XTC MRI Parameter Optimization: Theoretical Considerations

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Introduction: Xenon polarization transfer contrast (XTC) MRI (1,2) is a promising technique that exploits the gas exchange of Xe-129 between the alveolar gas phase and the lung parenchyma to obtain information about lung function and certain pulmonary-physiology parameters by means of gas-phase depolarization maps. However, the choice of the pulse sequence parameters that were used in previously reported studies was purely empirical. In this work we performed a theoretical analysis of how the available non-equilibrium magnetization of hyperpolarized Xe-129 should be expended to obtain maximum sensitivity to regional variations in the gas-phase depolarization. In particular, we investigated the impact of the RF excitation flip angles in the two imaging segments, the number of contrast-generating inversion RF-pulse pairs in between the imaging segments, and the gas-phase T1 on the predicted accuracy of the gas-phase depolarization due to gas exchange between the lung parenchyma and the alveolar volume.

Methods: From error propagation, we can calculate the standard deviation of the gas-phase depolarization σ_f as: $\sigma_f = \frac{\sigma_S}{N_C S_1^2}\sqrt{S_1^2 + S_2^2}\sqrt[N_C]{\left(\frac{S_2}{S_1}\right)^{1-N_C}}$,

where σ_S is the standard deviation of the image thermal noise, N_C is the number of contrast-generating inversion RF-pulse pairs, and S_1 and S_2 are the intensities of a given pixel in the first and second gas-phase images, respectively. Expressions for S_1 and S_2 are sequence specific and have to be determined to evaluate this result further. In the case of a gradient-echo sequence such as FLASH with sequential phase encoding, excitation flip angles of α_1 and α_2, and N_e phase encoding steps, and when the fraction of magnetization depolarized by one inversion RF-pulse pair is f_D and the repetition time for subsequent RF pairs is Δp, S_1 and S_2 can be estimated as:

$$S_1 = \sin\alpha_1(\cos\alpha_1)^{(N_e/2)-1}, \qquad S_2 = (\cos\alpha_1)^{N_e} e^{-N_C \Delta p/T1}(1-f_D)^{N_C} \sin\alpha_2(\cos\alpha_2)^{(N_e/2)-1}.$$

Previous studies determined $T1$ to be at least 20s and the average f_D in healthy animals to be about 5% (2).

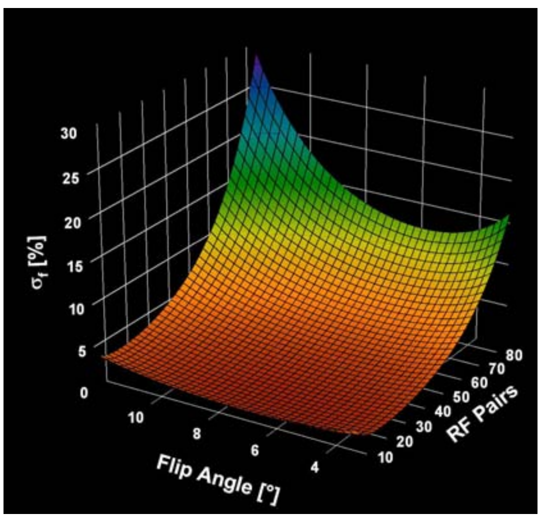

Figure 1: Predicted error in the XTC MRI depolarization maps as a function of the number or contrast-generating inversion RF-pulse pairs and the selected excitation flip angle.

Results: Figure 1 depicts the wide range of predicted errors σ_f for $\alpha_1 = \alpha_2$, N_e = 64, $T1$ = 20s and f_D = 5% as a function of N_C and the flip angle α_1. Nevertheless, in the region of minimal error, the function varies slowly and is thus somewhat forgiving towards flip angle calibration errors. The error in the measured depolarization can be further reduced by selecting α_2 as 2.8 times α_1 (Fig. 2A). For most physiologically encountered T1 values, σ_f is only mildly T1 dependent (Fig 2B). Therefore, local variations in the oxygen level will hardly affect the measurements. Figure 2C illustrates how the relative predicted error changes if the depolarization in a given pixel deviates from f_D = 5% for which the sequence was optimized. In the physiologically most relevant depolarization range of 2-8% the error would always be in the 20-30% range for commonly found image noise levels σ_S.

Discussion: This work demonstrates that substantial improvements in the accuracy of the measured XTC MRI depolarization maps can be achieved through pulse sequence optimizations. The optimal configuration (α_1 = 3.6°, α_2 = 10.1°, N_C = 22) is predicted to increase the measurement sensitivity to regional variations in lung function by approximately 200% compared to that for previous, non-optimized configurations (2). This would be equivalent to increasing the polarization from 10% to 30%.

References

[1] Ruppert K, Brookeman JR, Hagspiel KD, Mugler III JP. MRM 2000; 44:349-357.
[2] Ruppert K, Mata JF, Brookeman JR, Hagspiel KD, Mugler III JP. MRM 2004; 51:676-687.

Acknowledgements
This work was supported by NIH grant R01EB003202, CTRF grant IN2002-01 and Siemens Medical Solutions.

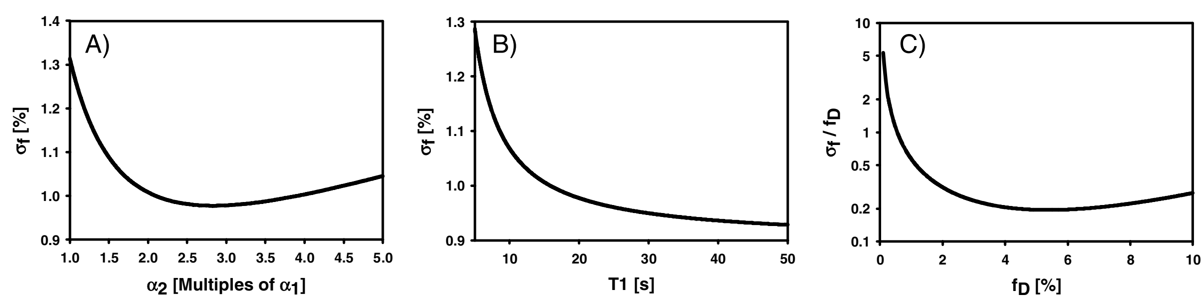

Figure 2: Predicted error in the XTC MRI depolarization maps as a function of (**A**) the value of α_2 relative to α_1, (**B**) $T1$. (**C**) The relative error as a function of the actual gas-phase depolarization f_D.