Efficient and Accurate Bloch-based Simulation of Intra-voxel Dephasing using Multiple Isochomats and Magnetization Spatial Gradients

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Introduction: Bloch simulation is crucial in numerous aspects of MRI research, including designing pulse sequences, validating quantitative measurement techniques (e.g. for $T_1/T_2/B_1$+ mapping), and understanding MR artifacts. Recent developments in Bloch simulation based on realistic electromagnetic field distributions and human tissue models have enabled Bloch solvers to act as full MRI system simulators [1, 2]. Accurate simulation of MR phenomena due to intra-voxel dephasing is essential for many common MR applications such as spin echo imaging, stimulated echo imaging, high resolution imaging, and gradient spoiling schemes. Because the commonly-available models of human anatomy are generally limited in voxel resolution, careful utilization of the principles of Bloch simulation for optimal computational efficiency and accuracy is required. Here, we describe previously published methods before presenting our improved method for accurately simulating intra-voxel dephasing, with comparisons of this method to existing methods as validation.

Theory: A straightforward method for Bloch simulation based on a given input model is to assign one magnetization vector for each input model voxel, apply three dimensional vector rotation about the effective applied magnetic field through time, B_{eff} (considering B_0 inhomgeneities, B_1, and gradient fields), allow relaxation due to T_1 and T_2, and sum the total magnetization vectors at ADC events weighted appropriately by coil receptivity distributions. In order to simulate accurate intra-voxel dephasing, at least three methods have been presented previously: Method 1 (Isochromat Summation, IS) numerical methods populating the input model voxel with numerous isochromats (magnetization vectors) and thus effectively increasing the model resolution [3], Method 2 (Magnetization Spatial Gradients, MSG) analytical [4] or Method 3 numerical [5] methods keeping track of the low order intra-voxel dephasing pattern (first order approximation of the input model voxel based on the magnetization vector it is assigned). Although each of these methods was validated in specific cases for accuracy, they each have certain limitations. Method 1 is the most accurate if a large number of isochromats per voxel (N) are used. However, it also requires computational time and memory proportional to N^3. In comparison, Method 3 also requires similar trend of computation resources although it usually requires N = 4. Because Method 3 not only uses the magnetization vectors to calculate zeroth order MR signal, but also keeps track of the first order intra-voxel dephasing pattern, it is demonstrated to be more accurate than Method 1 with N = 4. On the other hand, because Method 2 also keeps track of the first order intra-voxel dephasing pattern (though using an analytical approach), it should act equally well as Method 3 in most cases while requiring ¼ of computational resources. Although it is possible to keep track of higher order (>1) intra-voxel dephasing patterns with Method 2 to achieve a better approximation based on one magnetization vector for each model voxel, it is expected that such higher order approximations will require greater computational resources compared with the existing first order approximation. Furthermore, these approximations will be limited in accuracy due to the limited number of isochromats available from each model voxel. We therefore propose that a combination of Method 1 and Method 2 (a hybrid numerical method that aims at both increasing the effective input model voxel resolution as well as calculating analytical first order magnetization spatial gradients) should perform efficiently and accurately with a reasonable number of isochromats per voxel to simulate intra-voxel dephasing.

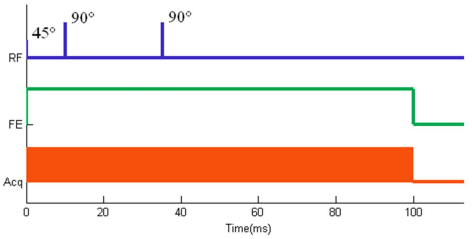

FIG. 1. The pulse sequence used to simulate the stimulated FID.

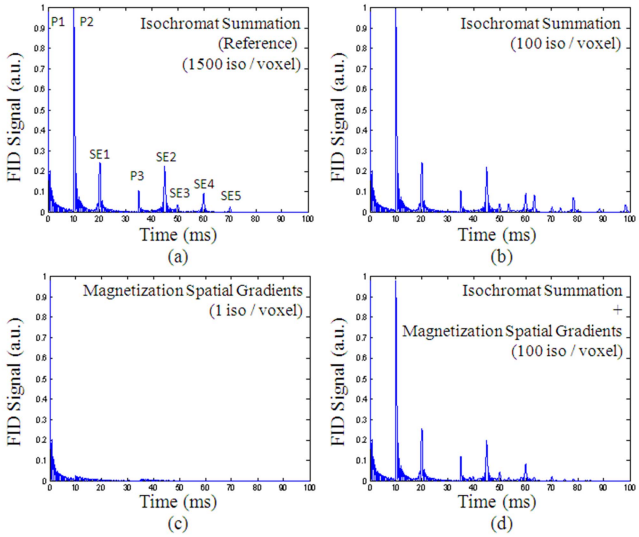

FIG. 2. Simulated stimulated echo FID with different signal calculation methods.

Method: In order to validate the proposed method for intra-voxel dephasing, two different studies were performed. In the first study, four different Bloch simulation strategies were compared with the same sequence (Fig.1) for stimulated echo free induction decay (FID) from a single input model voxel (T_1 = 291 ms, T_2 = 30 ms). Such a sequence contains three RF pulses (45° – 90° – 90°) and a constant frequency encoding gradient as a linear ΔB_0 distribution across the voxel. Five stimulated echoes are expected at 20 ms, 45 ms, 50 ms, 60 ms, and 70 ms. Four scenarios were compared: 1) Method 1 with 1500 isochromats per voxel as gold standard, 2) Method 1 with 100 isochromats per voxel, 3) Method 2, and 4) Proposed hybrid method of 1 and 2 with 100 isochromats per voxel. In the second study, a human digital phantom with its realistic ΔB_0 distribution was used to simulate proton density weighted image due to a spin echo sequence with crusher gradients straddled before and after the slice-selective 180° refocusing pulse. Both studies were performed with our own MR system simulator package [2].

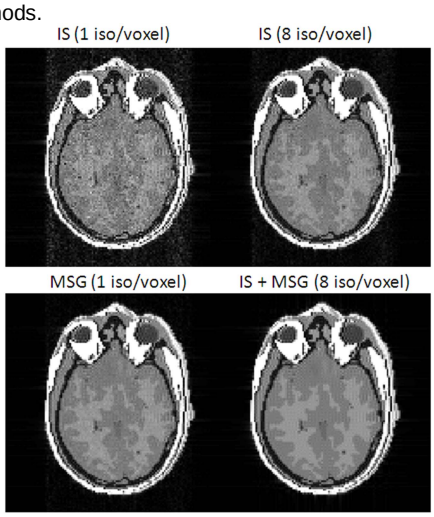

FIG. 3. Spin echo images simulated by various methods. The proposed combination of Isochromat Summation (IS) and tracking Magnetization Spatial Gradients (MSG) is more capable of simulating accurate dephasing due to crusher gradients than either method alone.

Results and Discussions: The results for validating the accuracy and efficiency of the proposed method comparing with Method 1 and Method 2 are shown in Fig. 2 and Fig. 3. With large number of isochromats (Fig.2(a)), Method 1 was capable of generating accurate stimulated echoes (SE1~5) as expected. With less than adequate number of isochromats (Fig.2(b)), erroneous spurious echoes showed up in the FID. Method 2 (Fig.2(c)) alone also generated a problematic FID under the same scenario. In comparison, with similar computational resources and time, the proposed method requiring 0.6 seconds (Fig.2(d)) generated more accurate MR signal than Method 1 with the same number of isochromats per voxel, which required 0.5 seconds (Fig.2(b)). The proposed method was also further validated by simulating a spin echo sequence. The combination of multiple isochromats per voxel and magnetization spatial gradients is better able to remove the common artifacts due to inaccurate intra-voxel dephasing in simulation of crusher gradients compared to either method alone (Fig. 3).

References: **[1]** Stöcker *et al*., MRM 2010; 64:186–193. **[2]** Cao *et al*., ISMRM 2010, p2842. **[3]** Kwan *et al*., IEEE Trans. Med. Imag. 1999; 18: 1085–1097. **[4]** Jochimsen *et al*., JMR 2006; 180: 29–38. **[5]** Latta *et al*., JMR 2010; 203: 44–51.

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