NMR IMAGING NEW STRATEGIES: MAGIC ANGLE IMAGING

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INTRODUCTION

Until now, the major part of NMR Imaging studies were finalized to diagnostic goals. Hence the main subject of imaging works were the water mobile molecules of biological tissues. Other fields of recent interest were the imaging of nuclei different from protons and high spatial resolution (NMR microscopy). Another branch of great interest is the imaging of the broad band components of biological tissues or in general of the solid-like systems.
As the main sources of broad band spectra in biological tissues are proteins, amino acid etc., the knowledge of their large band components distribution characterize in a specific way the normal or pathologic state of living tissues.
In spin systems with large bandwidth, the imaging induced broadening needs very intense gradients to get a good spatial resolution Δr. Actually the fundamental imaging relation

$$\Delta r \; G > \Delta B \qquad |1|$$

with G the magnetic field gradient and ΔB the internal local field, is not easy to realize experimentally with a small enough Δr. The main cause of spectral broadening is a strong dipolar coupling between spins, hence ΔB is the local dipolar field.

A method of imaging(1) that averages the dipolar interaction and therefore narrows the line bandwidth is here presented. In this method the rotating frame acts like a probe spinning at frequencies much higher than those experimentally available in the common sample spinning experiments.

THEORY

In the Rotating Coordinate Frame (RCF) at frequency ω around the Zeeman field $B_o \hat{k}$, the secular dipolar hamiltonian can be written(2)

$$\mathcal{H}_R \simeq \mathcal{H}_{zR} + \tfrac{1}{2}(3\cos^2\theta - 1)\mathcal{H}_L \qquad |2|$$

where $\mathcal{H}_{zR}$ is the rotating Zeeman hamiltonian and $\mathcal{H}_L$ the usual dipolar term in the Laboratory Coordinate Frame (LCF). The RCF parameter θ is defined by

$$\operatorname{tg}\theta = \frac{B_1}{\Delta} \qquad |3|$$

where B_1 is the radio frequency field intensity and $\Delta = B_o - \frac{\omega}{\gamma}$ the resonant off-set. From |2| the second moment $\overline{\Delta\omega^2}_R$ in RCF is related to the second moment $\overline{\Delta\omega^2}$ in LCF by(3)

$$\overline{\Delta\omega^2}_R \simeq [\tfrac{1}{2}(3\cos^2\theta - 1)]^2 \overline{\Delta\omega^2} \qquad |4|$$

Equation |4| clearly shows that at the "magic" angle value

$$\theta_M = \cos^{-1}\frac{1}{\sqrt{3}} \qquad |5|$$

the second moment in RCF vanishes and a narrowing of the linewidth is reached.

This narrowing technique in RCF can be utilized for spatial imaging, as it is possible to make imaging completely in RCF by a modification of Hoult's method(4). The Full Rotating Frame Imaging(5) encodes the spatial information completely in RCF. Infact, if the experiment is performed with $t \ll T_2$, the evolution of the z component of local magnetization can be written as

$$m_z(r,t) = m_o(r)\sin^2\theta(r)\cos\omega_E(r)t \qquad |6|$$

where $m_o(r)$ is the equilibrium magnetization of the r-plane along the space direction r in which the effective field

$$B_E(r)=\left[\left(\Delta + \frac{\partial \vec{B}_o}{\partial r}\cdot\vec{r}\right)^2+\left(B_1+\frac{\partial \vec{B}_1}{\partial r}\cdot\vec{r}\right)^2\right]^{1/2} \qquad |7|$$

change linearly in intensity. The space variation of B_E in |7| is obtained by the static gradient $(\partial B_o/\partial r)$ and the radio frequency gradient $(\partial B_1/\partial r)\cos\omega t$. In this way the precession frequency of the magnetization around B_E, namely $\omega_E(r)= \gamma B_E(r)$, is characteristic of one space position. Actually the Fourier transform of |6| gives

$$m_z(r,\omega)=m_o(r)\sin^2\theta(r)\cdot \int_{-\infty}^{+\infty}\cos\omega_E(r)t\, e^{i\omega t}dt \sim$$

$$\sim m_o(r)\sin^2\theta(r)\,\delta[\omega-\omega_E(r)] \qquad |8|$$

The Fourier component |8| means that the plane r=const has

$$\omega = \omega_E(r) \qquad |9|$$

that characterizes the precession frequency of magnetization $m_o\sin^2\theta$ of the plane r. Hence the whole spectrum is

$$M_z(\omega) \sim \int_{L_r} m_o(r)\sin^2\theta(r)\cdot \delta[\omega-\omega_E(r)]\,dr \qquad |10|$$

where L_r is the maximum extension of the sample in the r direction. Eq. |10| represent the magnetization profile of the sample along r, if θ does not depend on space. The application of the condition |3| also for the gradient intensities, i.e.

$$tg\theta = \frac{\partial B_1}{\partial r} \Big/ \frac{\partial B_o}{\partial r} \qquad |11|$$

is enough to have θ constant.

After eq. |11|, the eq. |10| represents the magnetization distribution of the sample along the r direction, like a δ envelope. By putting the result |10| in the hamiltonian |2|, a new hamiltonian $\mathcal{H}'_R$ in RCF is obtained(6)

$$\mathcal{H}'_R \simeq \mathcal{H}_{zR} + \tfrac{1}{2}(3\cos^2\theta-1)\,\mathcal{H}_L + -\gamma\hbar\sum_i \vec{r}_i\cdot\overleftrightarrow{G}_E\cdot\vec{I}^i \qquad |12|$$

In $\mathcal{H}'_R$, the nine components tensor $\overleftrightarrow{G}_E$

can be reduced to on "effective" vector

$$\vec{G}_{E_r} \equiv \frac{\partial \vec{B}_E}{\partial r} = \left[\left(\frac{\partial B_o}{\partial r}\right)^2 + \left(\frac{\partial B_1}{\partial r}\right)^2\right]^{1/2} \frac{\vec{r}}{|r|} \qquad |13|$$

whose components can effects the RCF "resonant" frequencies, when its associated hamiltonian term produce an induced broadening on Δr greaster than that produced by the dipolar term. This situation is easily reached when the magic angle value |5| is set. The new spatial resolution condition in RCF then becomes

$$\Delta r \left|\frac{\partial \vec{B}_E}{\partial r}\right| > \tfrac{1}{2}(3\cos^2\theta - 1)(\overline{\Delta\omega^2})^{1/2} \qquad |14|$$

An extension of the Magic Angle Imaging Technique can provide the spatial distribution of macromolecules, like proteins, amino acid etc. in biological tissues. Actually since the dipolar interaction in tissues water is naturally narrowed, its bandwidth does not depend on θ. Hence a spatially encoded RCF spectra at $\theta = 90°$ and at $\theta = \theta_M$ differ for the broad components only, on condition that the broad part spectral component is narrowed to the water width. This requires that

$$\gamma \Delta r \left|\frac{\partial \vec{B}_E}{\partial r}\right| > \Delta\omega_{MM} \simeq \Delta\omega_w \qquad |15|$$

where $\Delta\omega_{MM}$ is the Magic Angle spectrum width of the macromolecular part and $\Delta\omega_w$ that of the water.

EXPERIMENTAL RESULTS

The simplest manner (5,6) for detecting the ω_E precession in RCF is a coil tuned at ω_E with its sensitive axis parallel to $B_o\hat{z}$. Because $\omega_E \sim 10^{-3}\ \gamma B_o$, the emf induced on the low frequency coil is much lower than the signal induced at usual NMR frequencies and therefore the signal-to-noise ratio (S/N) in a RCF experiment is much lower than the one in LCF. It is possible to compensate the lower frequency effect of RCF by increasing the number of turns of the RCF coil. It can be shown than the S/N in RCF is given by

$$\Psi_R \sim \left(\frac{N}{R}\right)^{1/2} \omega_E B_o \sin^2\theta \qquad |16|$$

where N is the total number of turns of the coil and R the dc resistence of one coil turn. From |16| the S/N in RCF can be increased by increasing N, at least as long as the coil stray capacitances make the coil self resonant frequency higher than ω_E.

The first result(7) with the Magic Angle Imaging Technique was obtained on polycrystalline adamantane, whose NMR spectrum at $\omega_o \simeq 21$ MHz is about 25 kHz. The maximum narrowed spectrum in RCF was about 2.5 kHz, more than that theoretically aspected because the poor homogeneity of B_o. The spatially resolved spectrum shows a spatial resolution of about 3 mm with a good signal to noise ratio. The magic angle condition both on gradient and on the effective field was obtained with $B_o = 4.8$ kG, $\Delta = 4.7$ G, $B_1 \simeq 6$ G, $(\partial B_o/\partial r) \simeq 1.3$ G/cm, $(\partial B_1/\partial r) \simeq 1.7$ G/cm while with the traditional methods a gradient greater than 20 G/cm should have been used in order to get the same resolution. Both the relations |14| and |15| are fully confirmed. The saddle low frequency coil has about 1200 turns and is

tuned to 56 kHz. The radio frequency gradient was obtained by linearly varing the turn density of the high frequency coil.

With the RCF Magic Angle Imaging technique can be obtained images of solids or of other large bandwidth systems, in particular the spatial distribution of the macromolecules in biological tissues. Due to the low ω_E "resonant" frequency, the images in RCF can be sensitive to $T_{1\rho}$ or $T_{2\rho}$ and so to the slow or ultra-slow molecular motion. These parameters with the macromolecular spatial concentration and the usual LCF parameters could characterize in a specific way the tissue pathologies or its normal metabolic state.

The S/N we have obtained is quite satisfactory but by considering our simple electronics based on an old Bruker SPX Spectrometer, we conclude that the S/N could be easily increased with a more sophisticated experimental apparatus.

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