Magnetic Field Mapping and NMR Imaging by Multi-Frequency SENEX

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Nuclear magnetic resonance imaging (MRI) of selectively excited protons has been used for magnetic field mapping in a 1.5 T whole body imager. The imaging has been performed with a modified two pulse SENEX sequence, adapted to single- or multislice operation. The usual spin-echo image is superimposed by field markers which are created by a periodic non-excitation. Results of the method in the fields of image quality control, influence of the susceptibility of an object, and shim and gradient current field response are presented.

Introduction

Nuclear magnetic resonance imaging (MRI) is now a well established method for medical diagnosis. This tomographic technique requires a static magnetic field with a high homogeneity over a large volume in order to keep image distortions below a certain level. In addition, however, the externally applied field is modified by the object itself, and a magnetic field shimming procedure is often run to reduce this effect. Some imaging sequences, especially those with a gradient refocusing scheme, are more sensitive to a poor homogeneity than others, but this can also mean that the image distortions are only better visible. However, local inhomogeneities within the sample cannot be compensated for by applying additional shim fields. It is therefore of great interest to get insight in the behaviour of the internal magnetic fields in order to elucidate the origin of artifacts, to quantify their influence, or to built up a basis for correction programs. A method which combines the usual imaging mode with a presentation of the internal magnetic fields produced by the inhomogeneity of the sample could solve such problems.

Apart from the routine use in MRI it is also important from the manufacturer's point of view to have a quick display method for magnetic field contour plots to check the final homogeneity of the field, e.g. after installation of the magnet at the customer's site. It should also be possible to monitor the field response of shim and gradient currents in all three dimensions.

Mapping of magnetic fields is based upon the conversion of the intrinsic phase information of the magnetic resonance imaging experiment to intensity variations of an image. However, only a few approaches to this problem have been published [1–5] in the past. In the following we present a method which is based upon the SENEX spin echo sequence [6] where the $90°$ excitation is splitted in two $45°$ pulses. It will be shown that the spectral resolution is variable and the multislice option allows a rapid three dimensional representation of the internal magnetic field of phantoms and other objects without time-consuming data handling. We shall compare this technique to a sequence recently introduced by Willcott et al. [4] which is essentially based upon a Hahn triple-pulse spin echo experiment [7].

The Field Imaging Pulse Sequence

The complete imaging sequence used is shown in Figure 1. Because the chemical shift cannot be discriminated against the spatial changes of the strong static field we shall consider samples with only one chemical shift component at the moment. A graphic illustration of how pulse trains in NMR work is often given in terms of magnetization vectors in the rotating coordinate frame which can serve to explain the temporal behaviour of depicted spins. We first consider the state before the first excitation pulse and select two volume elements of a sample consisting of only one chemical shift component as shown in Figure 2. The magnetic field strength at these points may slightly differ.

Fig. 1. Timing protocol of the whole two pulse SENEX spin echo sequence for magnetic field imaging.

Fig. 2. Simple vector representation of the two pulse excitation in the inhomogeneous field for two selected volume elements 1 and 2.

At the beginning the magnetization vectors are aligned along the ground field direction B. The first excitation pulse rotates both of these spin ensembles 45° out of this direction. During the following evolution period they begin to dephase due to the different resonance frequencies. After a time τ has been allowed to elapse both of the vectors show a phase difference of 180°. If the second pulse is applied now, it will move the magnetization of one of the volume elements back to the direction of the static field B. No NMR signal of this ensemble can be detected. The other will be rotated another 45° down to the transverse plane and will therefore complete a standard 90° excitation. For these extreme cases this will simply speaking give rise to a bright pixel for the latter and a dark pixel for the other volume element. The corresponding difference in field strength and hence the resolution is given by the waiting period τ.

This instructive view may hide some special features of the technique. We therefore start from the complete description of the NMR experiment by directly looking at the solution of the Bloch equations [8]. The function of both the two [6] and three pulse [4] technique may be understood by their frequency dependence. The transverse magnetization obtained by this excitation is plotted versus frequency in Figure 3. Apparently there is no net transverse magnetization at certain equidistant frequencies.

Now these frequency positions can serve as "field markers" if we let define the frequency axis by the inhomogeneities of the ground field in the image plane. In other 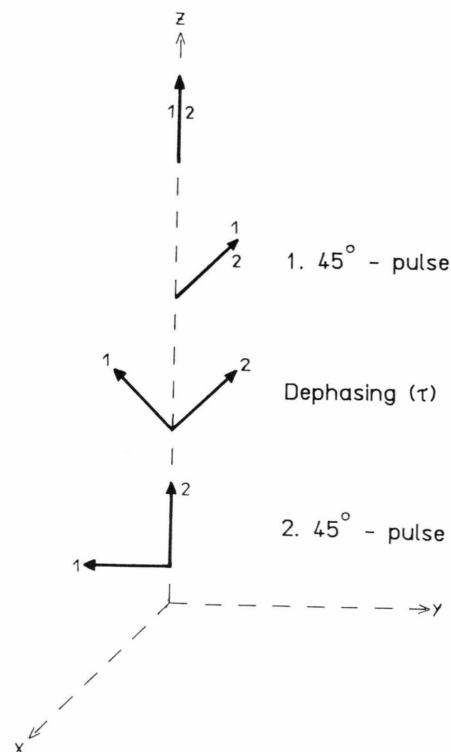words, the intensity of each pixel is now a function not only of the spin density and the relaxation times T_1 and T_2 of the material in the corresponding voxel but is additionally governed by the local magnetic field variations in the object. Therefore we expect dark pixels from non-excited voxels where the local field deviates by a pre-set value from nearby points which are exposed to the full 90° excitation resulting in contour lines of equal magnetic field. In contrast to the two pulse technique (Fig. 3a) the three pulse method will show more minima and intermediate grey levels due to the side maxima occurring in the frequency dependence of the transverse magnetization (Figure 3b). It should be mentioned that these "interference" techniques allow access to phase shifts due to the ground field inhomogeneity without making use of phase images. This is the general principle of interference which is frequently used in several fields of physics. The double-pulse technique e.g. shows some physical aspects of optical interferometry where imperfections of an object's surface cause the phase shift between interfering light beams. The me-
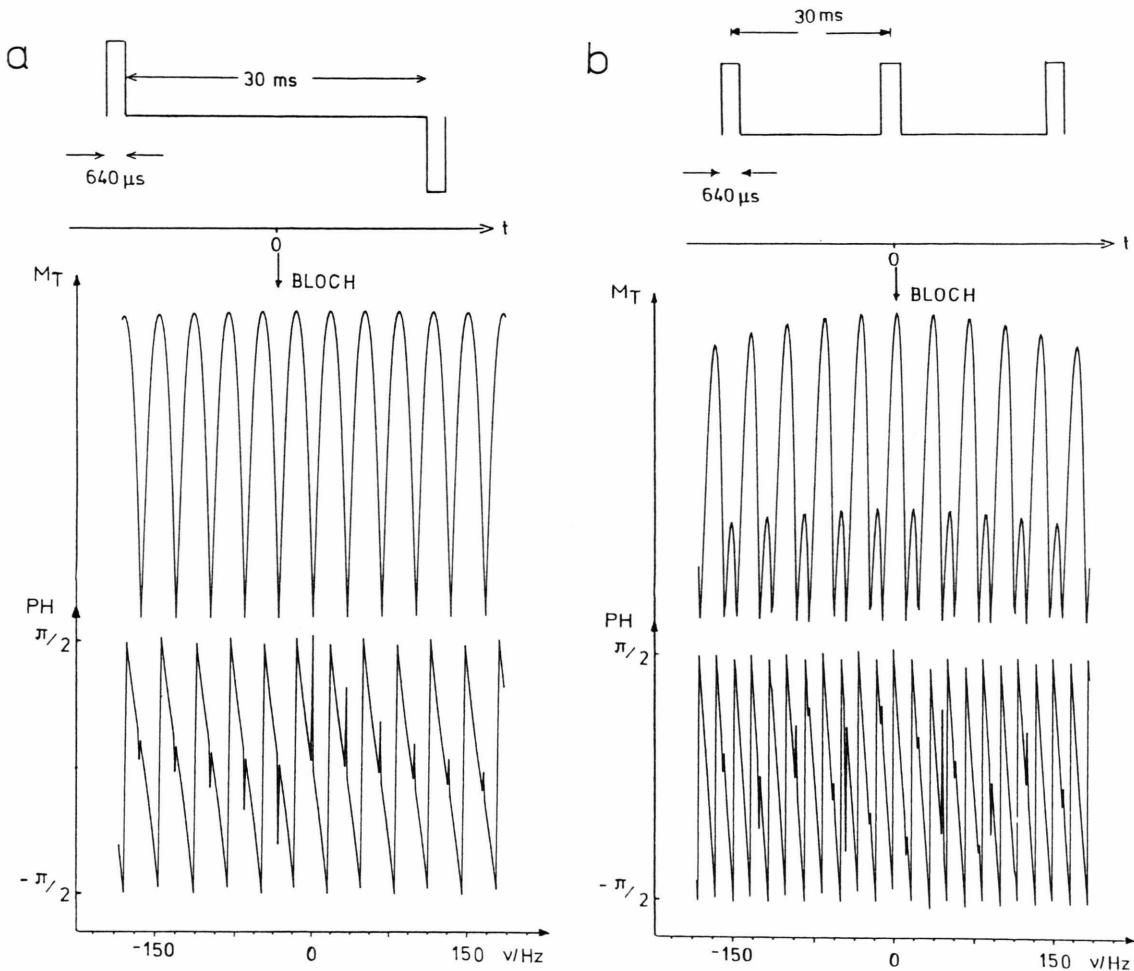
Fig. 3. Transverse magnetization M_T and phase PH after application of the two pulse excitation (a) and the three pulse sequence from Willcott et al. [4] (b) as function of the frequency in the vicinity of the carrier frequency, obtained from the numerical solution of the Bloch equations. Remark the side bands for the magnetization in the case of the three pulse sequence.

chanical depth information is obtained from contour lines which are nothing else than the extreme values of the Airy-function. It is this function which describes the conversion of phase differences to intensity variations in this case. In our case it is done by the Bloch equations.

Experimental

The experiments have been performed on a whole body imaging system Siemens Magnetom at a magnetic induction of 1.5 T. The gradient and signal detection timing protocol of the 1-$\bar{1}$ imaging sequence

(Fig. 1) is basically the same as reported for the 4- and 5-pulse frequency selective SENEX schedule [6].

In fact, the rf-pulse train timing was consequently developed from that sequence making some considerations to meet the different experimental requirements: where the multi-pulse technique demands a broad unexcited region around the central frequency to be insensitive to ground field inhomogeneities and a certain frequency offset between the excitation maxima in order to suppress one chemical shift component of the sample, the double-pulse SENEX is designed to offer a series of consecutive frequencies or field markers spaced fine enough to be sensitive to the inhomogeneities of the ground field. Again, both of
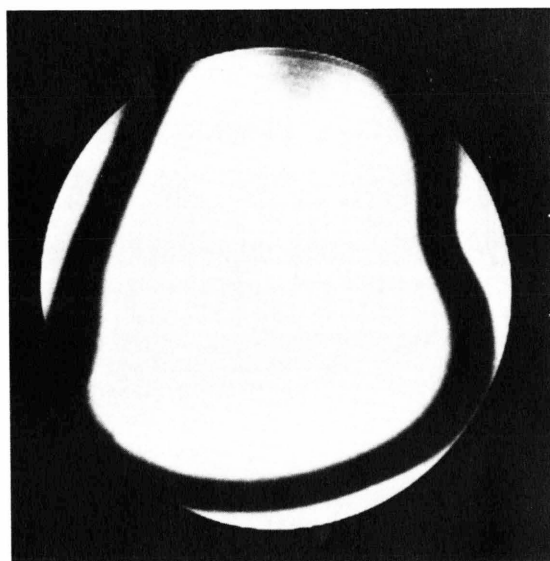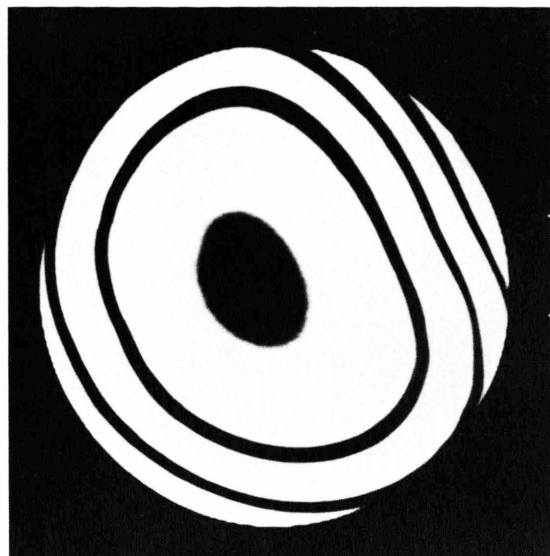
Fig. 4. Magnetic field images using a doped water phantom ($\emptyset = 25$ cm). *Upper*: In the magnetic field with the standard shim currents. *Lower*: With shim currents optimized for the object by the manufacturer's shimming procedure. The distance between the dark structures corresponds to 64 Hz, that means 1 ppm. Experimental parameters: Slice thickness: 10 mm, matrix size: 256 × 256, measuring time: 4.27 min.
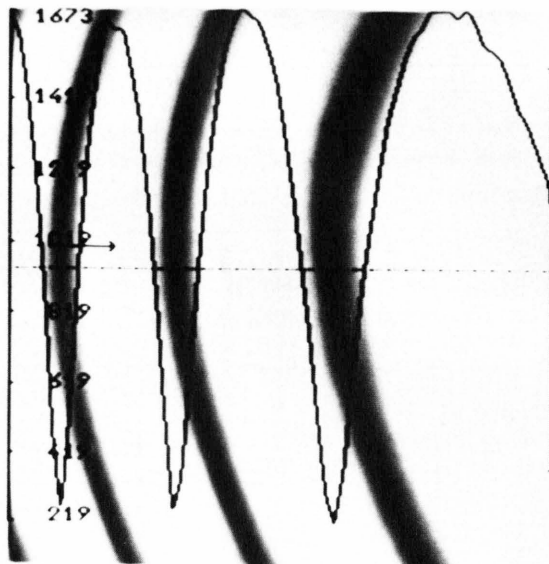

Fig. 5. Intensity profile of a region extracted from an NMR image using the double-pulse SENEX field mapping method. This profile exactly reflects the frequency dependence of the magnetization function given in Figure 3a.

As long as this disc phantom is used no slice selection has to be performed. However, this becomes necessary if internal field distributions of the object itself are to be shown. Special care has to be taken in the construction of phantoms if the shape of the external magnetic field are to be monitored and not the one perturbed by the object placed into the magnet. A multi-slice version of the imaging sequence is obtained by replacing the two rectangular pulses by slice selective sinc-pulses. Refocusing of the slice selection gradients which are applied during the rf-pulses can more easily been done in the case of the double pulse technique compared to the three pulse method. Another advantage is it's better signal-to noise ratio, which is exactly that of a usual standard spin echo imaging sequence.

Results

The results are mainly documented by the following figures: Fig. 4a shows the magnetic field image of a cylindrical phantom (diameter: 25 cm, length: 8 cm, filled with doped water), the symmetry axis of which is oriented along the main field direction. The alternation of bright and dark zones can be clearly seen.

the methods do not depend upon the absolute rf-field strength.

For testing the imaging sequence, a flat cylindrical phantom with a diameter of 38 cm and a thickness of 2 cm, which was filled with water, has been constructed.
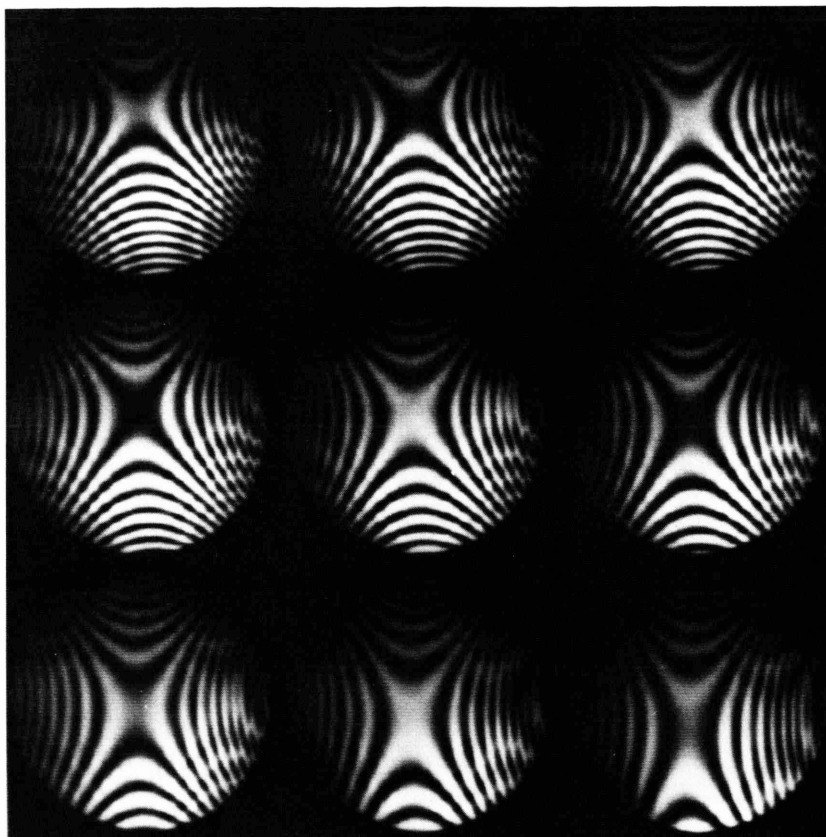
Fig. 6. Multi-slice magnetic field images of a cylindrical phantom ($\varnothing = 25$ cm) filled with doped water showing the field response for the shim channel (X^2-Y^2). – *Slice thickness*: 10 mm, slice distance: 3 mm, matrix size: 256 × 256 for each image, total measuring time: 6 min., the distance between the dark structures corresponds to 32 Hz, that means 0.5 ppm.

The magnetic field resolution can be adjusted by the choice of the interpulse delay. It amounts to $\tau = 15$ ms or $\Delta v = 64$ Hz, i.e. 1 ppm at 1.5 T, for the spacing of the lines in the example of Figure 4a. The homogeneity of the ground field was governed by the shim current values set to "local", that means the manufacturer's standard values. Using the manufacturer's shimming procedure, the magnetic field homogeneity was optimized for this object by the twelve correction shim coils. The result is presented in Fig. 4b which shows now a homogeneity of about 1 ppm on nearly the whole object in the x-y-plane. The intensity profile of a section of an image which was achieved in the presence of a shim gradient in x-direction is given in Figure 5. This intensity profile corresponds very well with the magnetization profile given in Figure 3a. The usefulness of the two pulse field mapping method is demonstrated further in the next figures: Fig. 6 shows the field response of a selected shim-channel. Starting from the ground-shimmed state an additional offset current was applied on the x^2-y^2-channel. Further

details are given in the legend. Finally a phantom normally used for relaxation studies was imaged with the double-pulse technique. Obviously the field change by the paramagnetic content of the vessels is clearly visible as well as the images of the vessels. The susceptibility jumps between the different media strongly influence the homogeneity of the magnetic field in this case. The difference between two dark lines corresponds to a field change of 0.5 ppm.

Conclusion

We have described a simple two-pulse NMR imaging sequence. It is based upon a double-pulse SENEX [6] scheme and displays magnetic field contour plots plus the normal spin echo image. The field resolution is variable and the signal-to-noise ratio is that of a standard spin echo image. Some applications shown demonstrate the usefulness of this new MRI technique, e.g. the 3D representation of the ground field,

Fig. 7. Two-pulse SENEX sequence applied to a relaxation phantom containing vessels with different amounts of GdDTPA. The characteristics of the frequency selective excitation are visible as contour plots superimposed to the NMR image. Clearly the image plus the magnetic field behaviour, changed by the object itself, can be recorded. – *Slice thickness*: 10 mm, matrix size: 256×256, measuring time: 4.27 min., frequency difference between two dark structures: 32 Hz that means 0.5 ppm.

the field response of different shim channels, the behaviour of the magnetic field within objects, and the disturbance of the ground field by the objects to be imaged. Further applications are running.

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