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Introduction to SWIFT (Sweep Imaging with Fourier Transformation) for Magnetic Resonance Imaging of Materials

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ABSTRACT

A novel, fast, and quiet method of magnetic resonance imaging (MRI), called SWIFT (sweep imaging with Fourier transformation) has recently been introduced. In addition to SWIFT's potential for *in-vivo* MRI, it creates new opportunities for MRI of materials.

SWIFT currently operates in 3d radial acquisition mode. A series of segmented hyperbolic secant excitation pulses is accompanied by acquisition in the gaps. After correlation with the pulse, each excitation results in a free induction decay (FID). The spectrum corresponding to the FID is a projection. There is very little “dead time” between excitation and acquisition, making SWIFT useful for imaging of short T_2 materials, but in total imaging times comparable to fast gradient echo sequences.

We anticipate great interest in this new MRI sequence in the materials MRI community and look forward to exploring SWIFT's advantages and potential relative to existing short T_2 imaging techniques.

INTRODUCTION

The SWIFT sequence[1] consists of a simple series of RF pulses, incremented gradients, and simultaneous data acquisition (see figure 1).

In SWIFT, a time-domain signal is acquired during the gaps of a segmented frequency-swept pulse. The field gradient used for spatial encoding is not pulsed on and off; instead, its orientation is stepped in an incremental manner. The gradient waveforms are nearly continuous, resulting in low stress on hardware and quiet operation. With virtually simultaneous excitation and signal acquisition, new possibilities exist for imaging materials consisting of spins with fast transverse relaxation rates, T_2, in the 25-250 μs range, such as polymers, macromolecules, semi-solids, and quadrupolar nuclei. Due to the frequency sweep and sequential excitation, peak RF power requirements are reduced compared to hard pulse excitation.

The gradient creates the space-to-frequency mapping well known from basic MRI. The RF pulse excites transverse magnetization. The time of excitation is largely determined by the frequency sweep of the hyperbolic secant (HS1) pulse [2]. Magnetization is excited when the frequency sweep of the pulse reaches its local resonance offset[3] in the gradient.

The correlation method[4, 5] effectively removes the phase accumulated due to differing excitation times, and recreates an FID as if all the magnetization had been simultaneously excited.

Mathematically the excitation process can be represented (in the limit of linearity) as a convolution:

$$d(t) = p(t) * s(t)$$

where $d(t)$ is the acquired time domain data, $p(t)$ is the complex amplitude of the RF pulse and $s(t)$ is the underlying FID if the sample had been excited by a short hard pulse (an impulse response). "*" represents the convolution operation.

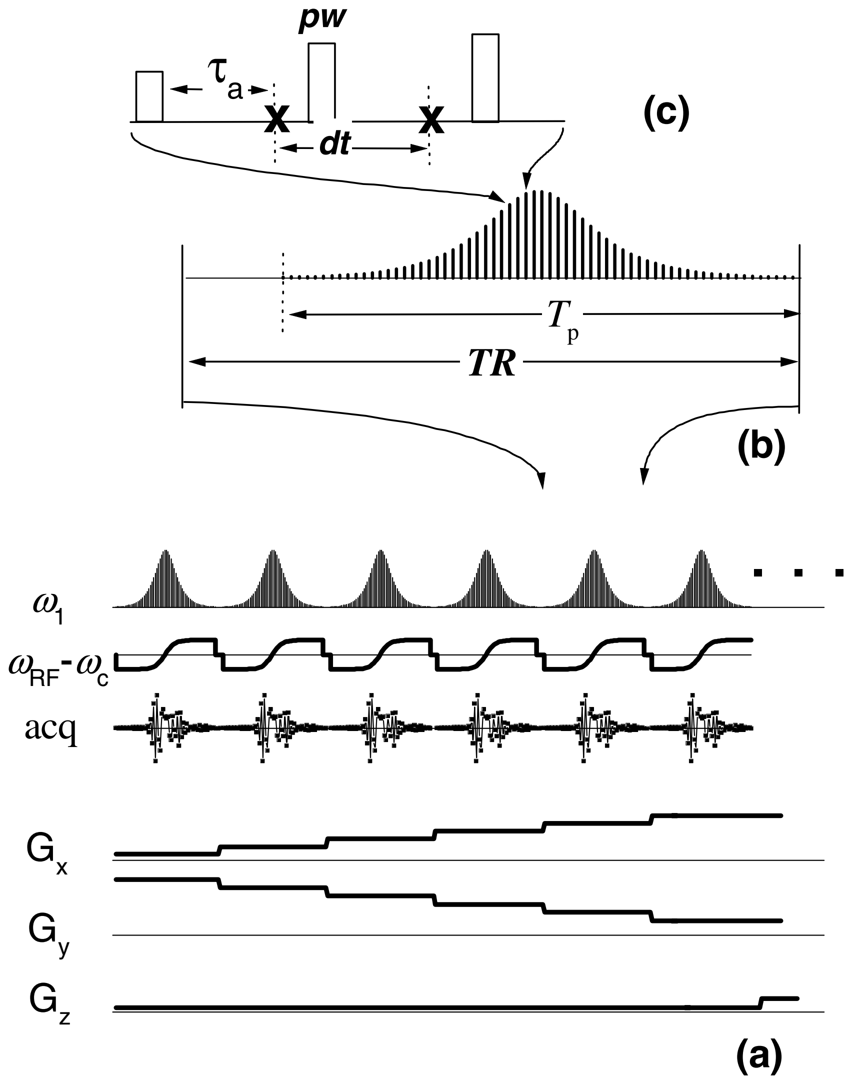

Figure 1 The SWIFT Sequence at three time scales, which also correspond to the loop structure of the sequence code.
a) SWIFT consists of a series of segmented HS1 pulses, applied gradients, and simultaneous A/D acquisition.
b) Each view in the 3d radial acquisition consists of one segmented HS1 pulse and a short delay between pulses for gradient updating and relaxation delay. c) At the shortest timescale the segmentation of the pulse is clearly seen. One or more A/D conversion points (marked X) are placed between the pulse segments.

The correlation operation can be carried out in the opposite Fourier domain. *D(f)* represents the Fourier transform of *d(t)*.

$$S(f) = D(f) / P(f)$$

One RF pulse applied during a fixed gradient value yields, after correlation of the corresponding data with the known pulse profile, one projection. The projection is just the spectrum *S(f)* one would have obtained with hard pulse excitation.

The gradient can be incremented in a number of view orders. We currently use an isotropic spiral order. The starting points of the views trace out a spiral on the surface of a hemisphere[6]. Reconstruction is accomplished by gridding[7, 8].

EXPERIMENT and RESULTS

We implemented SWIFT on a 9.4T T, 31 cm bore magnet system with Varian INOVA console and Magnex 45 gauss/cm gradient subsystem. The extremely short excitation-to-acquisition delay, τ_a, required that coils for SWIFT be stripped of polymers and other sources of short T_2 background signal, especially near the coil elements or electronic components. For the 9.4 T system we used a bare wire loop of about 1 cm diameter. In fact, we observed residual signal from the bare coil, probably due to solder flux or other residue, and could reconstruct an image of the coil loop.

^{1}H 3d high resolution SWIFT images have been obtained from several materials systems of interest. These include a curing epoxy adhesive, Lego brick (Acrylonitrile Butadiene Styrene), and 5 mm NMR tube caps (Ethylene Vinyl Acetate), most of which are invisible (or nearly so) with standard gradient echo MRI. Imaging time is on the order of minutes.

Figure 2 shows representative slices for 3d images acquired with FLASH and SWIFT of a Lego brick, most likely Acrylonitrile butadiene styrene (ABS) with T_2 in the 400 μs range. The Brick is in a 10 mm test tube containing Fluorinert™ FC-77 for susceptibility matching and pinned down with glass capillary tubes.

The SWIFT image (figure 2a) was acquired at 62.5 kHz spectral width (sw), had a TR of 6.1 ms, 256 complex points in each acquisition, 4000 views (nv), 16 averages (nt), pulse element width of 4 μs, and took approximately 6 minutes. The SNR is 20. Blurring due to chemical shift (about 5 ppm separation, or 2 kHz, corresponding to 8 pixels) of multiple ABS peaks is visible.

The FLASH image (figure 2b) is included to highlight the short T2 nature of the object. Parameters were 128x128x128 matrix, 80 kHz sw, TR of 50 ms and TE of 2 ms. An image could be obtained in 4 min, but had very low SNR of approximately 2.

We discovered several hardware limitations: fidelity with regard to harmonic content and blanking of the RF transmit system; phase stability and rapid gating of the RF receive subsystem; and timing variations introduced in sequence compilation for real-time. Some of these were correctable in post-processing.

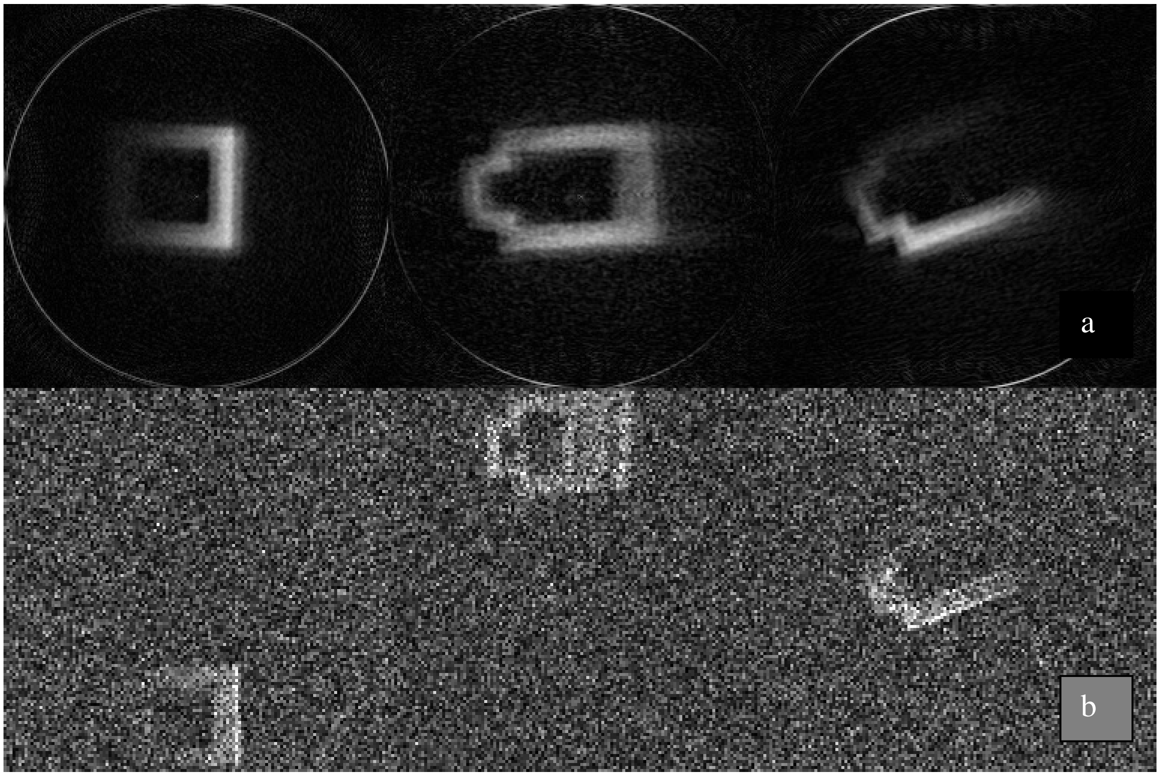

Figure 2 Image Comparison, Object is a "single-unit" Lego™ brick, made of ABS, in FC-77 solution.
a) Center slices from 3d SWIFT image taken on the 9.4 T system, FOV=2.7 cm, 62kHz sw, total time 6 min, with 4000 views, 16 averages, reconstructed to 256x256x256, Artifactual blurring due to different chemical shifts (~5 ppm) is visible, SNR ~20
b) Center slices from 3d FLASH image taken on the 9.4 T system, FOV=4 cm, 80kHz sw, total time 4 min, TE=2ms, TR=50ms, with 128x128x128 voxel resolution, SNR ~2

DISCUSSION

SWIFT has several intriguing properties. First, it has an intrinsically short excitation to acquisition time delay τ_a, at present hardware limited to ~5-10 μs. This provides sensitivity to very fast-relaxing spins, similar to that achieved by UTE (Ultra-short TE) sequences[9], SPRITE[10], or continuous wave[11] sequences.

Second, the use of frequency-swept pulses, particularly those of the HSn family of pulses[2], allows lower peak-power excitation. Peak power is especially low when compared to the peak power needed by single hard pulse excitation, making it easier to achieve larger effective flip angles and T1 contrast, without resorting to inversion preparation.

Third, the flat excitation profile and phase behavior of HSn pulses are well behaved at up to 90° flip angle, removing some of the disadvantages of previous correlation or stochastic based methods[5].

In its current implementation, SWIFT utilizes a radial sampling scheme with isotropic spiral (single or interleaved) view ordering. This gives rise to the fourth property: the gradient updating, which is nearly continuous, does not require much additional rise time. Very little stress is placed on the gradient subsystem and the sequence is quiet, even at short TR and rapid acquisition speeds. SWIFT also does not require the complicated gradient timing, area matching and associated eddy current compensation of sequences incorporating phase encoding such as FLASH, SPRITE, EPI, or fast spin echo sequences.

Finally SWIFT is fast. Currently, speeds of 200 views (of 256 complex points each) per second can be obtained at 62.5 kHz bandwidth, without parallel acceleration. We anticipate much more rapid acquisition speeds with solids hardware and/or digital IF acquisition/filtering.

CONCLUSION

We introduce SWIFT to the materials science community. We hope that SWIFT's combination of short T_2 sensitivity, high spatial resolution, and fast imaging times will open up new opportunities for imaging of materials.

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