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SMALL MR IMAGER AND NMR SPECTROMETER

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Small MR Imager and NMR Spectrometer

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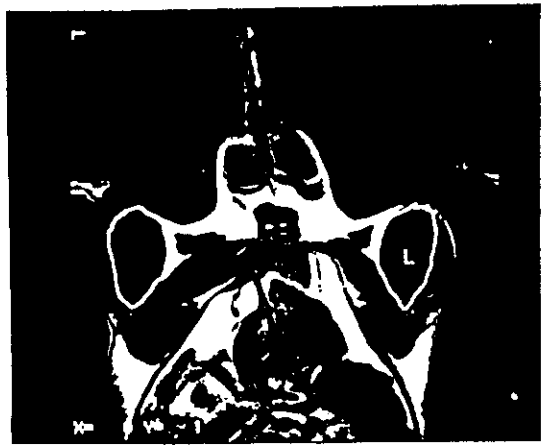
INTRODUCTION

Nuclear magnetic resonance imaging (MRI) is developing into a powerful tool in medical diagnostics. In order to produce the state of the art, medically useful images (Figure 1.), this technique has evolved into sophisticated and complex technology, that should in spite of this fact, be well understood by the medical personnel. Figure 2. shows a picture of a professional MR Imaging System. It is of course financially unacceptable to use such an instrumentation for teaching and demonstration purposes. As a consequence, demonstration of MRI which illustrates the essential features of NMR techniques, is of utmost necessity. The Institute Jozef Stefan NMR Spectrometer/Imager is the first demonstration instrument of this kind.

It was developed as the result of the joint efforts and experiences of Jožef Stefan Institute, Ljubljana, YU, Institute fur Medizinische Physik Wien, Austria and Waterloo NMR Spectrometers Inc., Waterloo, Canada.



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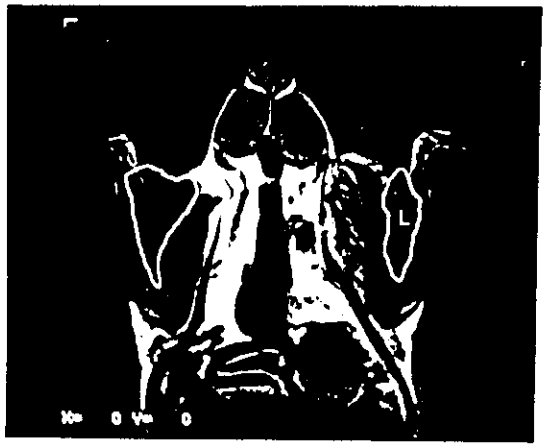

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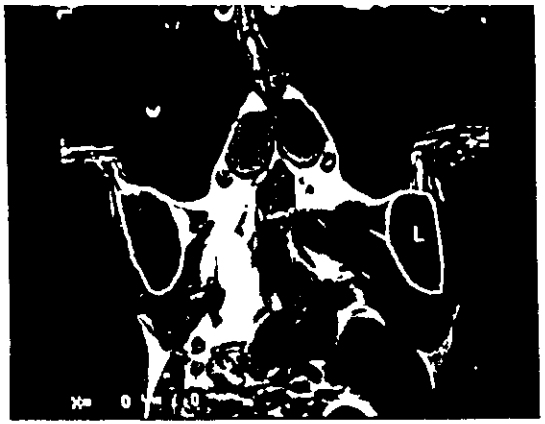

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Figure 1

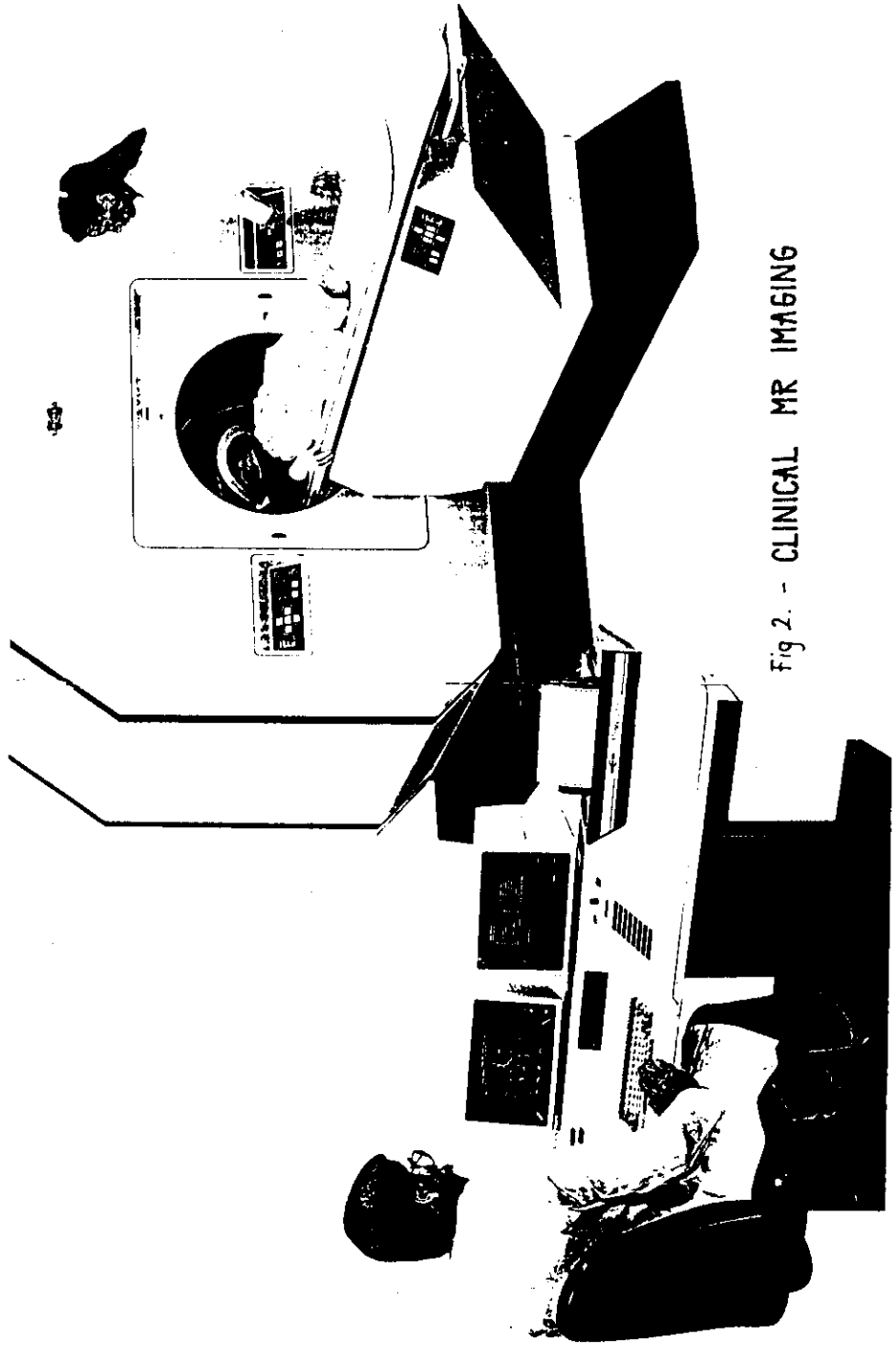


Fig 2. - CLINICAL MR IMAGING

SMALL MR IMAGER AND NMR SPECTROMETER (SMRI)

The instrument is ideal for undergraduate and graduate physics and medical physics laboratories. The special emphasis is given to the demonstration of MR imaging of phantom samples that can give an adequate understanding of NMR techniques without occupying expensive professional MR imaging instruments in hospitals for demonstration and teaching purposes. It can however allow for the demonstration of all other essential effects of NMR as well:

- free induction decay
- spin-echo
- spin-spin and spin-lattice relaxation
- self-diffusion of molecules
- FFT of the free induction decay
- NMR tomography

The Small MR Imager and NMR Spectrometer consists of two units:

- Pulsed NMR Spectrometer MS4
- Digital data acquisition & processing system LCD SCOPE

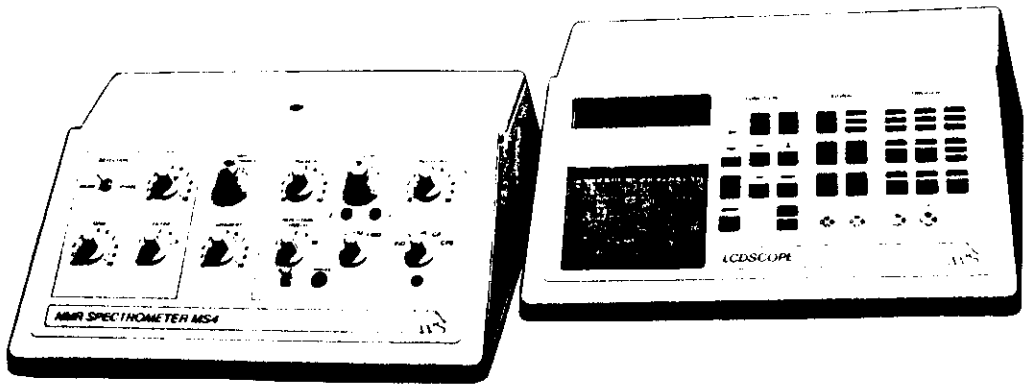


Figure 3. - Small MR Imager and NMR Spectrometer

The NMR spectrometer MS4 is a self contained fixed frequency spectrometer. It allows for the application and demonstration of all standard techniques (free precession, spin-echo, inversion-recovery, Carr Purcell, NMR tomography). The built in permanent magnet provides a stable, homogeneous magnetic field. In order to allow for the MR imaging, the magnet has a built-in gradient coil system, that can generate a linear gradient of the z-component of the magnetic field ($\frac{\partial B_z}{\partial z}$). The digital data acquisition and processing system (LCD SCOPE) has all the performances of the digital oscilloscope. The system microcomputer controls the operation of the entire measuring system and performs all necessary calculations (signal amplitude, digital averaging, integral, Fourier transform,...). It can also provide interfacing the external IBM PC XT/AT computer. The external IBM PC computer is in principle not necessary as long as one wants to perform the basic NMR experiments. However in the case of the MR Imaging experiment the external computer is unavoidable as it performs the image reconstruction. The available communication & data processing software guides the user through the entire set of basic NMR experiments providing all necessary information, performs MR image reconstruction and also allows for large screen live projection of the NMR experiments using the digital overhead projector (See fig.1. and Table I).

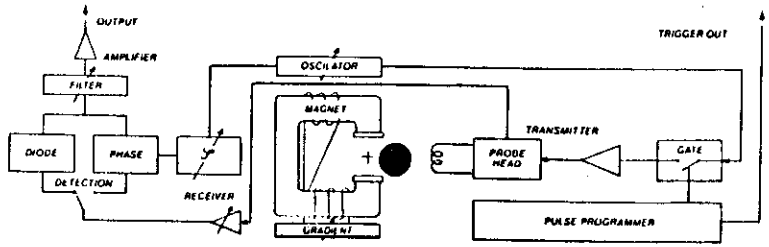
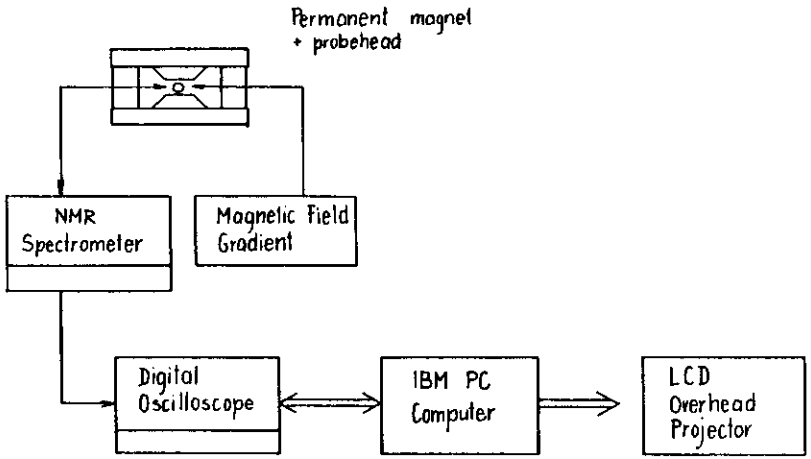


Figure 4. - NMR spectrometer MS4 - Block diagram



Small MR Imager and NMR Spectrometer
Block diagram

Figure 5.

SPECIFICATIONS

Frequency	9 MHz
Magnetic field: strength	0.21 T
homogeneity	10^{-6} T/cm
Magnetic field gradient	0 to 2 x 10^{-4} T/cm
Sample dimensions	outer diameter 8 mm, length 10 mm
Pulse sequences	$\Pi/2$; $\Pi/2 - \tau - \Pi$ Hahn echo;
	$\Pi - \tau - \Pi/2$ inversion recovery;
	Carr-Purcell sequence
R.f. phase channels	0°, 90° phase shifted
	with respect to the reference
R.f. transmitter power	$\Pi/2$ r.f. pulse is about 10^{-3} T
Receiver recovery time	≈ 100 μs
Detection	phase sensitive and diode
Signal to noise	≈ 100
Gain variation	two orders of magnitude
Sampling frequency	variable in steps 1-2-5-10
	from 2 MHz to 0.04 Hz
A/D resolution	0.5 %
Data memory	512 or 2048 bytes
Display	LCD matrix 200 x 120
External computer interface	RS 232 C

IBM PC XT/AT compatible

IBM PC communication and data processing software

Table I.

BASIC NMR EXPERIMENTS

The SMRI instrument is designed to measure the nuclear magnetic resonance observables such as free induction decay (FID), spin-echo, spin-spin and spin relaxation times, self-diffusion coefficient and in the first place, MR images of phantom objects.

When the sample containing protons is inserted into the NMR coil in the center of the built-in permanent magnet, the nuclear magnetization orients along the static magnetic field. If an intense radiofrequency field at a resonant frequency:

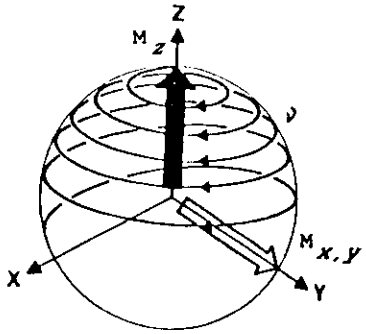
$$\omega_0 = \gamma B_0,$$

where ω_0 = Larmor frequency
γ = gyromagnetic ratio
B_0 - static magnetic field

the nuclear magnetization starts nutating away from the axis of the static magnetic field (z-axis). If the length of the r.f. pulse is properly adjusted, the magnetization will end up perpendicular to the static magnetic field (90° pulse). Being perpendicular to the magnetic field it will precess around the magnetic field axis at a Larmor frequency nducing a signal in the NMR coil -free precession signal. Due to the local inhomogeneities of the magnetic field caused by field gradient and spin-spin interactions the partial local magnetizations will precess with different Larmor frequencies. So partial magnetization will soon get dephased and the signal will decay to zero (See Fig. 6).

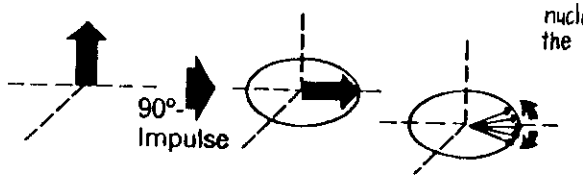
The entire process can be very well followed by the SMRI instrument that allows for the adjustment of the resonance condition, the 90° pulse length, the detector gain and the detector reference phase. Throughout the entire experiment the free precession signal is followed by the digital oscilloscope and displayed on its LCD matrix screen.

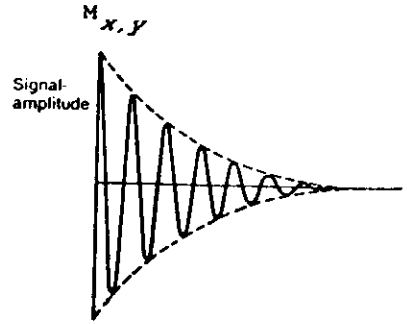
FREE PRECESSION SIGNAL



Rotation of the magnetisation under the effect of the r.f. pulse

Time dependence of the nuclear magnetisation in the rotating frame





FID

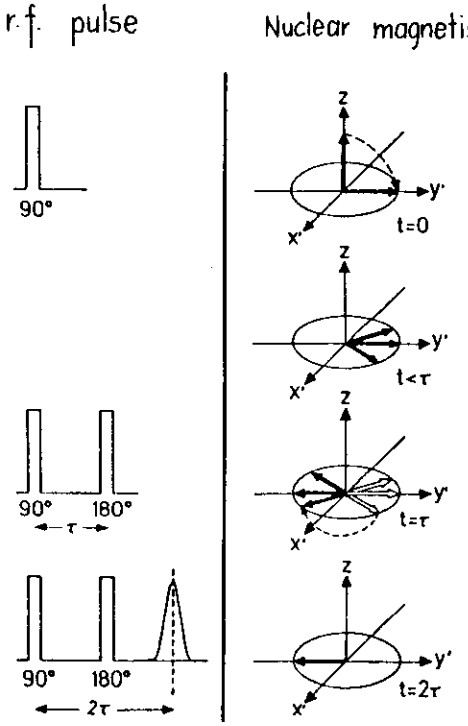
Figure 6.

If the static inhomogeneity of the magnet is the major reason for a decay of the free precession signal, the second r.f. pulse, being twice as long as the first 90° pulse - 180 ° pulse, will cause a time reversal in the relative motion of partial magnetizations. So the partial magnetization that got dephased during the time between the first r.f. pulse and the second r.f. pulse (180°) will refocus again after the same time that elapsed between the first and the second r.f. pulse. The signal called the spin-echo will appear (See Fig. 7). The refocusing of the spins would be complete (spin-echo signal = FID) if there were no spin-spin interactions. As these interactions are time dependent a time reversal" caused by a 180° pulse cannot correct for the partial magnetization dephasing due to spin-spin interactions. Therefore the amplitude of the spin-echo will decay with increasing delay time τ between the first and the second pulse with the characteristic time called spin-spin relaxation time T_2 (See Fig. 8). So repeating this experiment for a number of times with different delay times τ, one can get the spin-spin relaxation time T_2 from the dependence of the spin-echo amplitude of the delay times τ.

Instead of measuring the time dependence of the spin-echo amplitude by varying the delay time τ between 90° and 180° pulse, one can apply another 180° pulse after the time τ after the first spin-echo signal. This pulse will again cause refocusing of the magnetization and appearance of another spin-echo signal. Repeating this procedure for number of times one gets the well known Carr - Purcell pulse sequence. This sequence generates a train of spin-echo signals. Just as in the case of the single spin-echo experiment the amplitudes of the spin-echo signals generated this way decay with the spin-spin relaxation time T_2 See Fig. 9). So using this sequence one can measure spin-spin relaxation time T_2 in one single experiment.

The decay of the nuclear free precession signal is not governed only by the magnetic field inhomogeneity and spin-spin interactions described above. As the FID signal is caused by the precession of the transverse magnetization generated by the 90° r.f. pulse one can expect that this magnetization will sooner or latter return to its equilibrium orientation along the static magnetic field.

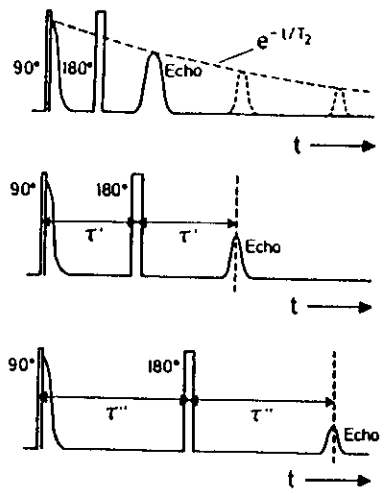
SPIN ECHO



Time evolution of nuclear magnetisation during the Spin-echo pulse sequence

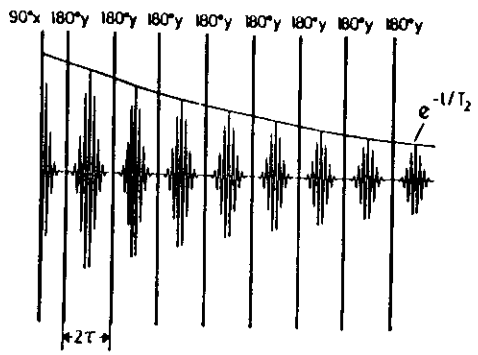
Figure 7.

SPIN SPIN RELAXATION TIME T_2



Time dependence of the spin echo amplitude

Figure 8.



Carr - Purcell pulse sequence

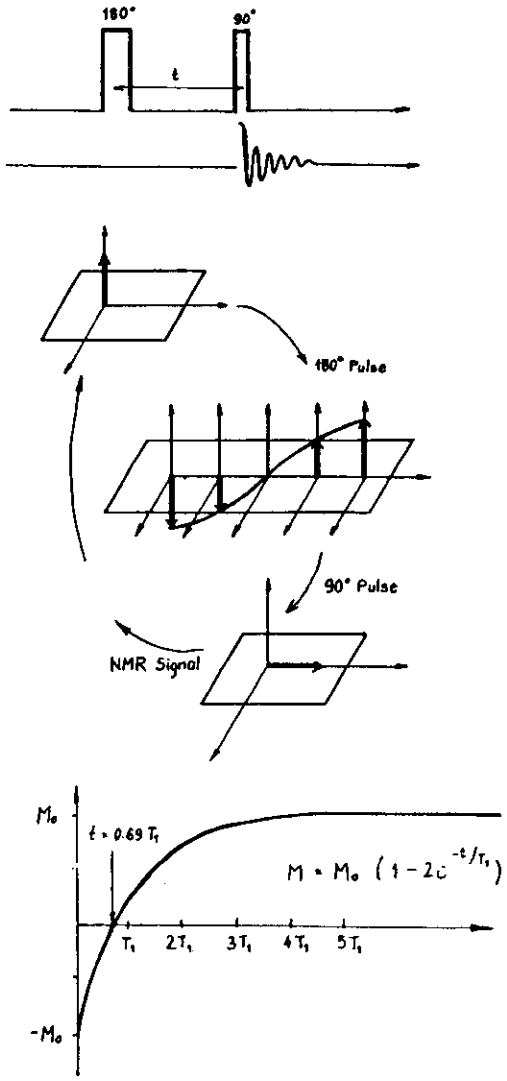
Figure 9.

A simple thermodynamic analogy of relaxation of nuclear magnetization towards original rest state is based on the concept of spin temperature. Following r.f. excitation, the spins can be considered "hot". The environment, generally referred to as "lattice", (even in liquids) can be perceived as a heat sink with a large heat capacity, absorbing the nuclei's excess energy through thermal contact (Fig.10). However, the spins are actually quite effectively insulated from the lattice. Hence the "heat" transfer is slow, and relaxation times are consequently long. In pure water, the proton spin-lattice relaxation time at room temperature is approximately 3 seconds. In biological tissue, it varies between a few hundred milliseconds and about 2 seconds.

The experiments that determine the spin-lattice relaxation rate are based on the fact, that the signal following the 90° pulse is proportional to the magnetization parallel to the magnetic field.

If at the beginning of the experiment, that has to determine the spin-lattice relaxation time T_1, 180° pulse is applied to the sample, the magnetization is inverted to be antiparallel to the magnetic field. As such orientation is not thermodynamically stable, the magnetization will relax with the spin-lattice relaxation time towards the equilibrium orientation. After time τ after the first 180° pulse a 90° pulse is applied. The signal following it is proportional to the magnetization component parallel to the magnetic field. Varying the delay time τ between the 180° pulse and the 90° pulse one can determine the time evolution of the component of the magnetization parallel to the magnetic field by measuring the amplitude of the free precession signal following the 90° pulse. This experiment is a well known inversion recovery method.

Inversion Recovery (180° - t - 90°)



Time dependence of the FID signal following the 90° pulse

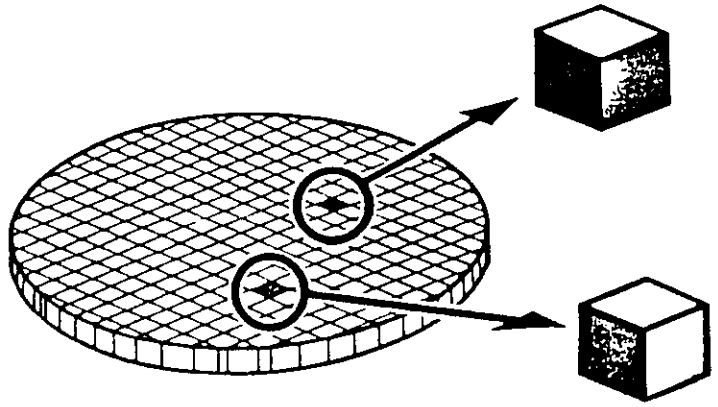
Figure 10. - Inversion recovery method

MR IMAGING

The basic principle of magnetic resonance imaging is the conversion of the spatial dependence of NMR parameters (spin density, spin lattice and spin-spin relaxation times) into the frequency dependence. As the Larmor precession frequency is proportional to the static magnetic field

$$\omega_o = \gamma B_o$$

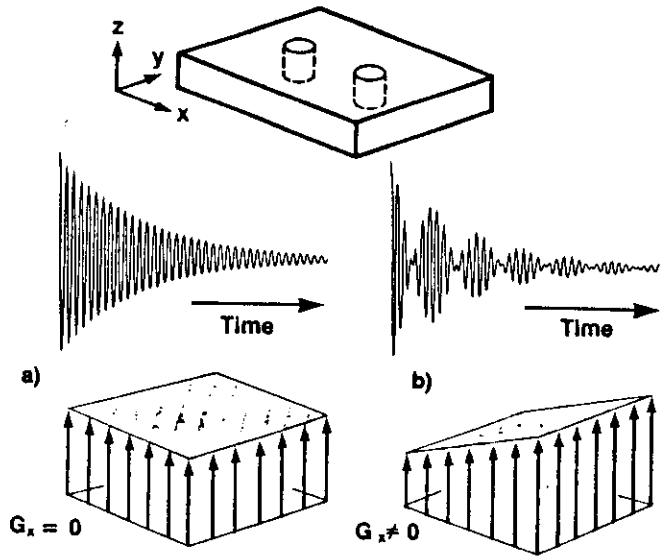
the spatial variation of the magnetic field induces spatial variation of Larmor frequency ω_o. The required variation of the magnetic field can be best done with set of gradient coils producing linear gradient of the z-component of the magnetic field. By making the nuclei "see" different static magnetic field values according to their spatial location, one can in principle, differentiate signals emitted from nuclei in different volume elements voxels. All NMR imaging methods are based on this fundamental principle (Fig.11).



Two different volume elements (voxels) corresponding to different values of the detected magnetization.

Figure 11.

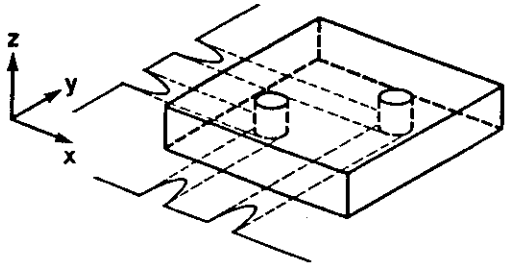
This can be illustrated with a simple phantom consisting of a teflon block having two water-filled cylindrical holes aligned with the z axis (axis of the static field), but with different locations with respect to x (Fig.12). In the absence of a gradient, (Gx=0) the samples are indistinguishable. They resonate at exactly the same frequency, because they experience the same field, and hence, the free induction decay contains only one frequency. (Fig.12a). However, as soon as the gradient is turned on, the two tubes will no longer experience the same magnetic field strength, and the resulting free induction decay will be the superposition of two different frequency components (Fig.12b).



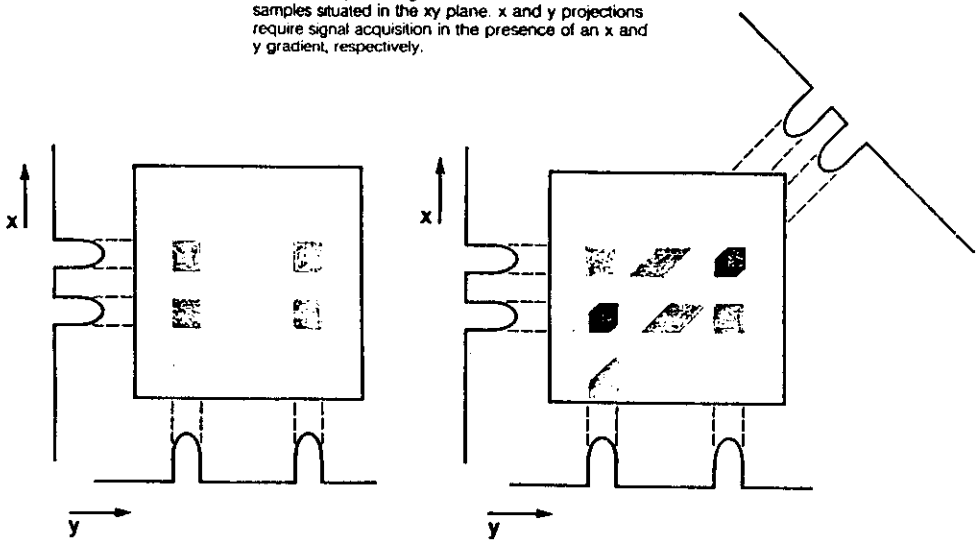
In the absence of the field gradient ($G_x = G_y = G_z = 0$) both samples sense the same field; the free induction decay therefore consists of a single frequency (Fig. a). In the presence of a gradient G_x, the two samples sense different fields, resulting in a free induction signal consisting of two frequencies (Fig. b).

Figure 12.

In reality, signals are collected from a multitude of spatial locations and the FID is a composite consisting of many different frequencies. To determine individual frequencies in such situations, one resorts to a mathematical analysis, carried out in a digital computer. The process is called Fourier transform. Whereas the FID represents the time evolution of the transverse magnetization, the Fourier transform represents its frequency distribution. This not only allows extraction of the individual frequencies, but also their associated amplitudes, which are proportional to the spin density at the particular spatial location. However, a Fourier transform of one orientation of such phantom sample is not sufficient to determine the actual spatial position of the phantom. To achieve this, one must generate signals which may be regarded as projections onto both x and y axes by first applying a gradient, Gx, collecting and transforming the resulting signal and then repeating the process by substituting gradient Gy for Gx as illustrated in Fig.13. One can see, however, from the back projection of these profiles, that an ambiguity remains (Fig.13b). At least one more projection, using for example, a gradient that is tilted 45 degrees, is required to unequivocally determine the location of the samples (Fig.13c). The construction of an image consisting of N x N pixels requires at least N independent views (projections), each defined by N points.



13.a. Projection signals obtained from two water samples situated in the xy plane. x and y projections require signal acquisition in the presence of an x and y gradient, respectively.



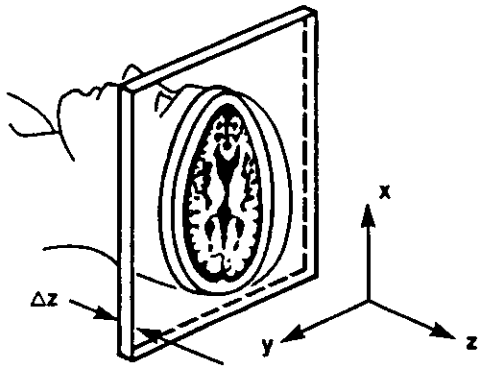
13b. Principle of image reconstruction by back projection. It is obvious that from two projections, the location of the two samples cannot unequivocally be constructed.

13c. By back-projecting a third independent profile, the correct coordinates of the two samples can be determined.

Figure 13

The method of image reconstruction by back-projection as demonstrated on Fig. 13 is analogous to x-ray CT, where the attenuation profiles take the place of the NMR frequency-domain signal. The blur, resulting from simple back-projection, is eliminated by first convolving the projection signals with suitable filter functions, a procedure again well known from x-ray CT.

Combining the presence of the linear gradient of the z component of the magnetic field with a r.f. pulse that is sufficiently weak and has small frequency bandwidth so that it can excite only a narrow slice of a thickness z, a cross-sectional images can be obtained (Fig. 14).

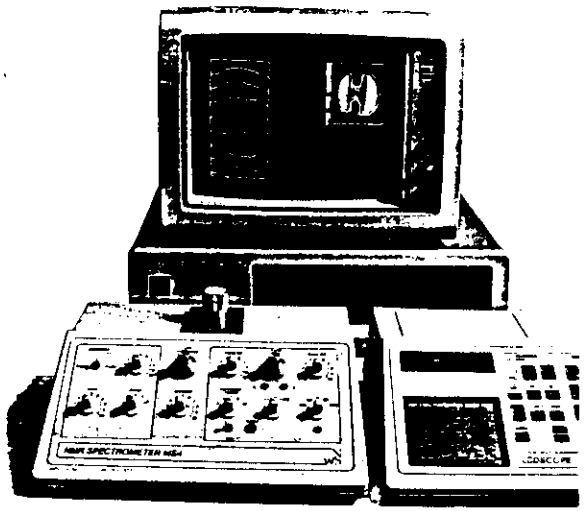


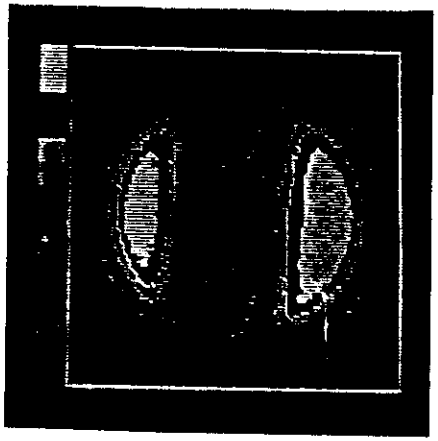
By combining a frequency-selective pulse in the presence of a z gradient, excitation can be confined to a slice of thickness Δz.

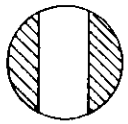
Figure 14.

The foregoing discussions describe conceptually the simplest NMR imaging experiment that can be also successfully demonstrated on phantom samples with the IJS Small NMR Spectrometer & Imager:

Fourier transforms of the phantom free induction decay (measured at 32 different orientations of the phantom with respect to the static magnetic field gradient), the x-z cross section of the phantom sample is calculated in the IBM PC computer using the standard back-projection reconstruction technique. The resulting MR image is shown on the figure 15.



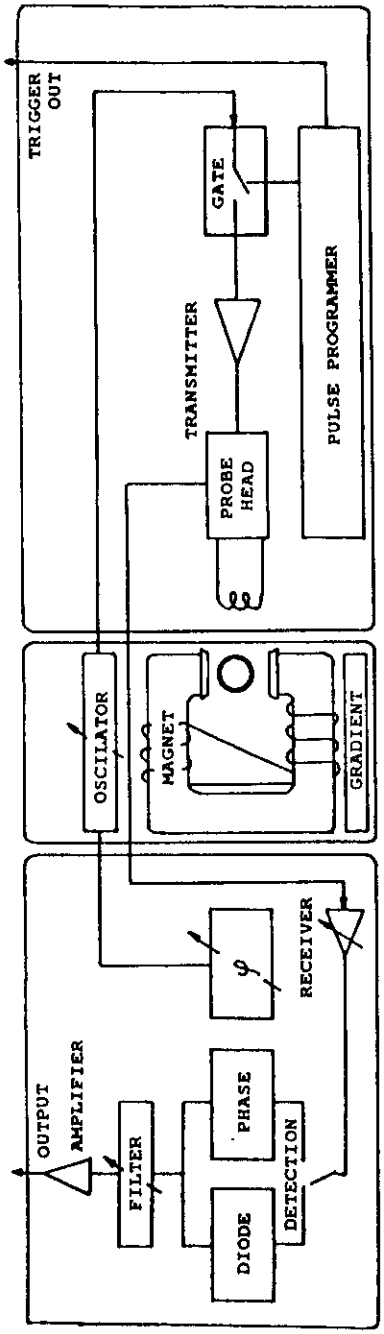


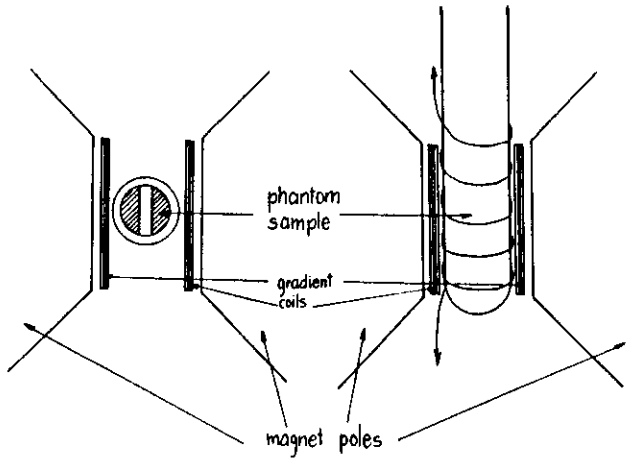


Phantom sample

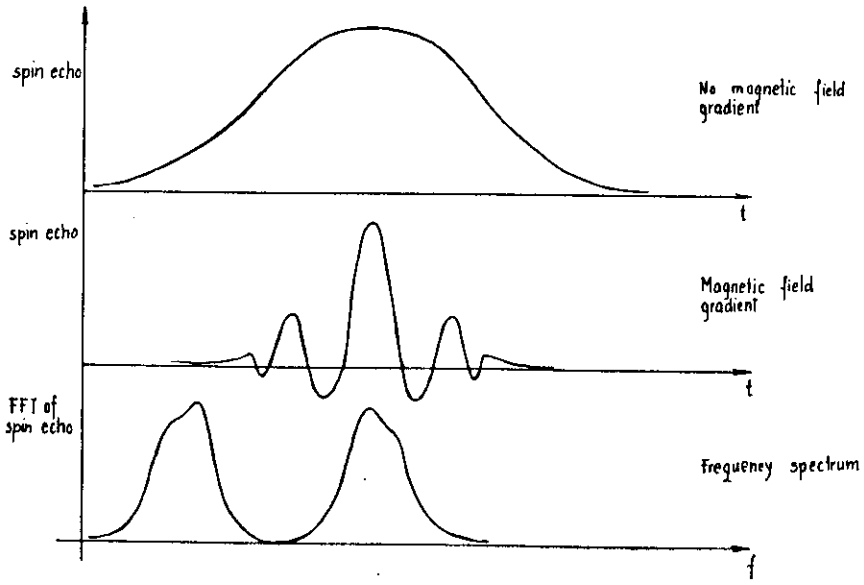
Figure 15. - MR image of the phantom sample

There are of course many other approaches to the problem of MR imaging and image reconstruction. Most of them make use of timed rather than stationary gradients. Such methods however require a more complex gradient coil system design and would be relatively difficult to demonstrate them in a small permanent magnet built in the SMRI instrument. Nevertheless the simple, one gradient axis, backprojection technique realized in the IJS Small MR Imager & NMR Spectrometer demonstrates clearly enough what the MR imaging is all about.

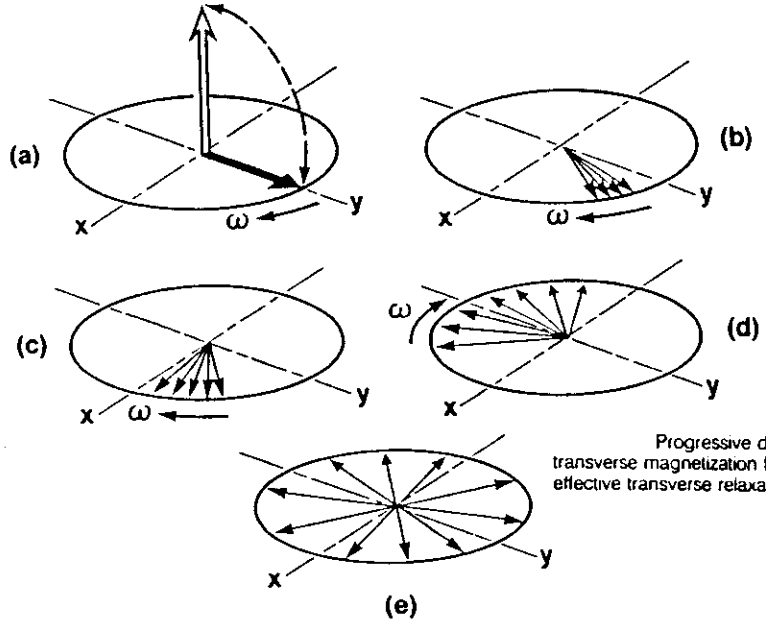




Top view Side view



NMR spin echo signal of a phantom sample



Progressive dephasing of the precessing transverse magnetization following a 90° pulse due to effective transverse relaxation.