Improving the quality of 3D hyperpolarized gas images using feedback-controlled flip-angle evolution

G. W. Miller[1], T. A. Altes[1], J. R. Brookeman[1], E. E. de Lange[1], J. F. Mata[1], J. P. Mugler III[1]
[1]Department of Radiology, University of Virginia School of Medicine, Charlottesville, Virginia, United States

Introduction: A true three-dimensional (3D) isotropic Cartesian data set is desirable for hyperpolarized gas lung ventilation imaging. Since ventilation defects occur most commonly around the periphery of the lung, it is difficult for example to identify and characterize anterior pleural defects using a set of two-dimensional coronal image slices. The ability in 3D imaging to easily reconstruct image slices along any of the primary planes makes it possible to better characterize the lung periphery and to identify defect boundaries, and allows true volume measurements to be made. Hyperpolarized gas images are not normally acquired in 3D, however, due to the difficulty of obtaining adequate signal-to-noise ratio (SNR). To make 3D acquisitions routinely practical, techniques must be developed which make efficient use of the available magnetization to yield the maximum image SNR for a given dose of hyperpolarized gas.

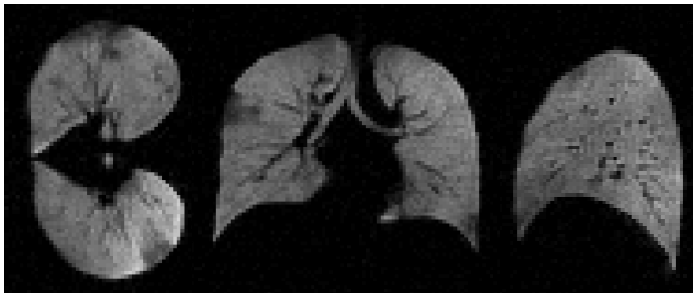
For sequentially acquired gradient-echo imaging using a constant flip angle, there is a value of the flip angle which yields the highest image SNR. But even when this optimum flip angle is used, 36% of the initial longitudinal magnetization remains unused at the end of the acquisition (in the absence of T1 decay, which is generally not negligible in relatively long 3D acquisitions). It has been proposed that image SNR and resolution may be improved by using a sequence of variable flip angles designed to yield a flat signal evolution while making use of all the available longitudinal magnetization [1]. The proper sequence can be derived iteratively using the formula $\theta_n = \arctan(\sin \theta_{n+1})$, for $n = 1, 2, \ldots, N$, where the terminal flip angle θ_N is set to 90° if all the longitudinal magnetization is to be used. The resulting evolution of the transverse magnetization (signal) generated at each excitation, however, is unstable with respect to miscalibration of the applied flip angle, and in practice the signal tends to accelerate rapidly upward or downward near the end of the acquisition, thereby compromising the theoretically improved SNR and resolution. Therefore this variable flip angle approach is not generally used.

In the present work we demonstrate a method to make the variable flip angle approach practical by implementing a sequence which dynamically calibrates the correct relationship between the transmitter voltage and flip angle, and which includes a feedback loop to keep the signal evolution stable throughout the acquisition.

Methods: The basic imaging sequence used is a standard 3D FLASH sequence with a nonselective excitation pulse. At the beginning of each partition, the sequence sends a "navigator," which is simply an extra excitation/readout cycle without any encoding gradients. The acquired FID signal is processed by the online image reconstruction system while the remainder of the partition data is being acquired. The measured size of the FID is fed back to the scanner, which uses the value to recalculate the transmitter calibration based on previous FID measurements and the known history of applied voltages, using the general relationship that the signal at the nth excitation is proportional to $\sin\theta_n \prod_{j=1}^{n-1} \cos\theta_j$. The new calibration is then used starting at the beginning of the next partition. Thus feedback is performed in near-real time, without pausing the acquisition. Since the calibration calculation is more accurate for higher flip angles, the original variable flip angle sequence is modified by scaling the flip angles in the first two partitions by a factor of 3 and 2, respectively. This allows the correct calibration to be determined more rapidly, so that the sequence can recover quickly from a large initial miscalibration.

The 3D feedback sequence was tested in 8 healthy volunteers during development and optimization of the feedback scheme. The final configuration was tested in 2 subjects with asthma. Imaging was performed on a 1.5T whole-body scanner (Siemens Sonata) during a 20 second breath hold immediately following inhalation of a mixture of hyperpolarized He-3 and nitrogen. Imaging parameters were: TR/TE, 3.9/1.8 ms; matrix, 88 x 128 x 56; FOV, 294 x 428 x 187; readout bandwidth, 390 Hz/pixel. The variable flip angle sequence described above was used, with a terminal flip angle of 10°. For one of the asthma subjects, a pair of acquisitions was performed, each following inhalation of a mixture containing 750 ml of ~40% polarized He-3 and 250 ml nitrogen. The same initial transmitter calibration was used for both acquisitions, but was intentionally set lower than actual. One acquisition was performed without feedback, with the flip angle nominally set to the optimum constant flip angle of 1.15°, while the other was performed using the variable flip angle sequence with feedback. Two additional navigator FIDs with the same transmitter voltage were acquired, one at the very beginning and one at the very end of the acquisition. The ratio of these two measured signals was used to determine the fraction of the initial longitudinal magnetization remaining at the end of the acquisition.

Results: The feedback sequence successfully measured the transmitter calibration and altered the flip angle evolution in the desired way for initial miscalibrations ranging from ±40%. The figure shows a set of three images from the intentionally miscalibrated 3D feedback acquisition. Each image was formed by adding three adjacent 3.33 mm slices to yield a single 10 mm slice in each orientation. The images show no obvious pathologies. Ventilation defects are visible at the periphery in each image. The SNR of these images are approximately 23% higher than the corresponding images obtained with the constant flip angle sequence. At the end of the feedback acquisition, 7% of the initial longitudinal magnetization remained, while 21% remained after the constant flip angle sequence.



Conclusion: Variable flip angle sequences can be combined with feedback to more efficiently use the available polarized gas signal and improve the quality of 3D lung ventilation images. This technique shows promise for consistently obtaining high quality 3D images without the need for a priori knowledge of the precise relationship between the applied transmitter voltage and flip angle.

References:

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