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LETTER TO THE EDITOR

Image formation in NMR by a selective irradiative process

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Abstract. A new method of image formation by NMR is described. It is based on selective RF irradiation of the sample in switched magnetic field gradients. Selective irradiation may be achieved by tailored (or simple) excitation or tailored (or simple) saturation. Preliminary experiments illustrating various aspects of the method are described, and a two dimensional picture or image of a simple object is presented.

We wish to report a new nuclear magnetic resonance (NMR) method for producing two and three dimensional images corresponding to the macroscopic density distribution of the nuclear spins within a sample. Other methods for image formation recently introduced (Lauterbur 1973, 1974, Mansfield and Grannell 1973, 1974) depend on lengthy computer calculations to reconstruct the image. The sensitive point method of Hinshaw (1974), though not requiring reconstruction calculations, would seem to be slower at producing images than the methods described here.

By means of a selective irradiative process, we prepare the spin system so that an NMR signal is obtained which directly arises from the spins within a small region, of virtually arbitrary shape, within the sample.

We first discuss the imaging process, outline six related experimental methods for the preparation of the spin system and then present illustrative experimental results for simple sample geometries.

Application of a static magnetic field gradient, in addition to the large static field, converts spatial variations of the nuclear spin density into measurable signal variations in the NMR frequency spectrum. This specializes to isochromatic planes of spins. However, in order to build up a two or three dimensional picture of an object, selection of the signal arising from a small specific volume of spins within the sample is ideally required. If this selected region is then swept over the entire volume of the sample, a full image of the sample can be unambiguously built up.

In our technique spatial selectivity is accomplished by the introduction of several ideas, not in themselves new but not hitherto applied together to the NMR image formation process. The spatial discrimination is achieved by appropriately irradiating the sample with the field gradient along one direction and then switching the gradient direction before applying the inspection or 'read' radio frequency pulse (the traditional method applies the 'read' pulse with no preparative irradiation),

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The vital trick in the preparative irradiation is to tailor the Fourier components of the radio frequency magnetic field so that parts of the spin spectrum are irradiated and others not. Broadly speaking, there are two ways of doing this: by tailored saturation and by tailored excitation.

In tailored saturation the RF pulsewidth is relatively long, of the order of the spin lattice relaxation time T_1, and those irradiated spins have their magnetization destroyed. Tailoring is achieved here by frequency and/or amplitude modulation of the pulse. The simplest case of tailored saturation by a radio frequency pulse of fixed amplitude and carrier frequency we call simple saturation.

Tailored excitation, however, tips the irradiated spins into the x–y plane, and may be accomplished more rapidly. Tailoring, in this case, is achieved by amplitude or pulsewidth modulation of the radio frequency pulse or pulse train. The simplest case of tailored excitation by the application of an unmodulated radio frequency pulse or pulse train with fixed carrier frequency we call simple excitation.

We define the selective irradiative process to comprise any of the preparatory irradiative procedures outlined above in association with the appropriate application and switching of linear magnetic field gradients. Ways of performing this process are now described.

For simplicity we first discuss 'two dimensional' samples. Consider a rectangular block, dimensions L_x, L_y, L_z, of spins in a field gradient G_x. Eventually, we wish to determine the spin density distribution $\rho(x, y, z)$ for all values of x, y, z. We first specialize to a thin slice of thickness Δx located at x_0 and proceed to measure the spin density $\rho(x_0yz)$. When $\rho(x_0yz) = \rho(x_0y)$, ie is independent of z, this may be achieved by preparing the sample in the state required by four basic methods, or their variants. They are:

(i) saturating all the spins in the block *except* those in Δx by tailored saturation;

(ii) irradiation of all the spins in the block except those in Δx in a transient experiment so that all unwanted spins are tipped into the x–y plane of the rotating reference frame, viz tailored excitation.

Rather than affect the spins outside the slice of thickness Δx, complementary experiments may be performed in which the spins within Δx are irradiated:

(iii) by defining a slot of width Δx in the sample by simple saturation; in this case the observed signal arises from the entire sample less the saturated spins within the slot, or

(iv) by defining a slot of width Δx in the sample by either (*a*) simple excitation or (*b*) tailored excitation.

In version (*a*) the tailored RF burst is replaced by a long duration low level $\pi/2$ ($3\pi/2$, etc) RF pulse. An RF pulse of duration D has a spectral width of approximately D^{-1}. Since some of the RF power is contained in the sidebands, displaced by roughly D^{-1} from the carrier frequency, the spatial definition of the slot is not as precise as in tailored excitation version (*b*). In both cases, the transient signal following excitation arises directly from the spins within the defined slot. Variants of methods (iii) and (iv) allow additional and/or alternative methods of directly observing the initially irradiated spins within the defined slot Δx. For example,

(v) by saturating a slot by simple saturation (iii), then inverting the whole spectrum by an intense π RF pulse. The saturated spins in the slot will produce a magnetization which grows out of the baseline towards the equilibrium value, whereas the main inverted spectrum will relax from an initially negative value, through zero to its positive equilibrium value. At the time when the inverted magnetization is zero the remaining magnetization arises only from the spins within the defined slot, or

(vi) by defining a slot by simple or tailored excitation (iv) then inverting the whole spectrum by an intense π RF pulse. This is the excitation method of version (v).

Having prepared the spin system in one of the manners indicated, the direction of the field gradient is quickly switched from G_x to G_y, that is to say, from along the x direction to along the direction y. (This may also be achieved by physically rotating the sample through 90°.) The spin density distribution in the slab is then 'read out' by applying a $\pi/2$ RF pulse. The free induction decoy (FID) is Fourier transformed to give the spin density $\rho(x_0y)$ along the slab. A CW technique could be used here for read out instead of the Fourier transform method.

The techniques described above may easily be extended for imaging the spin density in three dimensions. For example having prepared the slab of spins Δx as described above, one of the selective irradiation procedures as outlined in (i)–(vi) may be applied at right angles, that is, with G_x switched off and G_y switched on. The final result is a rectangular column of differentiated spins defined in the example. At this point G_y is switched off and G_z switched on followed by read out as before. The end result is the line density $\rho(x_0, y_0, z)$. The entire procedure may be repeated for all values of x_0, y_0 to obtain the full density distribution $\rho(x, y, z)$.

We shall now discuss the tailored excitation method (ii) in more detail. The sample is placed in a magnetic field gradient G_z which is initially along the x direction. Spins within the interval x_0 to $x_0 + \Delta x$ resonate with Larmor frequencies of f_1 to f_2. The spins are first irradiated by a tailored excitation pulse sequence (Freeman and Hill 1971; Tomlinson and Hill 1973) which nutates all the spins outside f_1 to f_2 by $\pi/2$ (or $3\pi/2$, etc). These spins dephase with a time constant of approximately $(\gamma G_x L_x)^{-1}$. The differentiated spins within f_1 to f_2 are still aligned along the z direction. At a time greater than $(\gamma G_x L_x)^{-1}$, but much less than T_1, the direction and in general the magnitude of the gradient is switched from G_x to G_y and a second tailored excitation is performed. Here the undisturbed

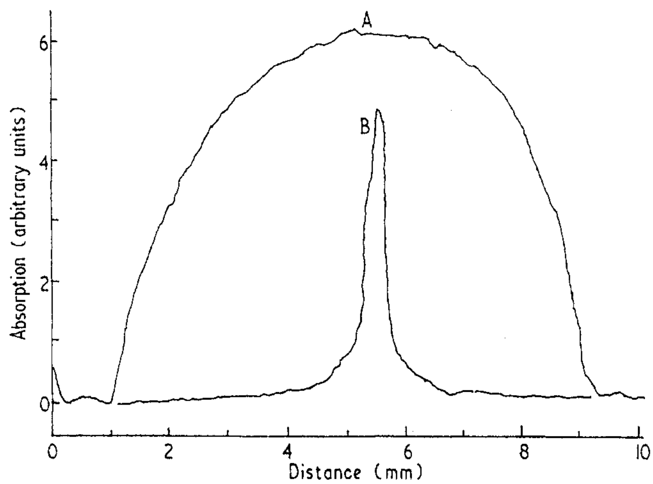

Figure 1. Proton absorption line shapes for a cylinder of water in a magnetic field gradient transverse to the cylindrical axis. A, simple line shape obtained by taking the Fourier transform of the response following a single intense $\pi/2$ pulse. B, Fourier transform of response signal immediately following a tailored burst of RF excitation Only the spins in a narrow slot through the cylinder close to its diameter are observed.

spins lie within a new frequency interval f_3 to f_4, corresponding to y_0 and $y_0 + \Delta y$. When the signal from the unwanted spins outside the frequency range f_3 to f_4 has decayed, the gradient is then switched from G_y to G_z and a single intense $\pi/2$ 'read' pulse is applied. In the limit as Δx and Δy are very small, the Fourier transform of this signal is directly proportional to the spin density along the line x_0, y_0, $0<z<L_z$. The entire procedure is then repeated with different values of f_1 and f_2, f_3 and f_4 to obtain the spin density elsewhere in the sample.

In our system the desired Fourier spectrum of the tailored excitation is entered into a Honeywell H316 minicomputer and the Fourier transformation obtained. The resultant amplitudes are converted into RF pulse widths by a software routine; negative RF amplitudes are obtained by changing the phase of the RF carrier by 180°. With this arrangement a spectrum of 17·2 kHz width may be irradiated in increments of 67·8 Hz.

Figure 1 shows a simple demonstration of one aspect of this tailored excitation sequence method (iv) *b*. An 8 mm cylindrical sample has been irradiated so that spins within a narrow slot (parallel to the cylinder axis) are nutated by about $\pi/2$ and other spins are

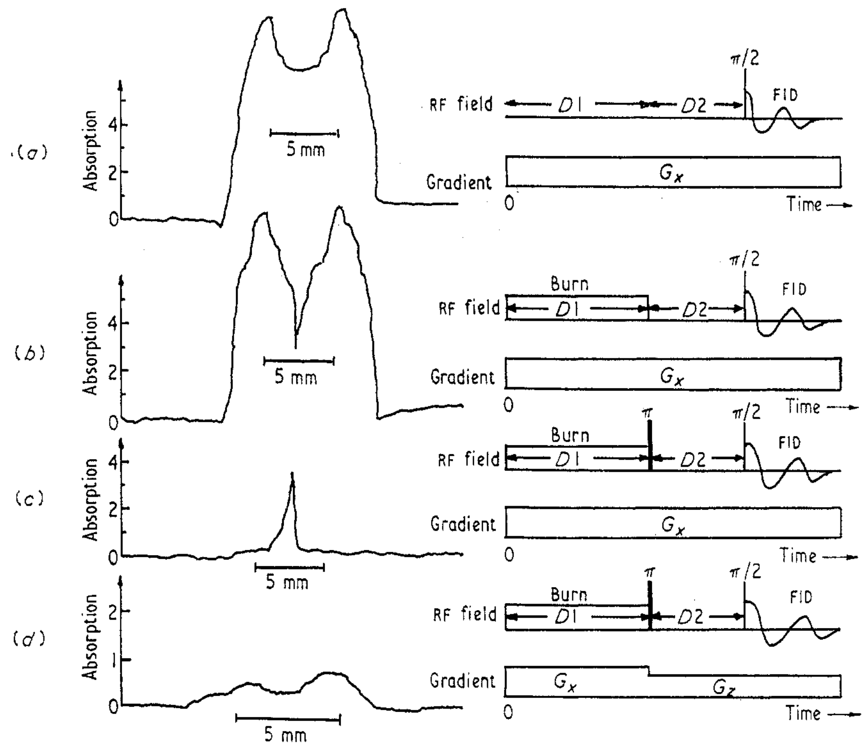

Figure 2. Proton absorption line shapes under various conditions of selective saturation for a cylinder of water containing a central cylindrical proton-free occlusion and with various applied magnetic field gradients as indicated. (*a*) Simple line shape obtained by taking the Fourier transform of the 90° pulse response of the sample in a gradient G_x; (*b*) as in (*a*), but with a preparatory 'burn' pulse of duration $D1 \simeq 2{\cdot}0$ s; (*c*) as in (*b*), but with the spectrum inverted by an intense π pulse at the end of the 'burn', followed by a delay $D2 = T_1 \ln 2$; (*d*) as in (*c*) but with the 'read' gradient G_z switched in at time $D1$ in place of G_x ($G_x \simeq 1{\cdot}5\ G_z$.) This experiment corresponds to the full method (iv). Notice the double bump in the lineshape corresponding to a section through the sample normal to the cylinder axis.

unaffected. The figure shows the Fourier transforms of the signal following a single intense $\pi/2$ pulse, from the entire sample and also of the signal immediately following the tailored excitation. Notice that this procedure has specialized to a slot of 0·35 mm width from a 8 mm diameter tube.

We now briefly describe a two dimensional mapping experiment based on method (iv). At the start of the experiment, the field gradient G_x is applied, together with a long low-level saturation or 'burn' pulse of duration $D1$ ($\sim$2·0 s). The spin system is thus locally saturated at a frequency set by a frequency synthesizer. This can be varied in a series of experiments to give a frequency scan of the sample. At the end of the 'burn' period, a gradient G_z (the 'read' gradient) is produced. At the same time an intense RF pulse is generated which inverts the spin population at time $D1$ (see figure 2) The locally saturated spins will grow to $+\Delta M(0)$ according to $\Delta M(t) = \Delta M(0)\,[1 - \exp(-t/T_1)]$ where T_1 is the local spin-lattice relaxation time of the spins. The remainder of the spins, since their populations are inverted, will grow back to $+M'(0)$ from their initial value of $-M'(0)$ according to the equation $M'(\mathrm{t}) = M'(0)\,[1 - 2\exp(-t/T_1)]$, where $M(0) = M'(0) + \Delta M(0)$. After a further delay $D2 = T_1 \ln 2$, the magnetization $M'(D2) = 0$. However $\Delta M(D2)$ is not zero. Thus locally saturated spins are made to yield a signal which is completely differentiated from the remainder of the spins in the sample. At time $D1 + D2$, an intense $\pi/2$ pulse is produced which inspects or 'reads' directly this localized magnetization, but with G_z switched on and $G_x = 0$. Thus we first isolate a slice of sample using the 'burn' gradient G_x and then we look at the spin density distribution along that slice by switching the gradient to the 'read' mode G_z along the slice.

We have illustrated this procedure experimentally by looking at the protons in a sample of water in the shape of a cylindrical annulus. The signals obtained at various stages of the experiment are presented in figure 2. Figure 2(*a*) shows the absorption line for the sample in the 'burn' gradient. The symmetrical dip in the signal is due to the absence of spins in the central cylindrical occlusion of the sample. Figure 2(*b*) shows the result of a 2·0 s saturation 'burn' at the centre of the absorption line in figure 2(*a*). Figure 2(*c*) shows the signal from the irradiated slice of sample, and was obtained by first 'burning' the slot in the centre of the absorption spectrum as in figure 2(*b*), and then inverting the entire spectrum with an intense π pulse. The signal was read by an intense $\pi/2$ pulse applied at

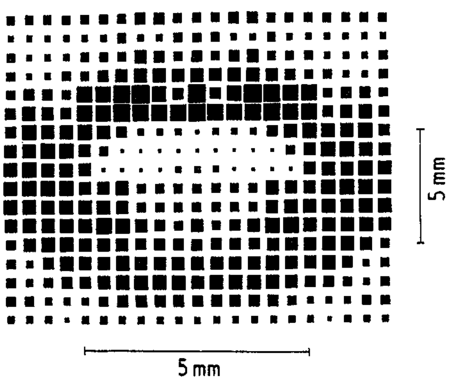

Figure 3. Two dimensional image of the cross section of a cylindrical annular sample. Each row of black dots corresponds to the spin density of a section through the annulus as in figure 2(*d*). The dot size is proportional to the spin density at that point. The whole picture is formed using ten grey levels or dot sizes. Elongation of the picture into an elliptical form is due to the inequality of the 'burn' and 'read' gradients.

time $D2 = T_1 \ln 2$ later. This time was 0·9 s in this experiment, and only the G_x gradient was used. Figure 2(*d*) shows the results of the full experiment, method (v). The initial 'burn' is produced in the sample as above with G_x on. Both the π pulse and the 'read' gradient G_z are applied. The delay $D2 = T_1 \ln 2$ is as for figure 2(*c*) above. After the delay $D2$, the signal is obtained following the intense $\pi/2$ 'read' pulse. The Fourier transformation of the transient decay signal is performed on line in the H316 computer and displayed or put out on the graph plotter. Notice that the experimental absorption lineshape obtained comprises two bumps and this is what one expects for the density distribution of a slice taken through the centre of an annulus.

Using data similar to figure 2(*d*) a spin density scan of half the annulus has also been performed using method (v). The signals obtained have been made up into a two dimensional dot picture, the area of a given black dot at a particular point in the image being proportional to the signal amplitude of the corresponding point in the sample. Ten grey levels or dot sizes have been used. The data obtained have been reflected about the annulus diameter and the complete picture is shown in figure (3). Notice that the picture appears elliptical although the object in this case was an annulus of outer diameter 9·7 mm and inner diameter 3·8 mm. The difference in the image principal axes arises from using different field gradient magnitudes for the 'burn' and 'read' gradients and illustrates a useful feature of the technique, namely that preferential magnification of the image may easily be performed.

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