A self-navigated feedback method for fast gradient-echo imaging of hyperpolarized 3He using variable flip angles

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Introduction: Because the longitudinal magnetization of hyperpolarized gas is not at thermal equilibrium, the use of a constant flip angle in a spoiled gradient-echo pulse sequence for ^{3}He MRI results in a transverse magnetization ("signal") that decays exponentially with each phase-encoding step. Depending on the flip angle chosen, this leads to either a substantial *k*-space weighting of the acquired data or a situation in which an unacceptably large fraction of the original hyperpolarized magnetization remains unused at the end of the scan. Both of these effects can be addressed by increasing the flip angle at each excitation to compensate for decay of the longitudinal magnetization. But to make this strategy work reliably in practice, the rate of T_1 relaxation and the proper transmitter calibration must be known. These can vary significantly from patient to patient, and since standard techniques for ^{1}H transmitter calibration cannot be applied to hyperpolarized magnetization, and T_1 (which depends primarily on the O_2 concentration and is typically on the order of the sequence duration) varies with breath hold, often neither is known precisely in advance. In an effort to make fast-gradient-echo, variable-flip-angle sequences reliably practical, we have developed an efficient feedback procedure that uses periodically acquired signal measurements to calibrate these parameters during sequence execution and dynamically adjust the variable flip angle sequence to achieve the desired signal evolution.

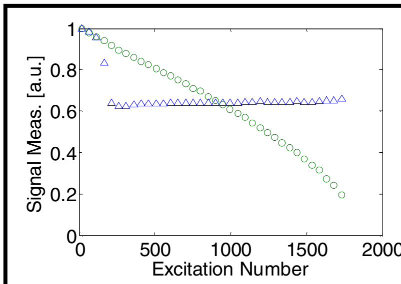

Figure 1: Evolutions of periodically measured signals in a Tedlar plastic bag containing ^{3}He. The results of two scans are shown. Both used the same initial transmitter calibration, which was set 50% too high, but feedback was enabled for the signal evolution depicted by blue triangles.

Methods: For steady-state incoherent imaging of hyperpolarized ^{3}He, the signal S_n at each excitation evolves according to the expression

$$S_n = M \exp\left[-(n-1)T_R/T_1\right]\sin\theta_n \prod_{i=1}^{n-1}\cos\alpha\theta_i \qquad \text{(Equation 1)}$$

Where M is the initial longitudinal magnetization, θ_n is the nominal flip angle of the *n*-th excitation RF pulse, and α is a constant of order unity representing the fractional error in the transmitter voltage calibration. If all the nominal flip angles are known and a subset of the signals S_n is measured, then the values of α and T_1 for a given scan can be determined by fitting the observed signal evolution to Equation 1. We use this strategy to periodically calibrate T_1 and α throughout the scan. The most computationally intensive part of the fitting procedure is evaluation of the cosine product in Equation 1. This product may contain thousands of terms in the case of a 3D acquisition, and will generally need to be re-evaluated at each step of the fitting procedure. We have derived a Taylor expansion with iteratively determined coefficients that dramatically reduces the computational complexity of this calculation while yielding a highly accurate approximation. A modified version of the Levenberg-Marquardt method is used to simultaneously determine the best fit values of M, α and T_1 following each signal measurement.

The feedback algorithm was incorporated as part of a 3D FLASH pulse sequence with sequential *k*-space ordering. High readout bandwidth (780 Hz/pixel) and short repetition times (3 ms) are used to allow whole lung coverage at 3mm isotropic resolution in a breath hold. The variable flip angle sequence is initially calculated to yield a flat signal evolution under the assumption that T_1 is infinite and $\alpha = 1$, with a terminal flip angle of 10°. At the beginning of every partition, immediately before execution of the lines loop, an extra event block is inserted in which the central *k*-space line is acquired, and the summed FFT is used as a measurement of the current signal. Following each signal measurement, updated values of T_1 and α are determined by fitting all previous signal measurements to Equation 1, and future values of the variable flip angle sequence are re-calculated using the new parameters.

The pulse sequence was tested in two regimes: (1) under conditions of essentially infinite T_1 by imaging a Tedlar plastic bag containing a mixture of hyperpolarized ^{3}He and N_2, and (2) under conditions of finite T_1 by imaging inhaled ^{3}He in healthy volunteers. Optimization strategies were explored, guided by computer simulations. All scanning was performed on a 1.5 T whole-body commercial scanner (Sonata, Siemens) and ^{3}He gas was polarized to ~35% using a commercial system (Model 9600, MITI).

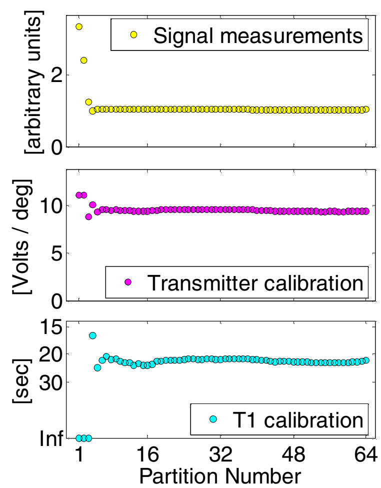

Figure 2: Evolution of periodically measured ^{3}He signals during the scan of a human volunteer are shown together with fit values of the transmitter calibration and T_1. Early flip angles were set artificially high.

Results: The feedback algorithm was found to be very robust when it could be safely assumed that T_1 is infinite. Figure 1 shows the periodic signal measurements acquired in a bag, both with and without feedback. The initial transmitter calibration was the same for both scans (approximately 50% too high), but the feedback algorithm quickly discovered the error and restored a flat signal evolution. The feedback algorithm was found to be less robust for the *in-vivo* scans, in which T_1 is finite, and the fit values tended to bounce around before beginning to converge approximately one quarter of the way through the scan. The problem is that early in the scan the variable flip angles are not changing very rapidly, which makes it difficult to separate the T_1 dependence from the α dependence in the face of measurement noise. To address this problem, one strategy was explored in which the flip angles for the first two partitions were increased by factors of 3 and 2, respectively, to create artificially changing flip angles for the feedback algorithm to lock onto early in the scan. This strategy works, as shown in Figure 2, but is not a particularly elegant solution. A more desirable strategy was explored in which χ^2 values calculated as part of the fitting routine are used to estimate the probability that the new values are better than the current values. By setting this confidence threshold to 95%, instabilities in the early signal evolution were greatly improved. While this strategy does not enable the algorithm to converge any faster, it has the desirable consequence that the signal evolution is not unnecessarily disturbed when the initially assumed parameters happen to be very close to actual.

Conclusions: The 3D fast-gradient-echo pulse sequence described here enables optimum usage of the available hyperpolarized ^{3}He signal for whole-lung imaging in a breath hold. When used with the χ^2 confidence strategy, the feedback method appears reliable enough to be implemented on a trial basis as part of a regular ^{3}He imaging protocol. It is worth noting that the use of intermittent signal measurements for this test implementation is driven not by concerns about feedback speed, but by the desire to minimize the amount of signal diverted away from imaging. For non-Cartesian trajectories such as spiral or radial, in which central *k*-space is traversed at every excitation, feedback could conceivably be performed every excitation, which might enhance convergence of the fit parameters.

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