# Reconstruction Strategies for MRI with Simultaneous Excitation and Acquisition

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## Introduction

Imaging of samples with very short T2 requires data acquisition to start immediately after excitation. In the radial FID method [1] this is accomplished by excitation and acquisition during a permanently applied gradient. However, for high bandwidths the FID approach must use very short RF pulses, limiting the possible flip angle according to the given maximum B1 amplitude. On the other hand, under identical conditions pulses with a frequency sweep and longer duration provide considerably larger flip angles [2]. With such an excitation, signals from different locations are shifted in time and dephased, and can be reconstructed after rephasing [3]. The SWIFT technique [4] combines the two described concepts by playing out a gapped frequency-swept pulse while concurrently acquiring data during the gaps. Thus samples with short T2 can be imaged also under B1 restrictions. Furthermore, the method incorporates the agreeable features of being fast and silent [1] and creating a reduced dynamic signal range [3]. With SWIFT a new, general concept of simultaneous excitation and acquisition (SEA) has been introduced. Data obtained in such a manner experience a hybrid net encoding that requires specific image reconstruction. For the SWIFT technique a deconvolution approach and different correction schemes have been proposed [5, 6]. Here, a more general reconstruction procedure is presented, derived from a description of the signal evolution for SEA. It is highly flexible and enables taking into account not only the pulse effects but also prolonged acquisition, gapped acquisition, and oversampling.

## Theory

Figure 1 shows the signal evolution in one-dimensional *k*-space over time for the experimental scheme indicated at the bottom, with a shaped RF pulse and the acquisition occurring during and also after the pulse [7]. The pulse shape is treated as a series of sufficiently short delta-like elements $p_i$. Assuming small flip angles, the spin system can be regarded as linear, and the total signal is the superposition of the signal contributions created by each pulse element. In Fig. 1 the signal of the first element $p_1$ is depicted by the uppermost diagonal line, travelling centre-out in *k*-space under the influence of the gradient. The signal contributions from the second and all further elements start later and are represented by shifted diagonals. Each of the signal trains is weighted with the amplitude and phase of the respective pulse element. Hence with SEA a hybrid net encoding is created by the B0 gradient and the time-varying B1. Signal acquired at a certain time point is the sum of all contributions coexisting at that moment, which all exhibit different encoding. In Fig. 1 each acquired sample is indicated by a vertical line. The shaded area represents the *k*-space range that corresponds to the targeted spatial resolution. Unlike the original SWIFT technique it is assumed that data acquisition continues after the pulse until all signals have fully covered this range. Early signal portions therefore reach much higher *k*-values.

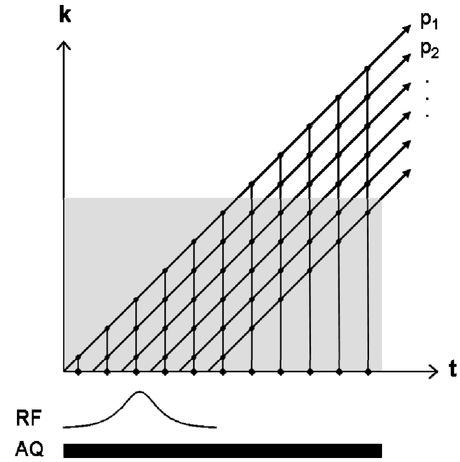


**Figure 1** Signal evolution and acquisition with SEA.

## Methods

Image reconstruction of SEA data is viewed as a general inverse problem based on a complete forward description of the linear encoding procedure. The encoding scheme described in Fig. 1 can be expressed in matrix form as $\mathbf{s} = E\boldsymbol{\rho} = PF\boldsymbol{\rho}$ where the vectors $\boldsymbol{\rho}$ and $\mathbf{s}$ represent the object and the acquired data, and the encoding matrix *E* is made up by the gradient-driven Fourier part *F* and the pulse description *P*. This matrix representation is illustrated in Fig. 2, where the structure of *P* reflects the signal evolution according to Fig. 1. Reconstruction now consists of building *E*, calculating its inverse, and applying it to the measured data. For 3D data only the last step has to be repeated for every projection, followed by Fourier transform and a standard gridding procedure. Besides being exact the general inverse perspective also renders image reconstruction very flexible. Oversampling, which can serve for implicitly extrapolating missing initial data [8], is easily integrated. The temporal spacing of the data does not need to be regular, readily accommodating the acquisition gaps during RF pulsing. Real or complex profiles can be reconstructed from half or full *k*-space acquisition, respectively. Specific attention has to be paid to the high *k*-values outside the shaded area in Fig. 1 and in *P* in Fig. 2, respectively. Straightforward consideration in a reconstruction for the targeted resolution causes ringing artefacts due to misinterpretation. Instead, the image data is requested for the resolution corresponding to the highest *k*-value, accompanied by regularisation. Alternatively, similar results are obtained by simply ignoring the high *k*-values and setting the corresponding part in *P* to zero.

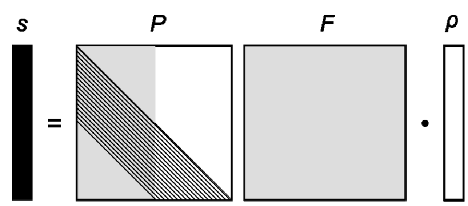


**Figure 2** Matrix representation of SEA encoding.

## Results

SEA imaging was performed on a 4.7 T Bruker BioSpec animal system. The scheme shown in Fig. 1 was applied with a hyperbolic secant sweep pulse during the first 240 µs of the 1.2 ms acquisition time. The used bandwidth of 50 kHz corresponds to dwell intervals of 20 µs that were recorded with 16-fold oversampling. Neglecting sub-pulse (2.5 µs), transmit-receive switching (5 µs), and group delay of the digital filter (3 samples) left 7 samples per dwell time to enter the reconstruction. Incorporating all this information into the reconstruction procedure, the image data was directly obtained without the need for further processing or corrections as suggested for SWIFT [4-6]. A spherical sample with long T2 was used to demonstrate the high reconstruction fidelity. Figure 3 shows a slice from 3D SEA data set with matrix size $96^3$. Besides common Gibbs ringing the image is entirely free of artefacts, in particular no bulls-eye artefact is present, as frequently reported for SWIFT. In conclusion, new reconstruction concepts for simultaneous excitation and acquisition have been proposed, enabling artefact-free imaging at about 10 µs echo time even under B1 limitations.

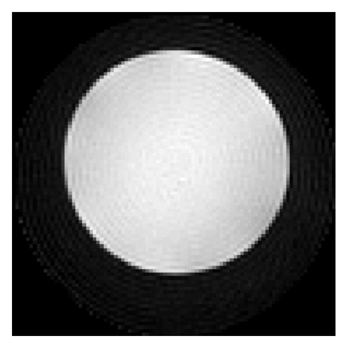

**Figure 3** SEA image with 50 kHz bandwidth.

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