Sweep Imaging with Fourier Transform (SWIFT)

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Target audience: Researchers, Technicians, and Clinician/Scientists interested in emerging SWIFT methodology, and related applications.
Outcome/objectives: Understand the principles of the SWIFT sequence and its modifications used for imaging objects with fast relaxing spins.

INTRODUCTION

SWIFT can be considered as a combination of three basic NMR techniques. As in continuous wave (CW) NMR [1, 2], this method uses swept radiofrequency (RF) excitation, but the sweep rate far exceeds the CW sweep rate even during a rapid-scan [3, 4]. Unlike the CW method in which the acquired signal is in the frequency domain, here it is considered to be a function of time, as in the pulsed FT method [5-8]. Finally, the method uses correlation, identical to that used in stochastic NMR [9, 10]. SWIFT is a non-Cartesian, fast and quiet MRI method with relatively low peak amplitude of RF pulses and greatly reduced demand on the field gradient efficiency of the scanner. The main advantage of SWIFT originates in its nearly simultaneous excitation and acquisition scheme that makes the SWIFT method a powerful tool for imaging objects having a broad distribution of relaxation times, including very short T_2 values.

THE ORIGINAL SWIFT TECHNIQUE AND ITS COMPONENTS

The original SWIFT uses a swept RF excitation and signal acquisition in a time-shared mode in the presence of a field gradient that changes its orientation incrementally from view to view.
a. Sweep excitation: In SWIFT spins are excited sequentially with sweep rate, a ($\sim b_W/T_p$- bandwidth/pulse length), satisfying the two following conditions: 1) *rapid passage* [11] $aT_2^2 >> 1$ and 2) linear region $a/\omega_1^2 >> 1$. It is important to note the difference between the *rapid passage, linear region* and the *rapid passage, adiabatic region*, wherein the second condition is $a/\omega_1^2 << 1$. Accordingly, the transition from the adiabatic to the linear region requires reducing the RF amplitude or increasing the sweep rate, while other pulse parameters remain constant. In this way, any adiabatic passage pulses, such for example, as a *HS*n pulses [12], can be used in the *rapid passage, linear region* to rotate the magnetization by an angle $<90^0$, as needed for excitation in SWIFT.
b. Gapped excitation and acquisition: SWIFT uses time shared excitation and acquisition. The dwell time of data sampling is $d_w = T_p/N$, where N is number of gaps. Usually N≤R, where R= $b_w T_p$. Discretization of pulses and the introduction of gaps in the pulses produce additional sidebands which can contaminate and destroy the flatness of the baseband excitation profile, as well as introduce systematic noise in the acquired data [13]. Additionally, because both the transmitted pulse and data acquisition are simultaneously amplitude-modulated in SWIFT, crosstalk between different frequency bands occurs in the data [14]. All these effects lead to a "bulls-eye" artifact in a radial SWIFT image. This artifact can be reduced by using both pulse oversampling and using the proper pulse function for correlation with the response of the spin system [13]. A further cancellation of this artifact can be achieved using gap cycled acquisition [14, 15] and a post-processing method based on the average projection for RF distortion correction [16].

The signal to noise ratio (SNR) depends on the acquisition duty cycle, which is the limiting factor for using high bandwidths when coil ring down time is comparable to the dwell time [17]. The acquisition duty cycle can be increased with continued acquisition after the gapped frequency-swept pulse [18].
c. Deconvolution: The signal acquired during the excitation is not a regular free induction decay (FID), but an FID convolved with pulse function which requires additional steps to remove the pulse contamination.

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Fortunately the sweep excitation up to high flip angles can be considered as a linear process. According to the standard nomenclature used in NMR, the unit impulse response $h(t)$ is the FID and the unit frequency response function is the spectrum $H(\omega)$ (projection), and these functions are related to one another by direct FT.

Correlation method: In the original SWIFT technique, the deconvolution is done by using a correlation method similar to that used in stochastic NMR [9, 10], which recovers the spectrum $H(\omega)$ by conjugate multiplication of the acquired signal with the pulse function in the frequency Fourier domain [19].

Algebraic methods: In this case, the acquired time domain signal, $\boldsymbol{s}$, is described in vector form as $\boldsymbol{s}=\boldsymbol{EH}$, where $\boldsymbol{E}$ is the encoding matrix and $\boldsymbol{H}$ is the projection of magnetization in the gradient direction. The projection can be found as $\boldsymbol{H}=\boldsymbol{E}^{*}\boldsymbol{s}$ where $\boldsymbol{E}^{*}$ is the pseudoinverse matrix calculated using a standard algorithm based on singular value decomposition. Algebraic methods are more flexible, because any specifics of the given sweep pulse and sampling scheme can be reflected in the encoding matrix [18]. At same time the quality of the results highly depend on the accuracy of the used model.

d. View ordering. Silent MRI: SWIFT uses three-dimensional radial k-space sampling, where the orientation of the readout gradient is updated in small increments instead of pulsed on and off. This results in low sound pressure level [20] and minimal eddy currents in the scanner [21]. No ear protection is necessary with a SWIFT-only MRI session. The terminus of the radial spokes are isotropically distributed on a sphere as a generalized spiral set [22]. The acoustic noise is slightly increased when using a view order optimized for acquisition with higher temporal resolution [23, 24] or in the case of magnetization–preparation modules embedded in the SWIFT readout.

Linogram Sampling: Linogram sampling is a “semi-Cartesian” k-space sampling method, where the sampling pattern is a cubic grid [25]. SWIFT acquisition with linogram sampling and Hermitian extrapolation in reconstruction removes off-resonance blurring that is common in radial MRI sequences; the off-resonance artifacts become displacement/distortion of images, which is similar to Cartesian MRI [26, 27].

SWIFT UTILIZATION

The SWIFT method is insensitive to T_2-contrast except for cases of extremely short T_2s (< 1/dw). The contrast is dominated mainly by proton density when the excitation flip angle is small and by T_1-weighting when the flip angle is large. A variable flip angle (VFA) method based on SWIFT has been used for T_1 quantification [28-30].

a. Magnetization Preparation schemes: Almost any type of contrast (T_1, T_2, $T_{1\rho}$, $T_{2\rho}$ etc.) can be manipulated by including magnetization preparation (MP) modules in steady-state SWIFT readout. Examples of MP modules include, but not limited to: an inversion pulse followed by a recovery period to produce T_1-weighting [20, 31]; a magnetization rotation to produce adiabatic $T_{1\rho}$-weighting [32] or Relaxation Along a Fictitious Field (RAFF) [33]; diffusion weighting produced by applying field gradients during the TE/2 delays of a spin-echo module [34], or a frequency-selective pulse to saturate one or more parts of the targeted spectra [35-37].

b. Look-Locker sequence: The saturation recovery Look-Locker [38] scheme was implemented in the 3D SWIFT sequence [39] to generate 3D T_1 maps from fast view-shared data acquisition [40]. The method is applicable for mapping the objects with ultrashort T_2* and less sensitive to B_1 inhomogeneity than the VFA method.

c. Spectroscopic imaging: This method is based on an old idea to reveal both the spatial distributions and intrinsic frequency spectra of NMR signals from a set of projections obtained in the presence of spatial gradients of varied strength and orientation [41]. Instead of collecting the FIDs after applying a hard RF pulse, as done in the original method, the new technique uses SWIFT, which is less demanding of RF field amplitude, and therefore, is more applicable to human study [42]. The application of this method is expected to be in ultra-short T_2 mapping, fat-water separation and B_0/susceptibility mapping.

SWIFT BRANCHES

a. Continuous SWIFT: This was the first effort to implement SWIFT in continuous mode, which uses direct measurements of spin signals during RF excitation [43]. The receiver signal was decoupled from the transmitter using a standard connection scheme of quadrature hybrid with a quad coil. Due to the complete absence of "dead time", continuous SWIFT has the potential to extend applications of MRI and spectroscopy in studies of spin systems having extremely fast relaxation or broad chemical shift distributions beyond the range of existing MRI sequences. The main concern in a direct method is object motion which can modulate the transmitter leakage signal through the changing of coil loading and preventing use of this method in-vivo.

As a more generic alternative to the direct method, it is proposed to use the modification of the old principle [44] of sideband modulation to separate the transmit and receive bands and thus permit isolation by analog and digital filtering [45].

b. Gradient-Modulated-SWIFT: The gradient modulated (GM) Offset Independent Adiabaticity (GOIA) approach [46] was used to modulate the RF pattern in the SWIFT sequence [47, 48]. GM-SWIFT offers more flexibility to the SWIFT sequence. By manipulating the gradient, GM-SWIFT maximizes the efficiency of RF power and allows the optimal settings that balance RF power/SAR, scanning time and image qualities. GM-SWIFT is the close analogue of the UTE sequence realized with SWIFT technology.

c. Multi-Band-SWIFT: Multi-Band-SWIFT utilizes sidebands to sub-voxel excitations of the field of view. Multi-Band-SWIFT allows greatly increased excitation and acquisition bandwidths relative to original SWIFT for the same hardware switching parameters and requires less peak amplitude of the radiofrequency field (or greater flip angle at same peak amplitude) as compared to ZTE [49]. Multi-Band-SWIFT provides a bridge between SWIFT and ZTE sequences.

APPLICATIONS AND FUTURE DEVELOPMENTS

It was shown that SWIFT can successfully be used for: dental imaging [50] and detecting early carious lesions [51]; visualization lung parenchyma [52, 53]; detecting brain calcification [54] and traumatic brain injury [55]; tracking iron-oxide nanoparticles [28, 39, 56] and PARACEST contrast agents [36]; high-spatial-temporal-resolution dynamic contrast-enhanced MR breast imaging [24, 57]; identification prostate to bone tumor [37]; detection of mandibular invasion by carcinoma [58]; brain fMRI [59]; analysis of osteochondral tissue [29]; and craniofacial imaging [30].

To date, fully functioning SWIFT sequences have been implemented only on research scanners. The main limitation for clinical scanners arises from the limited T/R switching capabilities of available coils, which prevent in practice reaching high enough bandwidths. As a proof of principle, a low bandwidth SWIFT sequence was successfully implemented on a Siemens clinical scanner [60]. Future efforts will aim at developing fast T/R switches interfaced to clinical scanners, in order to take full advantage of SWIFT. It should be noted that GM-SWIFT and MB-SWIFT have lesser hardware restrictions and thus can be more easily implemented on clinical scanners adopted to use UTE and ZTE sequences.

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