Effects of relaxation during RF pulses on the homogeneity of signal intensity in parallel transmission

M. Sekino[1,2], N. Boulant[1], M. Luong[3], A. Amadon[1], H. Ohsaki[2], and D. Le Bihan[1]

[1]CEA, DSV, I2BM, NeuroSpin, Gif-sur-Yvette, France, [2]Graduate School of Frontier Sciences, The University of Tokyo, Kashiwa, Japan, [3]CEA, Irfu, SACM, Gif-sur-Yvette, France

Introduction: Counteracting the inhomogeneity of the RF excitation is one of the technical challenges in high-field MRI. Dynamic RF shimming techniques in combination with parallel transmission have shown to be quite powerful for mitigating B_1 inhomogeneity [1, 2]. So far to our knowledge, these methods have been uniquely based on the spins' coherent dynamics, and do not account for relaxation during the RF pulses. Because the pulse duration can be on the order of a few milliseconds, relaxation can in fact lead to a degradation of signal uniformity via an alteration of the flip angle (FA) distribution but also via a non-uniform attenuation of the magnetization vector. For short T_2, large T_1 and short TR sequences, these effects should be assessed. The key is to realize that one to some percent attenuation of the magnetization vector can be comparable to $E_1=\exp(-TR/T_1)$ and can therefore have drastic effects on the measured signal intensity and homogeneity. In this study, we numerically investigate at 7 T the degradation of the spoiled gradient echo (SPGE) signal homogeneity when designing a transmit-SENSE pulse aimed at homogenizing only the FA over an axial slice of a human head. Although the final uniformity may still be very good, we show that the signal inhomogeneity can sometimes deteriorate by a factor of 10 because of relaxation and should worsen even more at higher fields. The effect seems mostly noticeable around the Ernst flip angle.

Methods: We modeled an RF coil with a length of 340 mm and an inner diameter of 270 mm using the Ansoft HFSS software, which incorporated a human head model produced by the Aarkid company. The coil consisted of 8 emitting half-wave dipole-type antennas. RF electromagnetic fields were calculated with a spatial resolution of 5 mm and a frequency of 300 MHz. Figures 1(a)(b) show the magnitude and the phase of the transmitted B_1 field for one channel. RF and gradient waveforms were designed using the transmit-SENSE and spokes method [1, 2] to homogenize the flip angle over a 3 mm thick axial slice located at the center of the RF coil. The five spokes were located at (0, 0), (k_0, k_0), ($-k_0$, k_0), (k_0, $-k_0$), and ($-k_0$, $-k_0$) with a displacement of $k_0 = 22.2\ \mathrm{m^{-1}}$, a length of 6283 $\mathrm{m^{-1}}$, and total duration of 3.8 ms. RF waveforms were designed based on the small-flip-angle approach [1, 2] with an acceleration factor of 1.0 and Tikhonov regularization parameters λ of 0.01 and 10, to give a target flip angle of 5 degrees. Magnitude least squares optimization using the local variable exchange method was performed to improve the homogeneity of the magnetization profile [3]. For higher flip angles, the RF waveforms were simply scaled. For each target flip angle and regularization parameter, Bloch equation with and without relaxation terms was integrated numerically to yield in each voxel a flip angle and a magnitude of the magnetization vector. T_1 and T_2 were taken to be respectively 2000 and 59 ms, which correspond to gray matter at 7 T [4]. These calculated values were then inserted in the following formula to calculate the signal intensity, accounting for relaxation, in a SPGE sequence: $S(n,\theta) \propto (1-E_1)\, n \sin\theta/(1- n E_1\cos\theta)$, where θ is the flip angle and n is the length of magnetization after RF excitation normalized by the one before excitation. TR was also varied to scan a large range of experimental parameters.

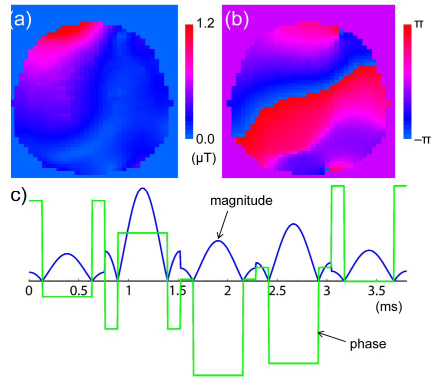

Figure 1: (a) Magnitude and (b) phase angle of RF magnetic field for one channel. (c) RF waveform for the channel.

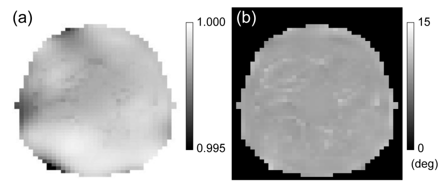

Figure 2: (a) Distribution of the length of magnetization after RF excitation for a target angle of 10 degrees. (b) Distribution of flip angle calculated with relaxation.

Results and Discussion: As shown in Fig. 1.c, the optimized RF waveforms were similar to a series of sinc functions because the target profile was uniform in the selected slice. As an example, Fig. 2 shows the distribution of the length of magnetization after RF excitation and of the flip angle for λ=0.01, and for a target FA=10°. Relaxation caused in this case an increase in the inhomogeneity of FA from 3.9 % to 4.5 % (see Fig. 3.a), while the average attenuation of the magnetization vector was 0.13 % with standard deviation of 0.062 %. In this example, the degradation of signal homogeneity (see Fig. 4. b), quantified by std/mean over the targeted slice, is primarily due to a difference in the FA distribution. In addition, Fig. 3.a shows that when λ is large enough, no severe degradation in the FA distribution due to the small tip angle approximation occurs and relaxation barely affects the uniformity of the FA. Furthermore, Fig. 3.b shows an increase and decrease of the dispersion of the values of n with respect to the FA and λ respectively. The larger the FA and the smaller λ are, the larger the excursion of the spin vectors from the z-axis during the pulse is and the more they shrink because of T_2. As a result, at higher flip angles, a degradation of signal uniformity due to relaxation during the pulses is mainly caused by an increased variability of n. For instance at 45°, the mean and std of n were calculated to be 2.0 % and 0.7 %. Although these are small numbers, inserted in the $S(n,\theta)$ formula above, they can sometimes have a large impact (depending on the value of E_1). We plot in Fig. 4.a. and 4.b. respectively the signal intensity $S(n,\theta)$ and inhomogeneity for the SPGE sequence, for λ=0.01, for several values of TR and again, with and without relaxation terms in our simulations. The loss of signal and degradation of signal uniformity are mostly noticeable around the Ernst angle, with 4.3 % of signal loss (TR=100 ms) and an increased signal inhomogeneity by a factor of 10 (TR=30 ms at FA=10°). While this relative effect is large, the absolute effect is still small (0.19 % without relaxation, 1.9 % with relaxation).

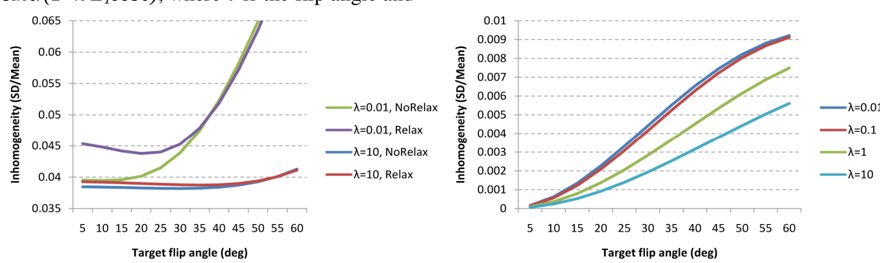

Figure 3: (a) Effect of relaxation on flip angle inhomogeneity (λ: Tikhonov regularization parameter). (b) Inhomogeneity in attenuation of magnetization vector.

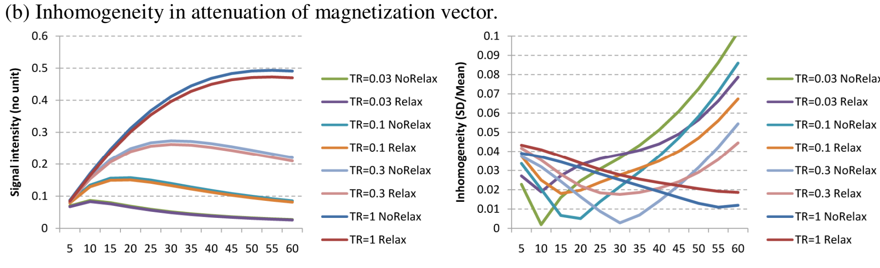

Figure 4: (a) Signal intensity (λ = 0.01). (b) Signal inhomogeneity (λ = 0.01).

Conclusion: In this study we have shown that relaxation effects during RF pulses can have a relatively large effect in SPGE sequences when designing B_1 pulse compensation schemes on the order of a few milliseconds. As the external magnetic field increases, T_1 and T_2 tend to respectively increase and decrease. It is therefore likely to become more and more important at higher fields. Last, it was shown that the Tikhonov regularization parameter could, in addition to decreasing the RF energy, also have a large impact on the effect of relaxation during the RF pulses.

References: [1] Saekho S. et al, Magn Reson Med 2006;55:719-724. [2] Grissom W. et al, Magn Res Med 2006;56:620-629. [3] Setsompop K. et al, Magn Reson Med 2008;59:908-915. [4] Pfeuffer J. et al, Magn Reson Imag 2004;10:1343-1359.