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FISP — a new fast MRI sequence

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We have developed a new pulse sequence, FISP, for magnetic resonance imaging. It allows recording magnetic resonance images with a high signal-to-noise ratio in a few seconds and is therefore well suited for scanning with low magnetic field strengths.

In magnetic resonance imaging (MRI) usually a spin-echo sequence is used, because it allows image contrast to be controlled over a wide range via repetition and echo time and is insensitive to static magnetic field inhomogeneities. Multislice and multiecho modifications allow the acquisition of 10—20 images in several minutes, corresponding to an average time of measurement of 10—20 s per single image. Respiratory gating makes possible the investigation of the chest and ECG triggering, even that of the beating heart [1].

In spite of the short average time of measurement per image the long total imaging time has led to the demand for methods to obtain a complete MR-image within a few seconds: This would permit the acquisition of survey images, making respiratory gating unnecessary, and make possible functional studies, e.g. with contrast agents. Indeed such images can already be created with the normal spin-echo sequence; by using a repetition time of less than 100 ms a complete matrix of 128 x 128 pixels is acquired within less than 13 s (see e.g. Fig. 2).

The signal-to-noise ratio, however, is decreased because of saturation of the spin system by the rapid sequential application of 180 degree pulses. So only tissues with short longitudinal relaxation times, such as fat, are displayed. Special fast pulse sequences such as echo planar imaging (EPI) [2] and RARE (rapid acquisition relaxation enhanced) [3] in principle enable the acquisition of a complete image within the order of magnitude of the transverse relaxation time, T_2, i.e. 100 ms. Besides the problem that the generation of the necessary strong, rapidly switching magnetic gradient fields has not yet been solved for clinical MR units, the signal-to-noise ratio from only one data acquisition might not be sufficient. Averaging, however, requires recovery within the longitudinal relaxation time, T_1, in order to avoid saturation, so that again only total measurement times of seconds are realistic for a single image.

A modification of the stimulated echo acquisition mode (STEAM) [4] has been proposed for fast imaging within the order of magnitude of T_1 by using so-called fractional pulses; these cause flip angles less than 90 degrees. Assuming n fractional pulses for a desired image of $n \times n$ pixels, however, each pulse reads out only $\frac{1}{2\sqrt{n}}$ of the signal from the total spin magnetization; EPI and RARE make use of the full magnetization in each echo. Therefore, fast stimulated echo imaging does not appear to be a very attractive alternative, even at high field strength.

FISP — Fast Imaging with Steady Precession

We have tested a new fast imaging scheme, which avoids the disadvantages of the above-mentioned sequences and nevertheless makes possible imaging within seconds. It has long been known that exposing a nuclear spin system to a steady series of equally spaced radiofrequency (rf-) pulses gives rise to a state of dynamic equilibrium, which for spins with $T_1 \approx T_2$ (e.g. fluids) shows a free precession magnetization of one half of the total magnetization when the rf-pulses are phase-alternating [5]. Imaging with steady state free precession has been demonstrated previously [6]. However, since image plane selection was achieved by nonselective rf-pulses and an oscillatory magnetic field gradient together with averaging, this method was not sufficiently fast.

In our case selective rf-pulses are applied and gradients are switched in such a manner that the phase of the transverse spin magnetization is preserved. Fig. 1 shows the pulse sequence for a 2-D Fourier experiment. Modifications for 3-D imaging are uncomplicated and consist of applying nonselective rf-pulses and a second encoding gradient. Using a sampling time of 50 µs, imaging times of 2.5 s for a matrix of 128 x 128 pixels are possible; to obtain a 3-D data set slightly more than 5 min will be required. Similar pulse sequences have been proposed independently as FEE (fast field echo) by *van der Meulen* et al. [7] and as FLASH (fast low angle shot imaging) by *Haase* et al. [4].

Fig. 2 shows an image of a volunteer taken with the normal spin-echo sequence at a rapid repetition rate (100 ms), resulting in an acquisition time of 13 s. Fig. 3 shows the same image plane taken with the FISP sequence within 9 s and two averages: The signal-to-noise ratio is definitely improved, while fatty and watery tissue are also displayed (see e.g. the harmless polyp in the paranasal sinus). A magnetic field strength of 0.23 T was used in both cases.

Another (abdominal) image taken with the FISP sequence at 2 T is shown in Fig. 4. Because of the short time of measurement breathing artifacts are reduced, but flow artifacts are still present.

Discussion

In order to maximize the image intensity, the interval between two adjacent pulses should be shorter than the relaxation times T_1 and T_2. Neglecting field inhomogeneities the signal intensity obtained with the FISP-sequence is a function of the pulse angle, α, the spin density, ρ, and the ratio of the relaxation times, T_1/T_2:

$$S = \frac{\rho \sin \alpha}{(1 + T_1/T_2) + (1 - T_1/T_2) \cos \alpha}$$

For 90° pulses, the image intensity is proportional to $\frac{T_2}{T_1 + T_2}$; in the case of $T_1 = T_2$, e.g. for fluids, this becomes $^1/_2$ of the total magnetization.

FISP images thus show different tissue contrast as compared with normal spin-echo images, and fluids yield maximum signal. For a given ratio T_1/T_2, the signal can be maximized by using a flip angle α according to:

$$\alpha_{opt} = \arccos \frac{\frac{T_1}{T_2} - 1}{\frac{T_1}{T_2} + 1}$$

This is demonstrated in the image series of Fig. 5, in which the flip angle of the rf-pulses has been successively reduced.

Starting the sequence with equally spaced rf-pulses, the magnetization will reach dynamic equilibrium after a few pulse periods. To avoid image artifacts it is therefore necessary to apply a number of prescans before data acquisition. The number of prescans depends directly on the longitudinal relaxation time, T_1. Continuously increasing the pulse angle will reduce the number of prescans and therefore shorten the preparation time.

The condition already mentioned, that of preserving the phase of the spins af-

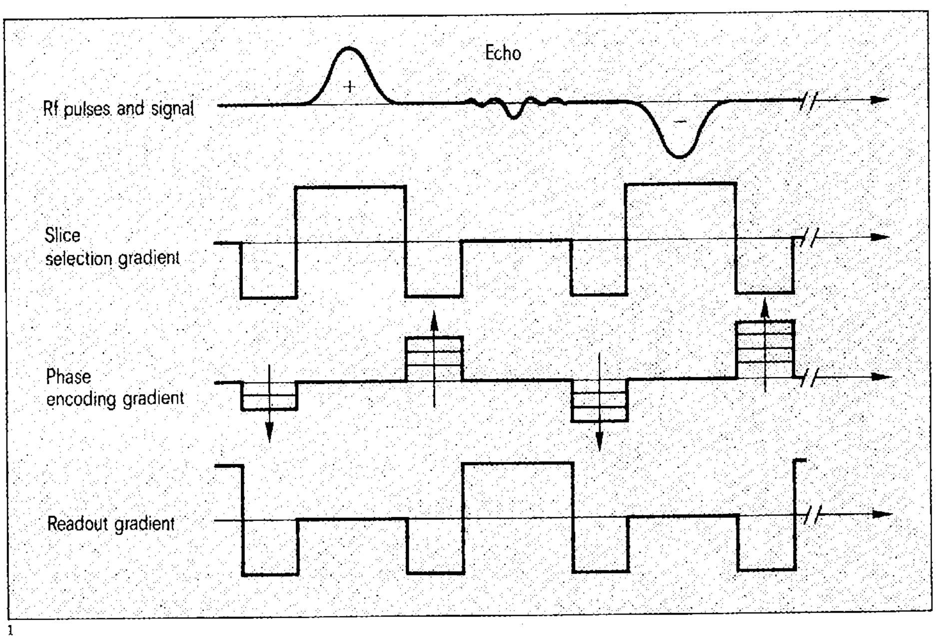

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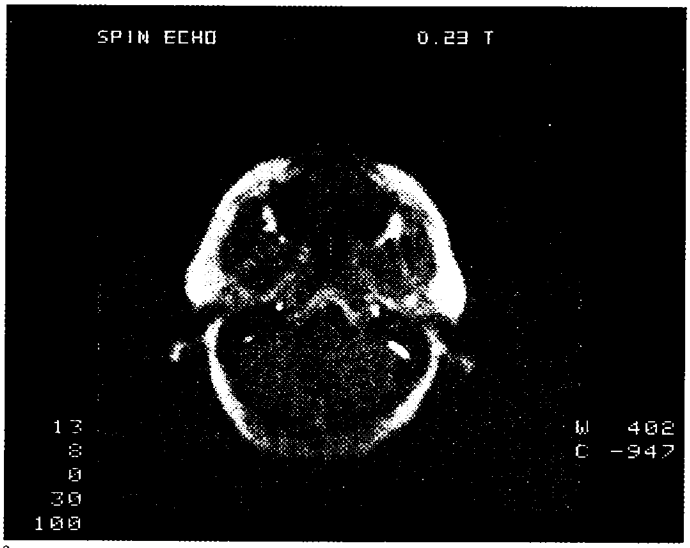
Fig. 1 FISP-Sequence for 2-D-Fourier-Method showing the alternating selective rf-pulses and the gradient switching to preserve the spinphase

Fig. 2 Section through the head using a normal spin-echo sequence with a time of measurement of 13 s. The image was taken with a magnetic field strength of 0.23 T (matrix size 128 x 128)

Fig. 3 Same section as in Fig. 2, using the FISP-sequence within a time of measurement of 9 s (with two averages) with a magnetic field strength of 0.23 T. The signal-to-noise ratio is higher than in the image of Fig. 2. Tissues with approximately equal relaxation times T_1 and T_2, e.g. fluids, appear bright. See e.g. the harmless polyp in the paranasal sinus

Fig. 4 FISP-image of the human abdomen of a healthy volunteer. The time of measurement was 10 s, and two averages were made using a 2 T superconducting magnet. Breathing artifacts are reduced, but flow artifacts are still present. Chemical shift artifacts are visible at the edges of the organs

Fig. 5 Four FISP-images of the same slice made with different pulse angles at 2 T. The upper left image was taken with a pulse angle of about 90°, showing the best contrast between fluid and other tissues. Decreasing the pulse angles in steps of about 20° results in a decreasing image contrast



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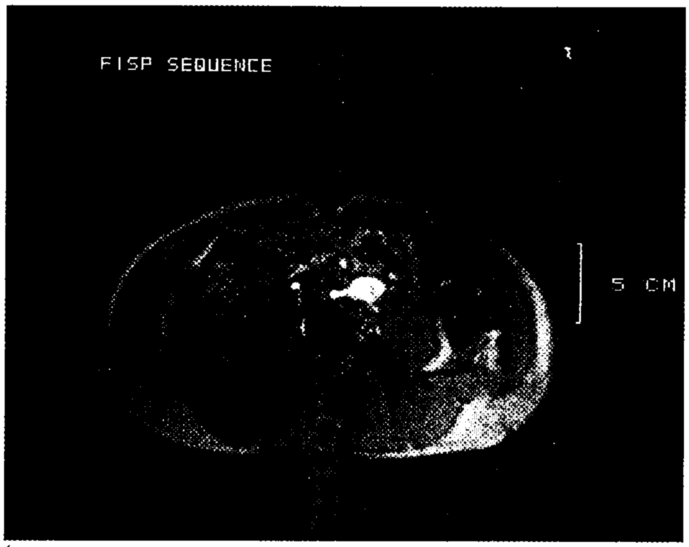

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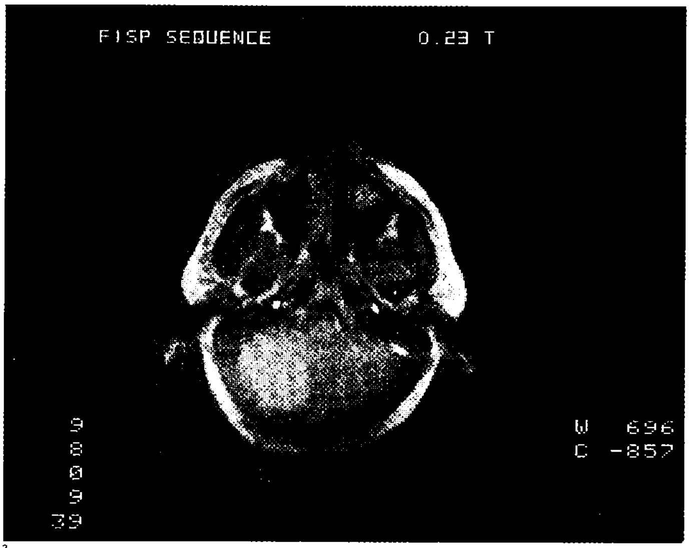

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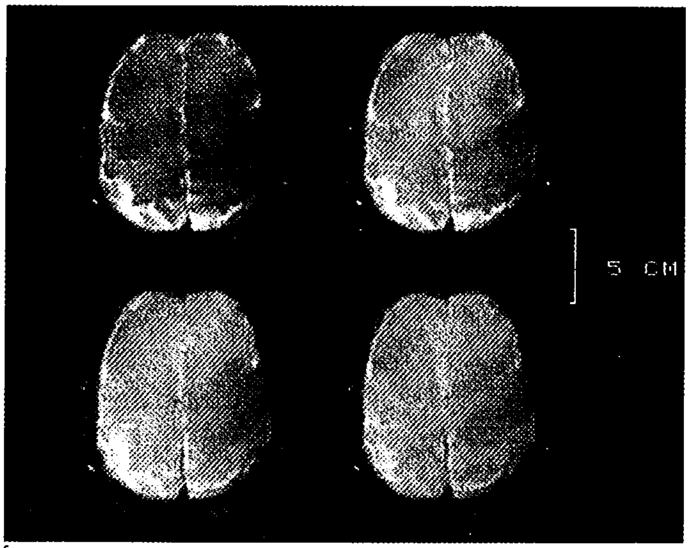

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ter the foregoing and before the next rf-pulse, requires either very homogeneous magnetic fields or very strong magnetic field gradients. Field variations of 10^{-5} T could be tolerated for head images at low fields, i.e. 0.2 T. Such low fields permit even less complicated pulse sequences, partially without rephasing gradients. Higher field inhomogeneities, however, led to intolerable artifacts. In the case of high-field whole-body images, a homogeneity of better than 10^{-6} T over the imaging regime has been achieved.

Concluding remarks

A new MR imaging sequence, FISP, has been developed. It makes MRI possible in a few seconds, with a very high signal-to-noise ratio; it is therefore well suited even for low magnetic fields. Since it uses only 90 degree (or less) pulses, less rf-power reaches the patient; this makes FISP attractive also for high-field imaging. Watery tissue and fluids deliver maximum signal, so that tissue contrast is different compared with the usual spin-echo sequence. Whether grey and white matter in the brain can be distinguished is still an open question.

No special hardware not already present in standard clinical MRI units is required, but high field homogeneity is essential. Though there is a large contrast between fluid and tissue, it remains to be seen if the contrast between different tissues is sufficient for medical diagnosis. Whether fast imaging with steady precession will be generally accepted or limited to special applications is therefore still not clear for the present.

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