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Technical Note

THE APPLICATION OF STEADY-STATE FREE PRECESSION IN RAPID 2DFT NMR IMAGING: FAST AND CE-FAST SEQUENCES

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In the classic spectroscopic steady-state free precession (SSFP) experiment, a regular sequence of phase-coherent radio frequency pulses is applied with constant flip angle and a repetition time shorter than the NMR relaxation times of the sample. As the steady state is reached, an NMR signal appears between pulses that consists of two distinct components: a free induction signal following the RF pulses and decaying during the repetition interval and a spin-echo-like signal forming at its end prior to the subsequent RF pulse. Both signals may be exploited for NMR imaging if the gradient schemes fulfill the phase coherence requirements of SSFP. This article describes two Fourier acquired steady-state sequences dubbed FAST and CE-FAST, which may be used for the rapid acquisition of NMR images from the SSFP signals.

Keywords: **FID, Free induction decay.**

INTRODUCTION

NMR pulse sequences with sequence repetition times shorter than the spin-lattice and spin-spin relaxation times may generate steady states in both the longitudinal and transverse magnetizations. This results in the partial saturation of the longitudinal magnetization and the establishment of transverse phase coherence between successive repetitions. In the steady-state free precession sequence,[1,2] phase-coherent RF pulses of the same flip angle are applied with a constant and short repetition time. The FID following each RF pulse is refocused by the next RF pulse to form a spin echo at the end of the next repetition interval. Accordingly, the SSFP signal has two contributions: an FID component occurring at the start of each repetition interval and an echo component (the "SSFP echo") at the end just as the next RF pulse is applied. Obviously, the FID component may be observed at any repetition time independently from any particular phase requirements since it is formed principally from fresh longitudinal magnetization. On the contrary, the echo component is formed only from coherences in the transverse magnetization and is observable for repetition times comparable or shorter than the transverse coherence time, T_2.

RF pulses are applied coincidentally with the formation of each SSFP echo. Of course, each pulse excites an FID from fresh longitudinal magnetization. The pulse also acts on the echo signal, carrying its coherent transverse magnetization into subsequent repetitions[3,4] where it will contribute to the signal in the form of stimulated echoes and higher-order spin echoes occurring coincidentally with later FIDs and echoes. In this way, coherence is transferred from the one interval to the subsequent intervals. Therefore, when the sequence repetition time is shortened there will be additional contributions to the FID signal that arise only from transverse coherence.

If the RF pulses are phase coherent, then all the echo and FID components will contribute to the observed signal in a coherent manner for all repetitions. This is the basic principle of SSFP. In a spectroscopic SSFP experiment, phase coherence simply implies a fixed phase relationship between subsequent RF pulses, but in an SSFP imaging experiment it leads to the

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additional requirement that the net effect of any applied gradient waveforms must be constant for all repetitions.

The FLASH technique[5] acquires only the FID part of the SSFP signal. It uses small RF pulse angles in conjunction with short repetition times. In this way, each RF pulse generates a small amount of transverse magnetization without significantly depleting the longitudinal magnetization. The resulting NMR signal is then interrogated using normal gradient echo methods. Any residual transverse magnetization at the end of the repetition interval is deliberately spoiled[6] and it is therefore assumed that it does not participate in later repetitions. The phase-encoding gradient necessarily has a different amplitude for every repetition and isochromats located away from the center of the phase encoding axis will experience different precession angles in every repetition. If there is transfer of transverse magnetization between repetitions, the constantly changing precession angle may give rise to image artifacts.[6]

This article describes a modification of the original FLASH sequence that meets the phase-coherence requirements of SSFP techniques by the addition of a second gradient pulse in the phase-encoding gradient axis, FAST. A further modification is described that may be used to form images from the SSFP echo signal, CE-FAST, providing access to different contrast capabilities.

METHODS

The basic sequence used to collect NMR data from the SSFP FID is shown in Fig. 1.[7,8,9] It is essentially identical to the FLASH sequence, collecting data by gradient echoes, and differs only in the phase-encoding gradient. The steady state is established by repeated application of the basic sequence. NMR data are then acquired for all the requisite values of the phase-encoding gradient. If a monopolar phase-encoding gradient pulse is used, the precession angle of spin isochromats will be different for every repetition, and the transfer of tranverse magnetization between successive repetitions will also be changing as the sequence proceeds, perturbing the steady state and causing image artifacts. The FLASH sequence may be modified by adding a second gradient pulse in the phase-encoding direction after data collection to exactly cancel the effect of the phase-encoding pulse. This ensures that the SSFP requirements are exactly met. This bipolar phase-encoding gradient forms the basis of the FAST and CE-FAST sequence—Fourier Acquired Steady State.

The echo contributions in the SSFP sequence may

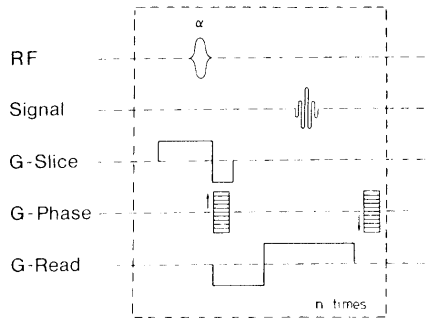

Fig. 1. Radio-frequency pulse and magnetic field gradient sequence for the acquisition of 2DFT images from the SSFP FID signal, the FAST sequence. The phase-encoding gradient pulse preceding signal collection is exactly canceled by the second pulse in the phase-encoding gradient. This approach ensures that the steady state is preserved throughout the experiment.

be easily understood in terms of the original Hahn spin echo experiment.[9] Two RF pulses separated in time by an interval will give rise to a spin echo after a further interval of the same duration. If adjacent pairs of pulses in the SSFP sequence are identified with the Hahn experiment, it is clear that the FID following the first pulse is refocused by the second pulse to give a spin echo that peaks just as the next RF pulse is applied, and the echo time is twice the repetition time. Therefore, in the steady state one may conclude that every pulse is followed by an FID and every pulse is preceded by a spin echo. And, of course, the spin echo will be overlapped by multiple echoes arising from more complicated coherence pathways as discussed later. The analogy with the Hahn experiment also leads to the conclusion that the signal intensity of the SSFP echo is simply that of the SSFP FID weighted by T_2 over two repetitions, leading to a corresponding improvement of T_2-based contrast for images derived from the echo as compared with the FID. Hence the acronym, CE-FAST, standing for Contrast Enchanced FAST.

The gradient scheme used in the CE-FAST sequence is shown in Fig. 2. The signal acquired in cycle $n + 1$ is the rising edge spin echo of the FID in cycle n. The slice selection rephasing for the spin echo is performed at the end of cycle n. The gradient-shifted SSFP echo forms in the presence of the read gradient in cycle $n + 1$ at a time when the integral gradient matches that in cycle n. The phase-encoding gradient in cycle n has no net effect and so the spin echo signal is encoded only by the phase-encoding gradient preceding it in cycle $n + 1$. The sequence is an exact time reversed version of the FAST sequence[8,11,12] and has, in principle, the same chemical shift and magnetic

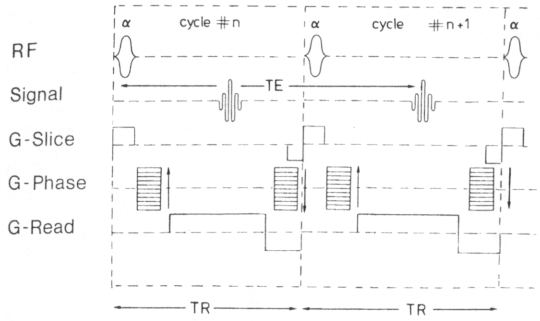

Fig. 2. Radio-frequency pulse and magnetic field gradient sequence for the acquisition of 2DFT images from the SSFP echo signal, the CE-FAST sequence. Two repetitions of the sequence are shown. The signal shown in interval $n + 1$ is the gradient shifted spin echo of the FID following the RF pulse in interval n. The slice selection rephasing for the echo is performed at the end of cycle n. The echo forms in the presence of the read gradient in cycle $n + 1$ at a time when the integral gradient matches that in cycle n. The phase-encoding gradient in cycle n has no net effect and so the echo signal is encoded only by the phase-encoding gradient preceding it in cycle $n + 1$.

field susceptibility dependences as normal gradient echo imaging.

RESULTS

Experiments on human volunteers and patients have been carried out using a 0.5-T Vista MR system (Picker International Ltd., Wembley, England) and a 0.26-T Picker system at the University of Manchester Medical School, England. Figure 3 compares images obtained from the SSFP FID (a) and from the SSFP spin echo (b) using the FAST and CE-FAST sequences, respectively. The images were acquired from the same volunteer using the same repetition time (20 ms) and RF flip angle (25°) on a 0.5-T system. The acquisition times were 10 seconds for the FAST image with 2 acquisitions per view and 80 seconds for the CE-FAST with 16 acquisitions per view. The poor contrast in the FAST image arises because the FID signal is strongly dependent on the ratio T_1/T_2,[2] and for gray and white brain this parameter is the same to within 1%.[2] The image taken from the SSFP echo using the CE-FAST sequence exhibits much more contrast between gray and white matter primarily due to T_2 differences. The signal intensity from the scalp and bone marrow are considerably reduced compared to the FAST image due to short T_2, and also the sagittal sinus is no longer evident. The contrast between gray and white brain for CE-FAST increased for flip angles less than about 25° and there appeared to be

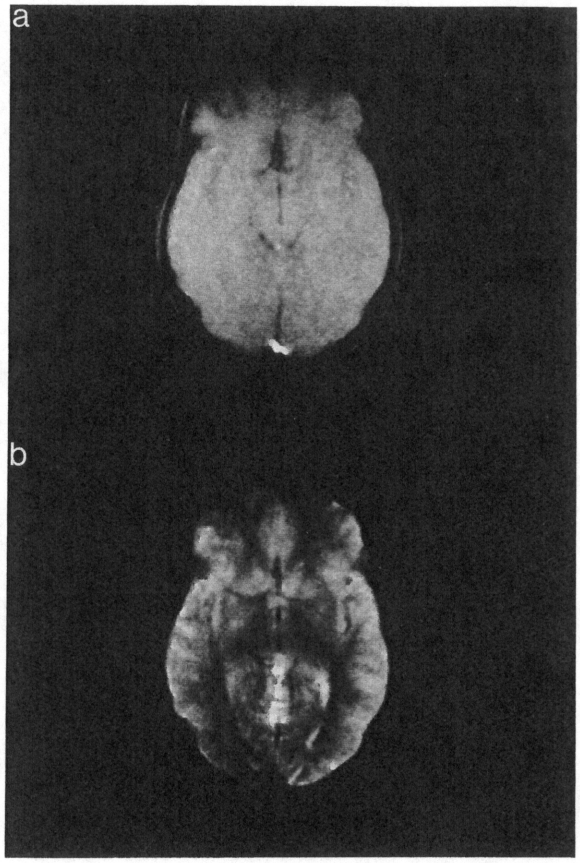

Fig. 3. 21-MHz ^{1}H NMR images (0.5 T) of the head of a normal volunteer obtained using the FAST and CE-FAST sequences with a repetition time of 20 ms and an excitation flip angle of 20°. The FAST image (a) was obtained in 10 seconds with 2 excitations per view. The CE-FAST image (b), obtained in 80 seconds with 16 excitation, shows far better image contrast for essentially the same imaging conditions.

no contrast between the two above 30 to 35°. It is also possible to increase the contrast between gray and white matter by increasing the repetition time, but there is a corresponding signal to noise penalty due to T_2.

Another major difference between the FAST and CE-FAST images is the appearance of flow through the slice that shows strongly in the FAST and is absent in the CE-FAST image. This difference arises because fresh material flowing into the slice between repetitions has not been saturated by the pulse sequence giving a strong signal in the FID, the absence of contributions due to flow in the echo signal is due to "odd-echo dephasing" and the fact the material may have moved out of slice before it has been acted on by the next RF pulse as is required for echo formation.

The improved contrast from the CE-FAST sequence compared to FAST is also evident for pathologic conditions.[14] Figure 4 shows FAST (a) and CE-FAST (b) brain images of a 68-year-old male who had been receiving radiotherapy for a suspected low-grade glioma. The sequence repetition time was 20 ms for both images and an RF flip angle of 45° was used. The acquisition times were 10 seconds for the FAST image with 2 acquisitions per view and 40 seconds for the CE-FAST image with 8 acquisitions per view. The improved time performance for the CE-FAST sequence as compared to the previous case may be attributed to the higher flip angle giving more accessible signal. The CE-FAST image (b) clearly shows the pathology. In this case, contrast between the brain and the lesion was optimal with a 45° flip angle and absent for flip angles of less than 15 to 20°. The poor contrast in the FAST image between the normal brain and the lesion arises because the ratio of the relaxation times is close to that of normal brain with only a 4%[13] difference in this case.

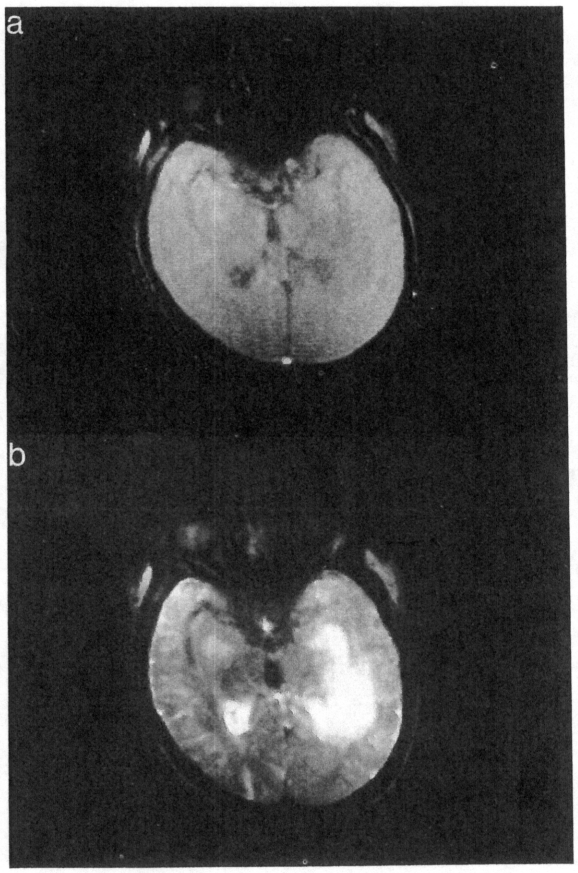

Fig. 4. 21-MHz ^{1}H NMR images (0.5 T) of the head of a 68-year-old male who had been receiving radiotherapy for a suspected low-grade glioma. Both images were acquired with a sequence repetition time of 20 ms and an excitation flip angle of 45°. The CE-FAST image (b) again shows far better image contrast and clearly delineates an area of involvement not demonstrated by the FAST image (a). The scan times and signal averaging parameters were 10 seconds and 2 excitations for the FAST image and 40 seconds and 8 excitations for the CE-FAST image.

DISCUSSION

Images of the brain acquired using the FAST sequence tend to show relatively poor contrast and this appears to be almost independent of pulse angle. This agrees qualitatively with a mathematical description of the SSFP signals,[15,16] which shows that on the basis of typical tissue parameters[13] the spread of signal intensities for the SSFP FID as a function of pulse angle for gray matter, white matter, malignant tumor, and infarct is only about 10% for flip angles in the range of 10 to 90°. The model predicts a better spread of signal intensities for the SSFP echo, for the tissues mentioned above, with a range of 50% at flip angles of 10° and 35% at 90°. It also indicated that the gray/white matter contrast would be better at lower flip angles, which again is in good qualitative agreement with the CE-FAST images. This is a somewhat surprising result, but of course the higher-order echoes with their more pronounced T_1 and T_2 weightings have increased importance relative to the principal spin echo at lower flip angles.

It has been suggested[17] that the ratio of the SSFP echo to the SSFP FID is simply given by the T_2 decay over two repetition intervals and independent of pulse angle (i.e., $S_{\text{echo}}/S_{\text{FID}} = \exp(-2T_R/T_2)$. In view of this and the fact that the image contrast for the SSFP FID is poor, at least in the brain, one might conclude that the better contrast observed for the SSFP echo is entirely due to T_2 effects, and furthermore that the CE-FAST images are just FAST images with a weighted by T_2 over two repetitions. This view is somewhat oversimplified in that it neglects contributions from stimulated echoes formed after three successive pulses and other echo signals formed after four or more pulses. The overlap of these echo signals complicates the T_1 and T_2 dependences of the SSFP echo signal and modifies contrast behavior.

If the difference between SSFP echo and the FID was entirely T_2 based, one would expect that the flip-angle dependence of contrast for CE-FAST would be the same as that of FAST. The fact that contrast in CE-FAST is strongly flip angle dependent, whereas that of FAST is only weakly flip angle dependent, suggests that other forces are at play. The spin echo

model only provides one part of the story and suggests only T_2 dependent differences between echo and FID.

If stimulated echo effects are considered, it is possible to draw an analogy between a three-pulse experiment and SSFP. The first pulse excites an FID. The second pulse applied after a short delay generates longitudinal magnetization from the FID. The third pulse applied after a further delay gives rise to a stimulated echo. If three consecutive pulses in the SSFP sequence are identified with the three pulses in the stimulated echo model, it is easy to see that the stimulated echo occurs at the same time as a subsequent RF pulse, and this is also coincident with the spin echo described earlier. Therefore, it can be said that the SSFP echo has a spin echo component and also a stimulated echo component. The ratio of the stimulated echo component to an FID will be $S_{ste}/S_{FID} = \exp(-2T_R/T_2) \times \exp(-T_R/T_1)$, and additional T_1 dependence has been introduced.

The flip-angle dependence of the spin echo component is $\sin^2 \frac{1}{2}\alpha$ compared to the FID whereas that of the stimulated echo component is $\frac{1}{2} \sin^2 \alpha$. If relaxation is ignored, the two components will contribute equally for a 90° flip angle, but for 45° the stimulated echo with its extra T_1 dependence will be over two times stronger than the spin echo, and T_1 will play a more important role at lower flip angles. Therefore, one must conclude that contrast behavior of the SSFP echo signal, being a composite signal, will be flip angle dependent.

Obviously, the consideration of four and more pulse echo pathways will reveal further complexity in the way that the SSFP echo signal is formed from the FID. A paper discussing theoretical aspects of SSFP is in preparation.[14]

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