NMR J IMAGING

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NMR imaging was proven in recent years to be a useful noninvasive technique (1). It gives the 3-dimensional structure of tissues in vivo; and exploits the differences in concentration of substances (usually water) and their relaxation times as a means to discriminate between tissues.

Methods of chemical shift-imaging were developed recently (2-6) which utilize the differences in substance content (NMR spectra) of different tissues to discriminate between them. However, the magnetic fields produced by normal whole body magnets are generally weak and crude, necessitating costly high field whole body magnets. Even with such fields the spectral resolution is too poor to obtain most of the high resolution information. NMR J imaging (7) offers a new probe for tissue discrimination with low resolution and low field magnets, without the limitations mentioned above. The pulse sequence is shown in Fig. 1.

In the Carr Purcell Meiboom Gill experiment, a 90° pulse is applied and followed by a series of 180° pulses applied at times $\tau, 3\tau, 5\tau \ldots (2n-1)\tau$. An echo train results at 2τ, 4τ, $6\tau \ldots 2n\tau$. Since the 180° pulses are shifted in phase by 90° relative to the first 90° pulse, the echoes are obtained with the same sign (8). The dispersions, which are due to either chemical shifts or magnetic field inhomogeneities, are refocused at the top of each echo. Dispersions due to two spin interactions, like scalar J-coupling or dipolar coupling (when anisotropic motion is present), are not refocused. As a result, sampling a single point at the top of each echo and filtering out high frequencies gives, after Fourier transform, a J (or dipolar) spectrum (9). In the J spectrum the multiplet structure of the resonances near the carrier frequency will appear. These lines will have natural linewidths, even if the magnetic field is inhomogeneous. Since the J couplings are field independent (unlike the chemical shift) relatively low and crude magnetic fields may be used.

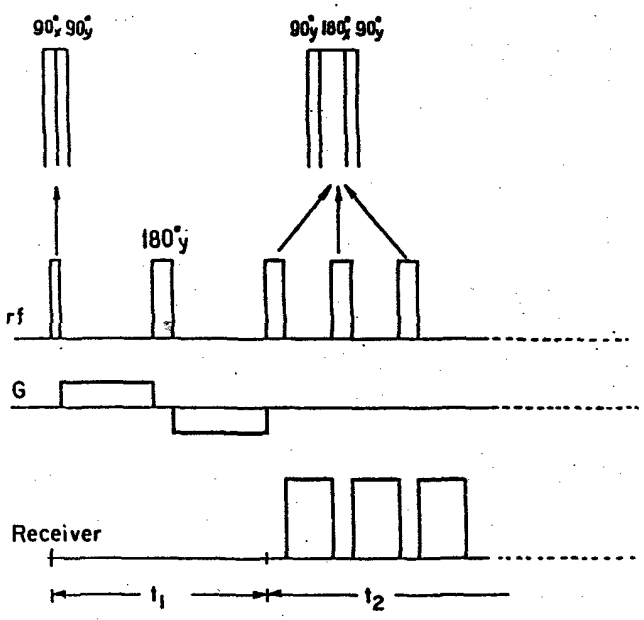
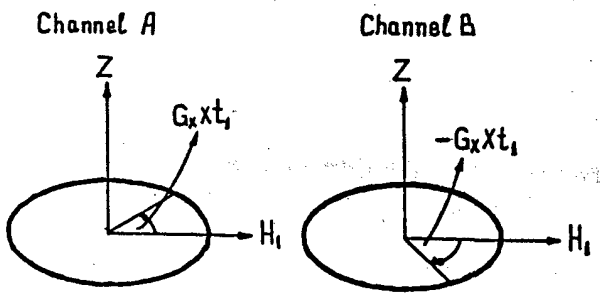


Figure 1. The pulse sequence for a NMR J-imaging experiment. In the final version of this experiment, 2 experiments are done with inverted phases of all the 180° pulses, and the results are added.

If a two-dimensional experiment is performed, and a field gradient is applied during the evolution period, the J spectra is spatially encoded. Two-dimensional Fourier transformation gives the spatial information in one axis, and the corresponding J spectra in the orthogonal axis. In order to eliminate the dispersion due to field inhomogeneity or different chemical shifts from the spatial dimension, a 180 pulse was applied in the middle of the evolution period, and the sign of the gradient was inverted.

When nonquadrature detection is used, the spatial dimension is folded: Since the phase of the magnetization is inverted after each 180° pulse, the spatial encoding of the odd numbered echoes is opposite to the spatial encoding of the even numbered echoes. However, when quadrature detection is used, odd numbered echoes are entered to channel A (Fig.2) and even numbered echoes to channel B. as a result, the complex quadrature signal will be unfolded. The echoes must be sampled exactly between the 180 pulses in order to avoid errors in the spatial encoding.



$$e^{-i G_x x t_1} = \cos(G_x x t_1) + i \sin(-G_x x t_1)$$

Figure 2. Quadrature detection prevents folding of the spatial information, because channel A is not sensitive to phase inversion of the magnetization. The sign of the phase is determined only by channel B.

It was found that the homogeneity of the r.f. field was an important factor in the formation of artifacts. The artifacts are due mainly to the fact that an imperfect 180° pulse tip some z magnetization onto the x-y plane, and some x-y magnetization onto the z axis. These effects have cumulative nature, as described in detail elsewhere (7). Based on the expectation, the r.f field produced by the large coils in whole body magnets would be inhomogeneous, we sought a way to produce reasonable spectra in such a field.

Most of the spurious responses that give artifacts come from longitudinal magnetization which is present during the application of 180 pulse. In order to minimize the amount of the z magnetization after the excitation pulse, a 90° composite pulse was used ($90^\circ_x\ 90^\circ_y$) (10). In addition, the 180° pulses which are applied during acquisition are replaced with composite 180 pulse (11) ($90^\circ_x\ 180^\circ_y\ 90^\circ_x$). This sequence ensures accurate inversion of the longitudinal magnetization, and as a result a smaller amount of such magnetization will be nutated to the transverse plane during the experiment.

The second advantage of the composite 180° pulse is that it ensures an accurate inversion of the magnetization with respect to the y axis. If the 180° refocusing pulse deviates from the nominal value, the composite pulse converts the longtudinal magnetization that might be left after a simple pulse, into a corresponding phase delay (11). This phase delay is compensated each second echo. Based on these considerations, the pulse sequence in Fig.1 is suggested. A further reduction of artifacts is obtained by phase cycling:

A phase shift of 180° in all the 180° r.f pulses applied in the J-imaging experiment does not change the sign of the signals of interest. However, most of the artifacts which are formed in the experiment appear with an opposite sign. Summation of the results of two experiments with opposite phases of the 180° r.f pulses will suppress these artifacts.

The experiment was done at a frequency of 90 MHz on a WH90 Bruker spectrometer controlled by an Aspect 2000 minicomputer and equipped with a 10mm proton probe in which gradient coils were incorporated. The main experimental problem was the inability to apply on r.f pulses during acquisition. This problem was solved by using the homodecoupler as a trigger for: 1. receiver blanking; and 2. simultaneously switching the transmitter and the phase shifter on and off in order to produce composite 180° pulses. The experiment was done on two capillaries, one with isopropanol and one with ethanol. (The high resolution spectra of isopropanol and ethanol is shown in Fig.3.) The carrier frequency and the filter width were adjusted to detect only the methyl resonances (at about 1.0 ppm) of the two compounds. Figs.4 and 5 show the results of the J imaging experiment without and with composite pulses and phase cycling respectively. In the spectra in Fig.5, the middle line was suppressed as a result of software correction. The ethanol image is reduced on the basis of smaller number of protons per line.

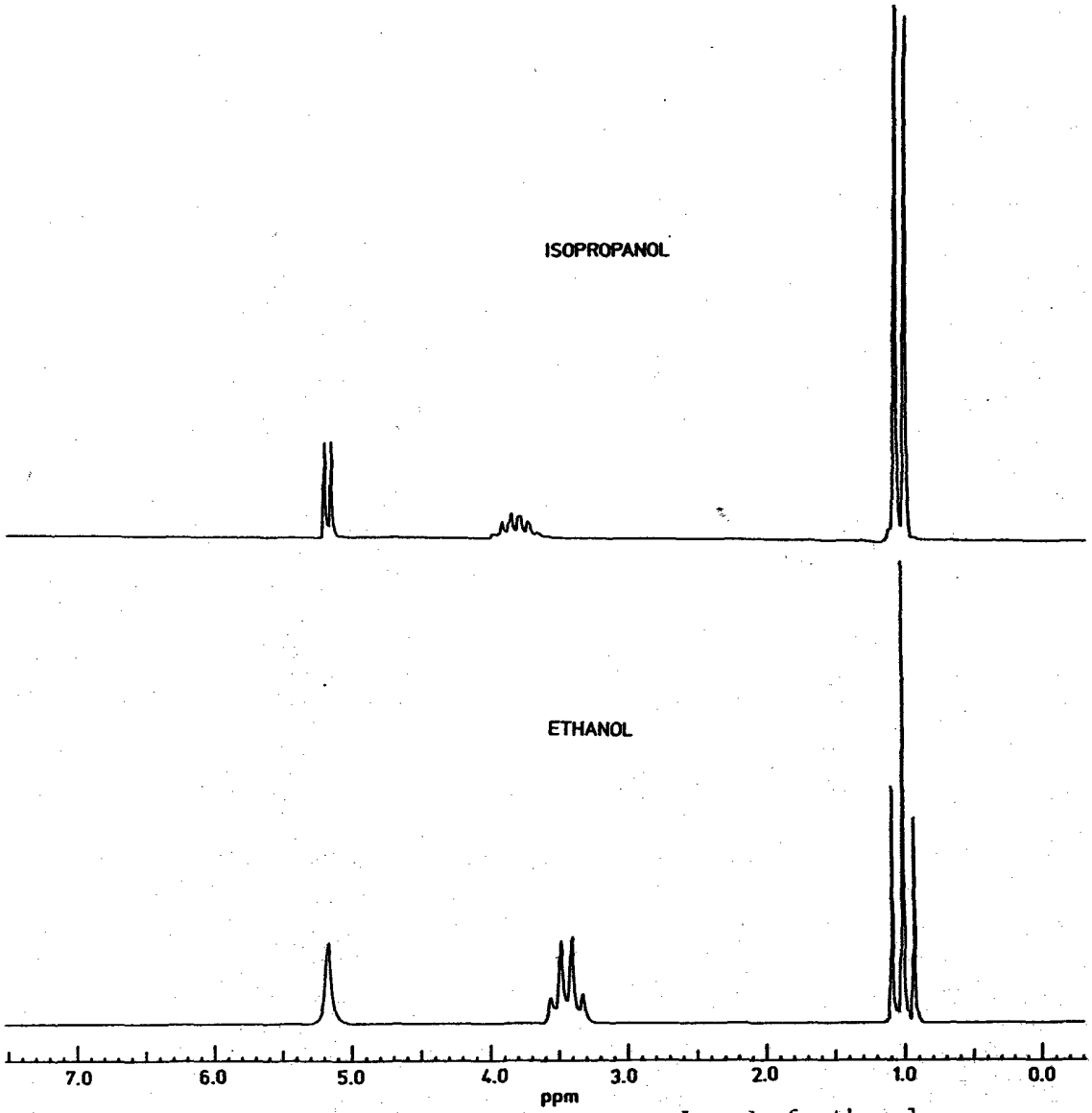


Figure 3. The high resolution spectra of isopropanol and of ethanol.

The experimental conditions were similar to those of whole body magnets. The static field inhomogeneity was 40 Hz, in which the multiplet structure of isopropanol and ethanol is not resolved. The relative r.f field inhomogeneity ($\Delta H_1/H_1$) was 0.25. Based on these results there is good reason to expect that the technique will be useful also with whole body magnets.

This technique may have many applications. One is the imaging of lactic acid for in vivo detection may have ischemic of regions. The technique might also be useful for detecting cancer mapping glycolysing tumours. A modification of the technique is heteronumber J imaging (Fig.6), which can be used, for example, in vi-vivo imaging of ^{13}C labeled glucose using the "C-H" coupling. Another possible application is the in vivo mapping of phosphorus metabolites using ^{31}P-H coupling and, as mentioned before, the techniques can be used for imaging of localized anisotropies in biological as well as in nonbiological samples.

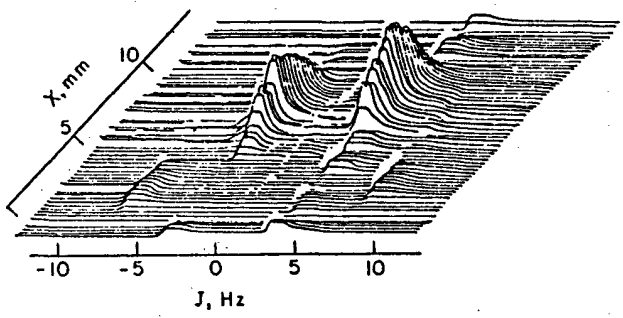


Figure 5. The results of a J-imaging experiment with composite pulses and phase cycling. The artifacts are suppressed.

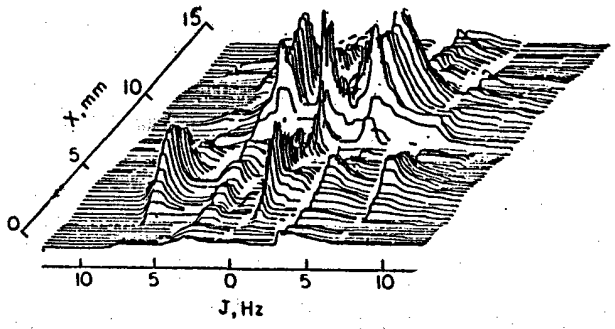


Figure 4. The results of a J-imaging experiments without composite pulses and phase cycling. The spectrum is distorted because artifacts are formed due to an inhomogeneous r.f. field.

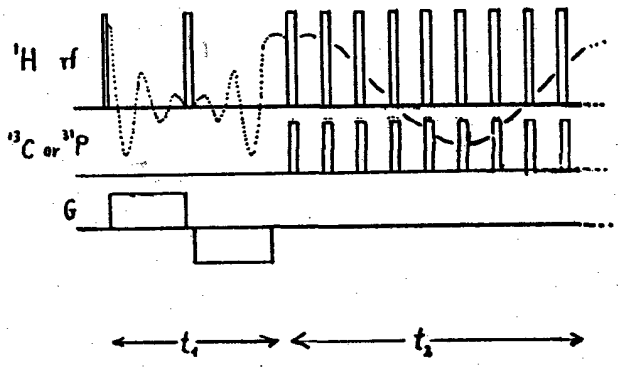


Figure 6. A pulse sequence for heteronuclear J-imaging experiment.

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