Progress in NMR Imaging
- From Proton Imaging to 4-D Spectroscopic Imaging

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1. Introduction

Recently Nuclear Magnetic Resonance (NMR) became a reality and extensive research efforts are underway both at academic institutions and industrial research and development centers all over the world.[1,2] It is also becoming apparent, now, that the recently obtained image quality appears to be comparable with X-ray CT images in resolution and superior in many other aspects, such as contrast sensitivity.

Although similarity seems to exist between X-CT and NMR-CT, basic principles underlying the NMR-CT differ substantially compared with X-CT and complexity involved appears much more with NMR-CT. It appears that our present understanding of NMR-CT imaging is at best pedestrian and nearly unexplored in terms of full utilization of the imaging parameters involved in NMR, such as exact evaluation of the T_1 and T_2 and imaging of these values in a variety of different conditions. Further exploration of new imaging methods, related instrumentation and algorithms appears to be unlimited. We will attempt to integrate basic image formation in NMR imaging and algorithms associated with it so that a coherent approach to the full understanding of NMR imaging can be realized.

2. Principles of NMR Physics[3,4,5]

NMR was discovered more than thirty years ago and has become an indispensable analytical method and tool in chemistry and physics. Although the basic physics of NMR is well founded and discussions can easily be found elsewhere, we will describe a few topics necessary for the understanding of NMR as an imaging tool.

Most of the materials contain nuclei that are either protons or neutrons or a combination of both. Nuclei containing an odd number of protons or neutrons, or both in combination, possess a nuclear "spin" and a "magnetic moment". This situation is equivalent to an aggregation of many small magnets. In the real world, many materials are composed of several nuclei, and the most common nuclei are ^{1}H, ^{2}H, ^{7}Li, ^{13}C, ^{23}Na, ^{31}P, and ^{27}I. Although materials may be composed of nuclei with an even number of protons and neutrons which possess no spin or magnetic moment, they usually contain some nuclei with an odd number of protons or neutrons as well. Therefore, NMR is practically applicable to meet solid and liquid-phase materials.

When a material is placed in a magnetic field, some of the randomly oriented nuclei experience external magnetic torque which tends to align the nuclei parallel to the direction of applied magnetic field. The fraction of magnetized nuclei is limited by thermal agitation,

and this small probability of magnetization of nuclei at room temperature is related to imaging sensitivity and has been a difficulty in NMR imaging. The spinning nucleus responds to the external magnetic field like a gyroscope precessing around the direction of the field. The rotating or precession frequency of the spins is usually called the Larmor precession frequency $\vec{\omega}_o$. To visualize the behavior of nuclei, three distinct nuclear-spin states associated with surrounding magnetic field situations. Two relaxation mechanisms are associated with these excited nuclear spins, namely, transverse or spin-spin relaxation and longitudinal or spin-lattice relaxation, respectively. Transverse relaxation is faster than longitudinal relaxation so that the spin-spin relaxation time constant T_2 is always smaller than the spin-lattice relaxation time constant T_1. It is interesting to note that both of these relaxation times (T_1 and T_2) are sensitive to the molecular bonding and environments surrounding the nuclei. For instance, the mean T_1 values of normal tissues compared with many malignant tissues are substantially different so that it allows us to differentiate malignant tissues from normal ones in many instances.

A similar tendency is observed for T_2 values. Imaging capabilities of these two important parameters, T_1 and T_2, together with the spin densities of the objects thus make NMR imaging a unique, versatile, and powerful technique in medical imaging.

3. Image Formation Algorithms

3.A Direct Fourier Transform Imaging[6]

First direct Fourier imaging method was proposed by Kumar, Welti, and Ernst (KWE). In this case, imaging can be procedeeded by total 3-D excitation of an object in three series of time sequences and the result of 3-D Fourier transform of those data is considered as the 3-D spin density function.

3.B Line-integral Projection Reconstruction (LPR)[7]

Projection reconstruction using a 2-D and 3-D image reconstruction algorithm is well developed, especially in the areas of X-CT and radionuclide emission tomography. Although there are several different ways of reconstructing the image, the basic form of data collection is similar, i.e., line-integral projection data of parallel or fan mode are obtained in angular steps, by rotating the object around 180^o or 360^o. The most familiar and convenient method of reconstructing 2-D or 3-D images is the Fourier convolution method.

3.C Imaging Methods

The spin density $\rho(x,y,z)$ obtained in the various imaging methods described above is not a real spin density but rather weighted by T_1 or T_2. T_1 variesgreatly between normal tissues and the image of spin density weighted by T_1 is found to be clinically useful. With this in mind there have been several attempts to extract T_1 information as well as spin density and T_2. Following are the typical imaging modes and corresponding terminology currently in use.

(a) Saturation recovery: The saturation recovery method involves simply repeating the pulse sequence at regular intervals T. The earlier equations are unchanged except for the replacement of $\rho(x,y,z)$ with $\rho'(x,y,z)$, i.e.,

$$\rho'(x,y,z) = \rho(x,y,z)\,[1-\exp(-T/T_1(x,y,z))] \qquad (1)$$

Now ρ' is a function of both T_1 and ρ.

(b) Inversion Recovery: Inversion recovery is similar to the saturation recovery technique except that the 180^{o} RF pulse is added first, then 90^{o} RF pulse follows at time T_I. $\rho'(x,y,z)$ is then related with $\rho(x,y,z)$ as,

$$\rho'(x,y,z) = \rho(x,y,z)\ [1-2\exp(-T_I/T_1(x,y,z))]. \tag{2}$$

It is easy to see that increased dependency of the image upon T_1 over that obtained in the saturation recovery.

(c) Spin echo: By application of 180^{o} pulse following the first 90^{o} pulse at time $t = T_s$, signal regrowth occurs at $t = 2T_s$ by spin echo. $\rho(x,y,z)$ is then replaced with $\rho'(x,y,z)$ which is given by,

$$\rho'(x,y,z) = \rho(x,y,z)\exp[-2T_s/T_2(x,y,z)]. \tag{3}$$

As seen, the image is now weighted with T_2 as is indicated.

4. Recent and Future Developments of NMR Imaging

4.1 High Speed Imaging[8,9]

In conventional NMR imaging methods such as IR and SR, imaging time is somewhat long mainly due to T_1. To reduce the imaging time, several fast NMR imaging methods such as echo-planar imaging and spiral-scanning imaging have been proposed and proved to be successful to some extent. In fast imaging, image data are obtained by use of oscillating gradient or a train of RF pulses. It has been experienced that oscillating gradient echo imaging methods have some advantages over multiple RF echo method. Among others, elimination of the idling time during data acquisition in gradient echo imaging are compared with r.f. pulse multiple echo imaging method. Further work, however, appears to be needed to improve the resolution and sensitivity of the image in high speed oscillating gradient imaging.

4.2 Flow Imaging[10,11]

NMR imaging techniques allow us to measure x,y and z directional flow information as well as 3-dimensional spatial information.

Several flow imaging methods have been developed in the last few years, such as phase encoding method. When time-varying gradient fields are applied in a appropriate sequence to a flow dependent object, the phase coding resulting from the time-varying gradients can then be divided into two terms - spatially coded term and flow velocity coded term. In the flow measurement, flow coding gradients are added in addition to the conventional RF and gradient pulse sequences, the resulting phases then become a flow velocity dependent function. The flow velocity then can be determined from the calculated phase velocity relation which is coded by the flow in the selected object. Increasing sophistication of this flow imaging indicates multidirectional simultaneous flow imaging in vivo.

4.3 Spectroscopic Imaging[12]

Most of the nuclei available for NMR imaging, such as ^{1}H, ^{13}C, ^{23}Na, and ^{31}P have multiple chemical spectra which often bear important information in biophysical changes or metabolism in living tissue. Since high magnetic field and good field homogeneity are essential for chemical spectroscopic imaging, superconducting magnet of field strength as

high as 2.0 Tesla or above with homogeneity as good as 1.0 ppm would be required. In the last few years a great deal of advances in spectroscopic imaging and related algorithm development have been made. It is hoped that, with the improvement in magnet technology and algorithm development, the clinically useful chemical spectroscopic imaging would soon become available.

5. Conclusions

Although diversity and complexity involved in NMR imaging is extensive and great deal of advancement have already been made, still further improvement in image quality such as resolution and signal to noise ratio are expected in many years to come, especially by use of superconducting magnet and new imaging techniques. Among the topics, such as fast imaging, flow velocity imaging and spectroscopic imaging etc. appear to be important future research topics to be developed in near future.

6. References

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