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Detecting Fleeting MRI Signals with Frequency-Modulated Pulses

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Abstract

We describe a fundamentally different approach to MRI referred to as SWIFT (sweep imaging with Fourier transformation). SWIFT exploits time-shared RF excitation and signal acquisition, allowing capture of signal from spins with extremely short transverse relaxation time, T_2^* . The MR signal is acquired in gaps inserted into a broadband frequency-swept excitation pulse, which results in acquisition delays of only 1 – 2 microseconds. In SWIFT, 3D k-space is sampled in a radial manner, whereby one projection of the object is acquired in the gaps of each frequency-swept pulse, allowing a repetition time (TR) on the order of the pulse length (typically 1 – 3 milliseconds). Since the orientation of consecutive projections varies in a smooth manner (i.e., only small increments in the values of the x, y, z gradients occur from view to view), SWIFT scanning is close to inaudible and is insensitive to gradient timing errors and eddy currents. SWIFT images can be acquired in scan times similar to and sometimes faster than conventional 3D gradient echo techniques. With its ability to capture signals from ultrashort T_2^* spins, SWIFT promises to expand the role of MRI in areas of research where MRI previously played no or negligible role. In this article, we show wood and tooth images obtained with SWIFT as examples of materials with ultrashort T_2^* . Early experience suggests SWIFT can play a role in materials science and porous media research.

Keywords

MRI; frequency modulated pulse; correlation spectroscopy; radial imaging; ultrashort T_2^*

INTRODUCTION

Although sometimes technically challenging, imaging of ultra-short T_2^* spins continues to increase in popularity in multiple MRI disciplines. Conventional MRI sequences need some amount of delay between excitation and acquisition, which is typically 1 ms or more. Conventional gradient- and spin-echo sequences, with delays on the order of 1 ms or more, are sub-optimal for imaging ultra-short T_2^* spins such as semi-solids and quadrupolar nuclei. Fortunately, due to much progress in modern MRI technologies, ultra-short T_2^* imaging sequences are becoming more routinely used in many areas of research. Pulse

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sequences able to capture signals from ultra-short T_2^* spins have been around for some years now (UTE [1], BLAST/RUFIS [2], SPI [3], SPRITE [4] and centric-SPRITE [5]). Generally, these techniques require using a short radiofrequency pulse, which means high peak power, to excite a broad and relatively flat band of resonance frequencies in the presence of an encoding gradient. A newer approach uses frequency-swept excitation to excite a flat and wide band of frequencies using low peak power, and by acquiring signals in gaps in the RF pulse, near optimal ultra-short T_2^* imaging is possible. This method is called SWEEP Imaging with Fourier Transformation (SWIFT) [6, 7]. Recent progress with SWIFT, as it relates to porous media research, is presented in this work.

PRINCIPLES OF SWIFT

The key innovation of SWIFT is the time-shared excitation and signal acquisition that is achieved by inserting gaps into a frequency-modulated (FM) pulse. Most studies to date have used one of the family of FM pulses that are known commonly as “adiabatic pulses” and are of the hyperbolic secant family (HSn) [8] (Fig.1a). Unlike adiabatic uses of the HSn pulse, in SWIFT the HSn power is dropped so as to produce a small tip angle for spin excitation. Alternate on-off switching of the transmitter and receiver, with only 1 – 2 μ s of acquisition delay in-between, allows efficient imaging of spins with T_2^* values in the range of tens of microseconds and beyond. Accordingly, the repetition time, TR, is comparable to the pulse length (~1 – 3 ms), providing relatively short acquisition time that is comparable to or sometimes faster than the gradient-echo equivalent. The gapped frequency-modulated pulse is repeatedly applied with a spatial encoding magnetic field gradient which is not pulsed on and off, but changes its orientation in stepwise manner with each TR (Fig.1b). Therefore, the gradient waveforms are nearly continuous, resulting in low stress on gradient hardware and quiet operation.

In SWIFT, each FID is contaminated with the frequency components of the excitation pulse. This RF pulse contamination is removed with the correlation method [9], which can be easily performed with complex conjugate manipulation in the frequency domain. The retrieved signal always passes through the center of k-space; therefore 3D k-space is sampled in a radial manner. Image reconstruction is achieved by performing gridding from radial to Cartesian sampled k-space [10] and Fourier transformation.

As with other MRI pulse sequences in which transverse magnetization is spoiled between excitations, in SWIFT the amount of T_1 -weighting of the signal is described by the Ernst equation [11,12]. Thus, depending on the choice of flip angle, the contrast can range from being predominantly proton-density weighted to predominantly T_1 -weighted. The ability to capture short T_2^* signals is limited by the acquisition (= excitation) bandwidth (sw), which is simply the reciprocal of the dwell time (dw). Bloch simulations have shown that approximately 50 % or more of the available signal is measurable when $dw \ll T_2^*$ [6]. Similar to other frequency-encoded methods, spatial resolution of SWIFT becomes limited as T_2^* approaches zero and the spatial encoding gradient no longer is the dominant factor determining the resonance line width. However, the reduction of spatial resolution can be minimized by employing a broad frequency sweep and a strong encoding gradient. Although the latter demands high gradient amplitude and duty cycle, significant heating of the gradient coil and amplifiers did not occur in any of our experiments; therefore, this issue does not appear to be a significant limitation, at least for the spatial resolutions shown here.

APPLICATIONS

Until now, SWIFT has been implemented mainly for biomedical investigations such as musculoskeletal [13], cardiac [14], lung [15] and brain [16] imaging. Since the SWIFT acquisition can capture a wide range of T_2^* components due to its favorable sensitivity,

contrasts on the SWIFT images can be modified to extract valuable information by combining preparation sequences such as fat saturation, spin inversion and spin lock. In the following sections, we introduce recent progress on SWIFT applications.

Dental Science

Nowadays, the X-ray technique using ionizing radiation is the main methodology in imaging of clinical dentistry. While progress in radiographic technology during the past 30 years has led to a considerable decrease in the dose [17], incremental risk from radiation exposure is still not negligible. Additionally, the X-ray technique does not have sufficient sensitivity in detection of early caries [18] and visualization of the pulpal tissue. Traditional MRI is free from ionization radiation and well suited for imaging of the soft tissue, whereas it fails to image hard dental tissue due to its extremely short relaxation times, which curtails its use in clinical dentistry.

The high sensitivity of SWIFT to ultra-short T_2^* nuclei is a great advantage for simultaneous imaging of soft and hard tissues of human teeth [19]. SWIFT can clearly resolve tooth structures (pulp, dentin and enamel tissues) (Fig.2a and b). This includes intra-pulpal structures assumed to be the radicular neurovascular bundles. The caries on the distal aspect of the crown (left side of tooth) are easily visualized with SWIFT, cone-beam CT (CBCT), and 2D radiograph. The hyper-intense signal in the SWIFT images (Fig.2a and b) clearly delineates the extent of demineralization associated with disease, whereas CBCT (Fig.2c) and dental radiograph (Fig.2d) do not show all the demineralization. Although these images were obtained in an *in vitro* setting, SWIFT shows the superiorities of both contrast and spatial resolution to other currently available clinical techniques. One practical limitation of SWIFT is its relatively long scan time, but it can be reduced to a few minutes while keeping valuable information in clinical applications [19].

Tree Physiology

Cells in a tree form a complex system that takes care of water transportation, and thus the physiological conditions of the tree fluctuate depending on the water status of their trunks [20]. Since MRI is well suited for investigation of water contents and has the benefit of being noninvasive and nondestructive, it is used for studies in wood science such as water transport, colonization by fungi, and defensive response to wounding. However, short transverse relaxation time of tree stem due to the condensed structure puts a serious burden on its applications; therefore, MRI studies of wood are mainly performed with low-resolution 2D imaging. In some cases, 3D acquisition has been performed, but it needs hours of scan time [21].

The high sensitivity of SWIFT to extremely short T_2^* spins is a great advantage for imaging of tree stem, especially at higher magnetic fields, since T_2^* decay of signal is accelerated along with an increase of the magnetic field strength. Additionally, relatively fast acquisition is a highly practical aspect of SWIFT; the acquisition can be performed within tens of minutes. While gradient echo (GRE) sequences applied at 16.4T can image only the surface of a piece of water-filled wood (Fig.3a), SWIFT can clearly visualize structures in the tree stem, including pith and xylem (Fig.3b). On the SWIFT image, annual rings are found within the xylem layer. Since SWIFT provides the high resolution 3D images, wood grain is clearly shown on the lateral surface on the 3D rendering image of SWIFT (Fig.3c).

FURTHER APPLICATIONS

Broadband frequency-swept excitation and extremely short acquisition delay make it possible to preserve signals from spins experiencing large frequency shifts due to magnetic susceptibility effects. For example, superparamagnetic-labeled nanoparticles (e.g., SPIOs),

which cause signal voids in images acquired with a conventional gradient echo sequence, give rise to positive contrast (bright spots) in SWIFT images [14]. In materials science and porous media research, SWIFT extends the range of MRI applications. One conceivable advantage will be for capturing signals in heterogeneous porous media with strong surface relaxivities (e.g., due to abundant iron or manganese) [22].

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FIGURE 1.

The gapped frequency-modulated pulse and its magnified presentation (a), and the SWIFT sequence scheme (b).

FIGURE 2.

SWIFT images (a), maximum intensity projection (MIP) of the SWIFT images (b), cone-beam CT (CBCT) (c), and 2D radiograph (d) of a human tooth. SWIFT measurement was performed on a 9.4 T Varian system. Sequence parameters were as follow: TR = 2.5 ms, flip angle = 15°, bandwidth = 125 kHz, number of projections = 128000, and scan time = 25 min. The amplitude of applied gradients was 9.8 Gauss/cm.

FIGURE 3.

Images of a piece of wood obtained with gradient echo (GRE) (a) and SWIFT (b), and a 3D rendering image of the SWIFT images (c). All measurements were performed on a 16.4 T Varian system. Sequence parameters in the GRE sequence were: TR = 6.5 ms, TE = 2.4 ms, flip angle = 4° , bandwidth = 100 kHz, FOV = $3 \times 3 \times 3 \text{ cm}^3$, and matrix = $256 \times 256 \times 256$. For SWIFT, TR = 3 ms, flip angle = 4° , bandwidth = 125 kHz, number of projections = 128000, and FOV = $3 \times 3 \times 3 \text{ cm}^3$. Total scan time is 14 min and 13 min for GRE and SWIFT, respectively. The amplitude of applied gradients was 9.8 Gauss/cm.