5T Siemens (Erlangen, Germany) MR scanner to evaluate T₁ and B₁ mapping performance of conventional RF spoiling and the proposed random spoiling methods, using a 3D gradient echo (FLASH) sequence modified to acquire radial data in the k₁-k₂ plane. For the first experiment, a phantom consisting of six tubes with the following gadolinium concentrations was constructed: 3.0, 1.5, 1.0, 0.5, 0.3 mM (T₁ ranging between 80-800 ms). Radial images were acquired with the following flip angles: α = 3°, 10°, 20° and 40°. The signal intensity S was then fitted to the following equation to determine the T₁'s: S/α = S₀/tan α + M₀/(1- e⁻¹). Where M₀ is the equilibrium magnetization and the E₀ = exp(-TR/T₁). The true T₁ values were determined with a separate set of inversion recovery measurements (TR = 3s; TI = 0, 23, 60, 100, 150, 200, 350, 500, 800, 1200 ms). The signal intensity S was determined from a separate set of inversion recovery measurements (TR = 3s; TI = 0, 23, 60, 100, 150, 200, 350, 500, 800, 1200 ms).

A second experiment was performed on a larger phantom (~56 cm in length) to demonstrate the effectiveness of our strategy in the presence of large B₁ variations. The T₁ mapping procedure was the same as the previous experiment, while the flip angle mapping procedure was carried out using the AFI technique (2). In AFI, two interleaved TRs (TR₁ and TR₂) with the same flip angle are used to establish an alternating steady state. It was shown that when TR₂<TR₁<TR₁, the signal ratio of two interleaved acquisition r = S₁/S₀ becomes independent of T₁, and the actual flip angle can be determined from this ratio as: α = arccos[(m-n) / (n-r)], where n = TR₁/TR₂. In our experiment, n = 4 and flip angle α=60°. A calibration factor was then computed as the ratio of the true flip angle α to the prescribed flip angle. This calibration factor was subsequently used to adjust the flip angle α used in the T₁ fitting.

Results and Discussions

Figure 2 shows the T₁ mapping results from the gadolinium phantom. While the T₁ measurement error values were consistently less than 3% with the proposed random spoiling scheme, it increases up to 15.7% for the tube with a small T₁ (~80 ms) with conventional RF spoiling. For the larger phantom, inhomogeneous B₁ fields near both ends of the phantom causes large T₁ errors when no flip angle correction is applied (Fig. 3a). When the AFI flip angle correction was performed with conventional RF spoiling, there is still significant residual T₁ variations within the homogeneous phantom due to suboptimal spoiling (Fig. 3b). In particular, the edge of the phantom shows significantly underestimated T₁ values. When AFI correction was performed with random spoiling (Fig. 3c), the resulting T₁ map becomes homogeneous throughout the phantom, including the edges. Comparison of the T₁ profile (Fig. 3d) confirms the superior performance of the random spoiling over conventional RF spoiling, in achieving flip angle correction and accurate T₁ mapping.

In conclusion, the proposed random spoiling scheme achieved more accurate T₁ measurement and flip angle correction than conventional RF spoiling. A significant advantage where the proposed technique may be particularly useful is in dynamic contrast enhanced imaging applications where T₁ maps are required to compute tissue perfusion while the use of undersampled radial imaging may be beneficial to enhance temporal resolution [5].