Commun. Fac. Sci. Univ. Ank. Serie A_2
V. 35, pp. 9-26 (1986)

NUCLEAR MAGNETIC RESONANCE IMAGING IN BIOMEDICINE

EROL AYGÜN AND D. MEHMET ZENGİN

Departments of Physics and Engineering Physics Science Faculty of Ankara University Beşevler-Ankara

(Received 15 September, 1986)

ABSTRACT

The objective of this article is to review the subject of nuclear magnetic resonance (NMR) imaging and emphasize its potential applicatio ı to biomedicine and foodstuffs. NMR imaging is a hazardless, promising and rapidly improving new technique proposed as a modality to computerized tomographic x-ray scanning in hospitals, medical centers and clinics. This article displays how biomedicine is converted from a descriptive art to a quantitative science by NMR imaging techniques. Also the study reviews the novel physical principles and instrumentations of NMR imaging besides its very broad applications from biomedicine to foodstuffs.

INTRODUCTION

Nuclear magnetic resonance (NMR) is a potential research branch of physics and chemistry. In this overlapping area of physics and chemistry the structural constants of molecules in liquids or solids are determined. The subject of NMR is a sub branch of magnetic resonance (MR) which can be schemed as shown in Fig. 1. As it is seen in the Fig. 1, in MR, there are NQR (nuclear quadrupole resonance), NMR (nuclear magnetic resonance), ESR (electron spin resonance) which they deal with bulk samples; besides ABMR (atomic beam magnetic resonance) and ODR (optical double resonance) which they study the structure of isolated atoms or molecules in gaseous forms of samples.

The inception of convensional NMR goes back to in 1946, by that time Bloch put the foundations of standard NMR spectroscopy. The contribution of Purcell, Abragam and others on the subject are inevitable to site here.

ISSN 0378-6260, Ankara Üniversitesi Basımevi

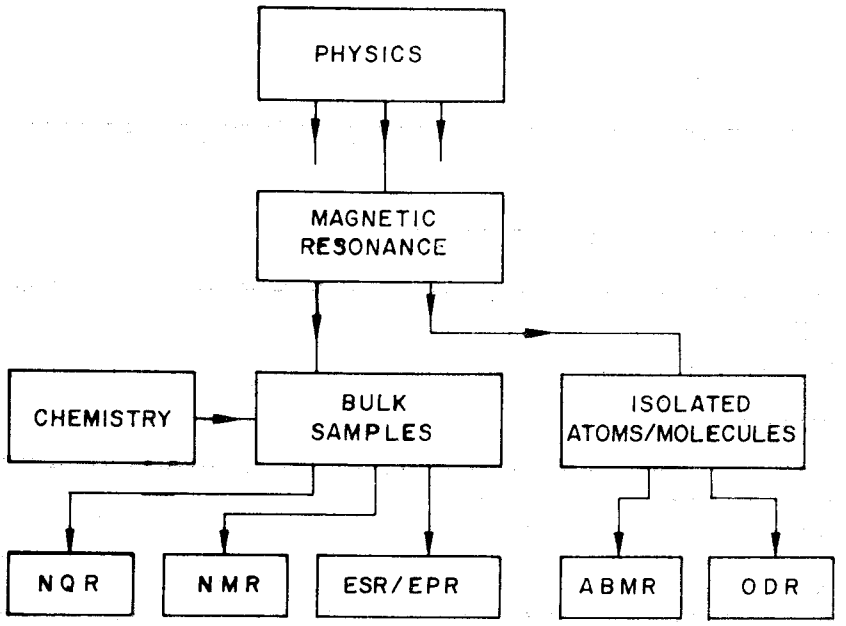

Fig. 1. The branching of the subject of magnetic resonance.

NMR application to organic materials is essentially consists of proton resonances of water molecules in the specimen. Proton resonance in H_20 is not the only means for NMR imaging, besides proton, other elements like C, N, O, F, Na, P and K are also of biological interest (Hoult, 1976). In those measurements structural constants of the sample are measured. Namely the spin density $\rho(r)$, the spin – lattice relaxation time T_1 and the spin-spin relaxation time T_2 measurements are made to explain the structure of the samples. An important and growing application of standard NMR technique is the study of water content in a variety of materials like foodstuffs and fuels. Most of the works to date on water in biological systems has been performed on materials by NMR technique besides a variety of other methods. Since human body containes 55 to 60 percent of water then one might examine human body by NMR techniques. This was the very original idea of the pioneers of the subject. Purcell and Hahn placed their heads in suitable NMR magnets in an effort to try to observe differences in NMR signal shapes

(Mansfield and Morris, 1982). But these very early experiments have nothing to do with the NMR imaging.

The inception of NMR imaging goes back to early 1970's. Damadian (1971), Lauterbur (1973), Mansfield and Grannell (1973) independently discussed the subject openly in period of 1971–1973. In the past decade dramatic changes in the subject and experimental accomplishments have occured. NMR imaging covers three main areas, namely mathematical and algorithmic techniques of image formation, physical principles involved and finally instrumentation. At present quite a number of papers are coming out on NMR computer simulation results and experimentally obtained images for the demostration of the potential of the method for clinical applications. The superiority of NMR imaging to computerized tomagraphic x-ray (CT x-ray) has already been demostrated by various researchers (Cho and Nalcıoğlu, 1984).

In standard NMR studies one wants to have a very homogeneous steady magnetic field in order to have a pure output signal. But it is highly difficult to achieve it over the size of the sample. While standard NMR researchers were putting quite an amount of effort to increase the field homogeneity in 1950's and 1960's, they were not aware of what would come out of the magnetic field inhomogeneities. (Because NMR images are obtained by making use of the spatial magnetic field variation over the sample volume). Consequently, to obtain an image of the specimen by making use of the spatial field gradient distribution of steady magnetic field, has been delayed to 1970's. The clinical trials of NMR imaging have been started in 1980 and since then developments have been very rapid (Damadian, 1981, and Mansfield and Morris, 1982). At present NMR imaging is being tested as a clinical diagnostic aid in USA, Britain and Japan by using prototype commercial spectrometers. An NMR imaging spectrometer is an alternative to CT x-ray scanning equipment and we feel sure that in the very near future commercial NMR machines capable of producing medical images for clinical use will be available in all countries.

Sensitivity of NMR machines is higher than CT x-ray scanning equipment: As long as the pathological deformation in a location of body is not sufficient enough, CT x-ray scanning does not yield an information to locate the area. But NMR imaging technique, since it makes use of the local water (proton) concentration, gives a clue about the start of pathology in its very early phase. Considering the vitality of early diagnosis of cancer, it is hard to imagine how and what a promising technique is the NMR imaging.

Certainly magnetic resonance imaging (MRI) is not the unique alternative to CT x-ray scanning. A third method is the ultrasonic imaging (Wells, 1972), which is also hazardless at low sonic powers.

Though NMR examines bulk samples and consequently pathological examination is in macroscopic level, it is envisaged that MRI machines will be capable of examining materials at microscopic level as well in near future. An NMR microscope will be capable of examining tissues at the cellular level (at present resolution is 10 μm) and could be of value in biopsy studies. After the high-speed computer processings, cell dynamics, diffusion processes, drug incorporation and cell nutrition will be traced by NMR microscopes. The physics here is essentially to trace the resonances of mobile protons in biological tissues.

The subject is so new that even the wordings of concepts are not settled down in literature yet. For example "NMR imaging" and "NMR tomography" are equally used for one another. A more involved name for imaging is "zeugmatography", based on the Greek word "zeugma" which means yoke. FONAR is an acronym formed from the words "field-focussed nuclear magnetic resonance". "Topical NMR" stems again from the Greek word "topos" meaning "point (or region) NMR". "In Vivo" and "In Situ" diagnoses are used for one another for the examination of the sample in live and in its place, respectively. While authors agree on "in vitro" diagnosis for surgically removed study of samples. Some of the authors prefer to use "X-ray tomography", "ultrasound echography" and "NMR zeugmatography" as they are stated here (Damadian, 1981).

BASIC NMR IMAGING THEORY

NMR imaging theory is essentially sat on the basic NMR theory in nuclear spectroscopy. The theory of NMR application in medicine and industry can be handled in two parts as; the principles of free precession and the mathematics of the field gradients. In almost all the applications of NMR, pulse techniques are used and when the rf pulse is off the magnetization precesses freely around the static magnetic field.

THE THEORY OF FREE PRECESSION

Bloch (1946) and Bloch et al. (1946) found that the equation of motion of the macroscopic magnetization $\vec{M}$, of a spin system in the

presence of a static magnetic field $\vec{Ho}$, could be explained in terms of phenomenological differential equations. Starting with the classical equation of motion,

$$\frac{\vec{dp}}{dt} = \vec{M} \times \vec{Ho} \tag{1}$$

where $\vec{P}$ is the angular momentum of the spin system. The motion is the so-called Larmor precession as shown in Fig. 2. Once the rf field $\vec{H_1}$, is applied perpendicular to $\vec{Ho}$, the magnetization starts to precess around the resultant magnetic field $\vec{H}$, which is given by

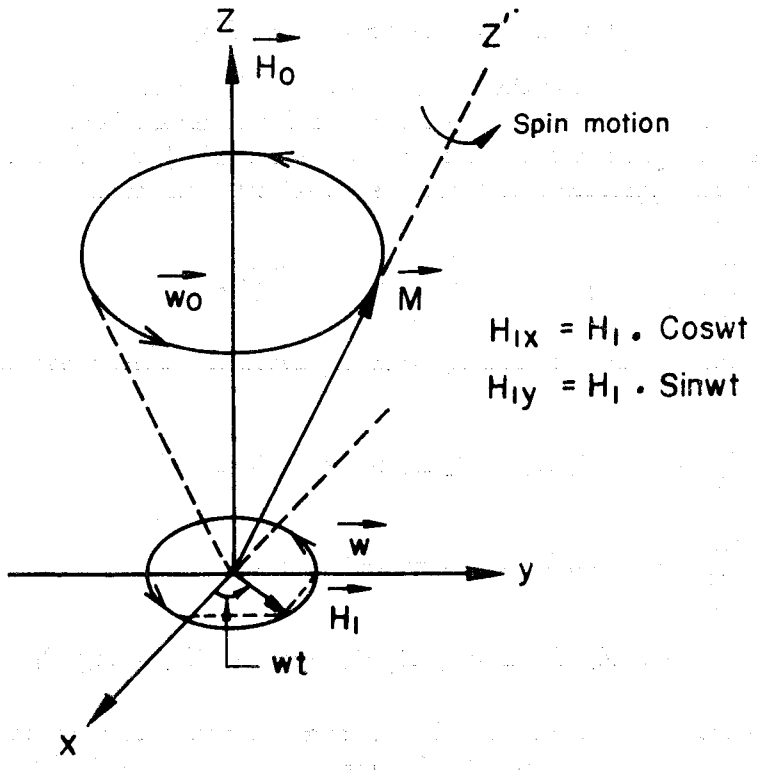

Fig. 2. Larmor Precession of a spinning magnetization and decomposition of rf field H_1

$$\vec{H} = \vec{Ho} + \vec{H}_1 \tag{2}$$

then the equation of motion of the spin system can be rewritten as

$$\frac{\vec{dp}}{dt} = \vec{M} \times \vec{H} \tag{3}$$

multiplying both sides by the magnetogyric ratio γ, and replacing $\gamma \vec{p}$ by $\vec{M}$, the eq. (3) becames

$$\frac{\vec{dM}}{dt} = \gamma \vec{M} \times \vec{H} \tag{4}$$

This equation can be expressed in terms of the components of $\vec{M}$ and $\vec{H}$. It is clear from the Fig. 2, that the components of $\vec{H}$ are

$$H_x = H_1 \text{ Coswt}, \quad H_y = -H_1 \text{ Sinwt}, \quad H_z = Ho, \tag{5}$$

Bloch has shown that the eq. (4) is a classical approximation. Indeed it must include the spin-lattice relaxation (longitudinal relaxation) time T_1 and the spin-spin relaxation (transverse relaxation) time T_2 in it as a first order approximation. Then the eq. (4) takes the form

$$\frac{\vec{dM}}{dt} = \gamma \vec{M} \times \vec{H} - \frac{(\vec{M})_z - \vec{M}_o}{T_1} - \frac{(\vec{M})_{x,y}}{T_2} . \tag{6}$$

Then the equation of motion, when separated in cartesian cordinates are

$$\frac{dMx}{dt} = \gamma (M_y H_o + M_z H_1 \text{ Sinwt}) - Mx/T_2 \tag{7a}$$

$$\frac{dMy}{dt} = \gamma (M_z H_1 \text{ Coswt} - M_x H_o) - My/T_2 \tag{7b}$$

$$\frac{dMz}{dt} = -\gamma (M_x H_1 \text{ Sinwt} + M_y H_1 \text{ Coswt}) - (M_z - M_o)/T_1 \tag{7c}$$

These equations are the so-called phenomenological Bloch equations. Once the rf pulse is turned off, the terms containing the rf field H_1 will vanish, and using the relation $\omega_o = \gamma H_o$, the eq. (7) becomes

$$\frac{dMx}{dt} = \omega_o M_y - Mx/T_2 \tag{8a}$$

$$\frac{dMy}{dt} = -\omega_o M_x - My/T_2 \tag{8b}$$

$$\frac{dMz}{dt} = -(M_z - M_o)/T_1 \tag{8c}$$

Considering the duration of the pulse $t_p \ll T_o = 2\pi/\gamma H_o$ and having rf pulse in x- direction, then one has initial conditions as;

$$M_x = O, M_y = M_p, M_z = O \tag{9}$$

with these initial conditions, the solution of the differential eq. (8) are

$$M_z = Mo\,(1 - e^{-t}/T_1) \tag{10a}$$

$$M_y = M_p\,Cosw_o\,t\,e^{-t}/T_2 \tag{10b}$$

So the spin system performs a damped precession in which the rotating transverse components of $\vec{M}$ decay to zero with a characteristic time T_2, while M_z relaxes towards its equilibrium value M_o with a decay time T_1. Figure 3 shows the longitudinal and transverse relaxations of the spin system separately. Those plots are known as free induction decay (FID) signals in literature.

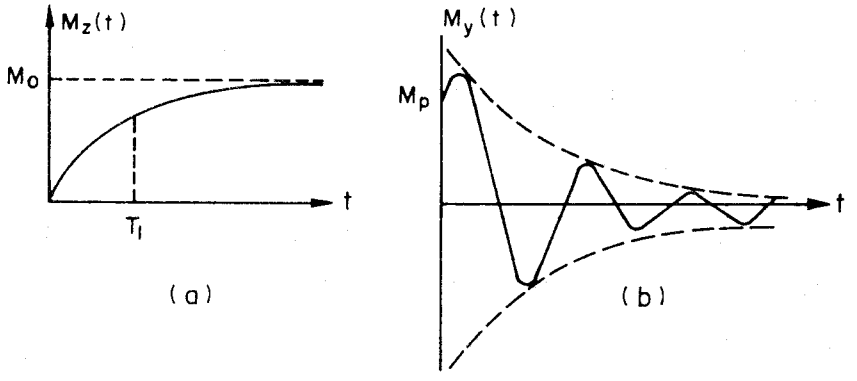

Fig. 3. (a) Longitudinal relaxation and (b) transverse relaxation of the spin system after a $\pi/2$ pulse.

FIELD GRADIENTS FOR NMR IMAGES

NMR images are created by linear magnetic field gradients added on the static background field. Once the rf field is applied the spatially differenciated discrimination of the NMR response of a distributed system of magnetic dipole moments is obtained. General technique in image production is to measure anyone of NMR parameters, like spin density $\rho(r)$, spin-lattice relaxation time T_1, spin-spin relaxation time T_2, and then map the spatial variation of the parameter throughout the volume of the sample. An easy way to do this is to create the spatial gradient of the magnetic field so that the magnetizations from different parts of the specimen precess at different Larmor frequencies. In this way, the spatial field displacements are turned into ferquency displacements. Magnetic dipole moments of protons of water molecules in the sample resonate in this process. The field gradient created is linear in general.

A Linear magnetic field gradient is a tensor $\mathcal{G}$ comprising nine components as a dyadic;

$$\mathcal{G} = \begin{bmatrix} \mathbf{ii}\dfrac{\partial H_x}{\partial x} & \mathbf{ij}\dfrac{\partial H_x}{\partial y} & \mathbf{ik}\dfrac{\partial H_x}{\partial z} \\ \mathbf{ji}\dfrac{\partial H_y}{\partial x} & \mathbf{jj}\dfrac{\partial H_y}{\partial y} & \mathbf{jk}\dfrac{\partial H_y}{\partial z} \\ \mathbf{ki}\dfrac{\partial H_z}{\partial x} & \mathbf{kj}\dfrac{\partial H_z}{\partial y} & \mathbf{kk}\dfrac{\partial H_z}{\partial z} \end{bmatrix} \tag{11}$$

The Hamiltonian for an isolated spin at position r in a static magnetic field $\vec{Ho}$, with gradient $\mathcal{G}$ is given by Mansfield et al. (1982),

$$\mathcal{H} = \hbar\,\omega_o\,I_z + \hbar\,\vec{I}.\,\mathcal{G}.\,\vec{r} \tag{12}$$

where the first term is due to the static field $\vec{Ho}$ while the second term stems from the gradient field. The tensor-vector product $(\mathcal{G}.\vec{r})$ can be expressed in terms of a vector field $\triangle\,\vec{H}$ having three components in x, y and z directions. If the static field $\vec{Ho}$ is in z-direction and $\vec{Ho} \gg |\triangle\,\vec{H}|$ then $\triangle H_x\,\vec{i}$ and $\triangle H_y\,\vec{j}$ can be neglected. Then the eq. (II) becomes

$$\mathcal{G} = \frac{\partial H_z}{\partial x} \vec{k}.\vec{i} + \frac{\partial H_z}{\partial y} \vec{k}.\vec{j} + \frac{\partial H_z}{\partial z} \vec{k}.\vec{k} \qquad (13)$$

Now defining a field gradient vector $\vec{G}$ which has

$$G_x = \frac{\partial H_z}{\partial x}, \; G_y = \frac{\partial H_z}{\partial y}, \; G_z = \frac{\partial H_z}{\partial z} \qquad (14)$$

as its cartesian components, then eq. (13) becomes

$$\mathcal{G} = G_x \vec{k}.\vec{i} + G_y \vec{k}.\vec{j} + G_z \vec{k}.\vec{k} \qquad (15)$$

The vector-tensor product $\vec{I}.\mathcal{G} \cong I_z \vec{G}$, then eq. (12) simplifies to

$$\mathcal{H} = \hbar \omega_o I_z + \hbar I_z \vec{G}.\vec{r} \qquad (16)$$

which is the expression for the total Hamiltonian of the spin system. Here the first term is the energy of the spin system due to the precession around $\vec{Ho}$ and the second term is the corresponding energy for the gradient field.

BASIC NMR IMAGING SPECTROMETERS

The block diagram of a basic NMR imaging spectrometer is shown in Fig. 4. Such spectrometers consist of the following main components;

a) rf transmitter units

b) Signal receiver components

c) Data acquisition and processing units

d) Magnetic field production and control components.

Maudsley and his coworkers (1984) give a good discussion on the basics of electronics and instrumentation for NMR imaging spectrometers. In their paper they give the specific requirements together with an overview of all components of an NMR imaging system.

The transmitter units in the Fig. 4 involve the frequency synthesizer, the rf gate and the transmitter. The rf magnetic field is supplied by these units to excite the nuclei in the sample. The signal receiving components are the preamplifier and the detector. The rediofrequency signal from the nuclei is detected by these components. And its strength determines intensities of the pixels in the image. The data acquisition unit, the computer and the user interface are the data handling units.

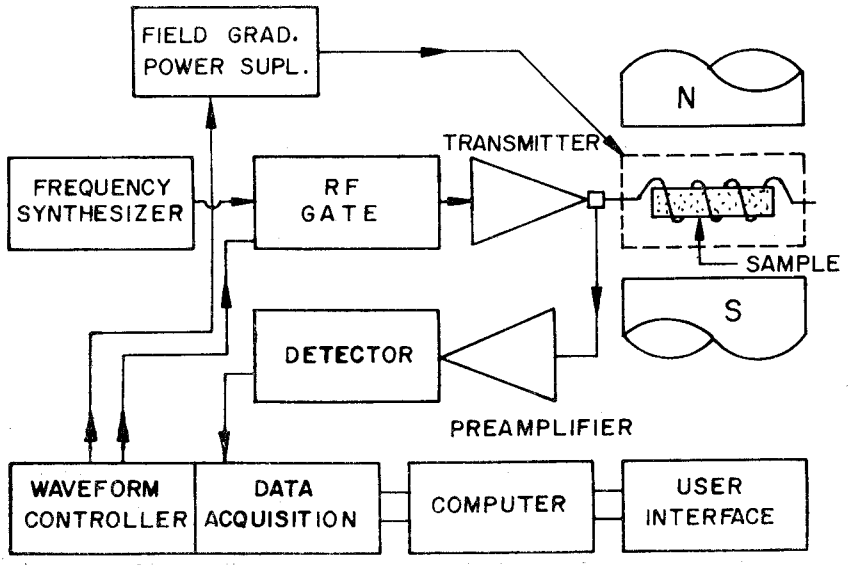

Fig. 4. Block diagram of a basic NMR imaging spectrometer (Maudsley et al., 1984)

The dipole magnet in the Fig. 4 provides the background field which is necessary for the standart NMR process. This field has to be strong, uniform and stable, because of the signal strength considerations. In an NMR imaging system, in addition to the steady field magnet, there are shimming coils to enlarge the volume of the homogenous field space and the gradient field coils to define the location of pixels for the mapping purposes. A typical high-resolution resistive electromagnet will operate with 25 kG, whereas super conducting magnets operate at 100 kG (10 T) producing static field inhomogeneities of the order of 1 parts in 10^8 over a volume of 1 cm^3.

In an NMR imaging spectrometer, one requires magnetic field gradients G_x, G_y and G_z over the range to be imaged as they have explained in the basic NMR imaging theory of this article. Field gradients are created by separate gradient coils as shown in the Fig. 4 symbolically. The simplest coil arrangement for the production of field gradient is the Maxwell pair (Tanner, 1986). Mansfield and Morris (1982) give a good discussion on how to get a linear field gradient for NMR imaging purposes. There are other structures, like quadrupole magnets to achieve spatial magnetic field gradients over the sample size (Ödberg, 1974 and Brener, 1985).

Presently, instead of classical permanent or water-cooled resistive electromagnets, more stable supercoducting magnets which work at low temperatures are preferred for NMR imaging spectrometers (Willams, 1984). In this very new application of NMR, the imaging process, data acquisition and display are all controlled by computers.

Signal-to-noise ratio of an NMR imaging spectrometer is defined as the following (Ernst, 1966):

$$\frac{S}{N} = \left(\frac{\text{total signal energy}}{\text{noise power/band width}} \right)^{1/2}$$

which means that signal-to-noise ratio of an MRI spectrometer is proportional to the square root of the total signal energy. MRI spectrometers with the field gradients over the sample give Lorentzian line shape of halfwidth $1/\pi\ T_2$, where T_2 is the spin-spin relaxation time. Brunner and Ernst (1979) give a detailed discussion on the sensitivity and performance time of NMR imaging in terms of S/N rations of such spectrometers.

NMR IMAGING METHODS

NMR images are created by regimes of data acquisitions. Namely, sequential point, sequential line, sequential plane and simultaneous volume techniques are the regimes of data acquisitions. This classification is done by Brunner and Ernst (1979). Figure 5 shows the data acquisition units of NMR imaging methods. In a point method, one would only receive information from a single pixel at a moment of time, whereas in other methods, informations are collected from a line, plane or volume of spin respectively. All these techniques are for the production of the NMR images of the sample object over its size and throughout its

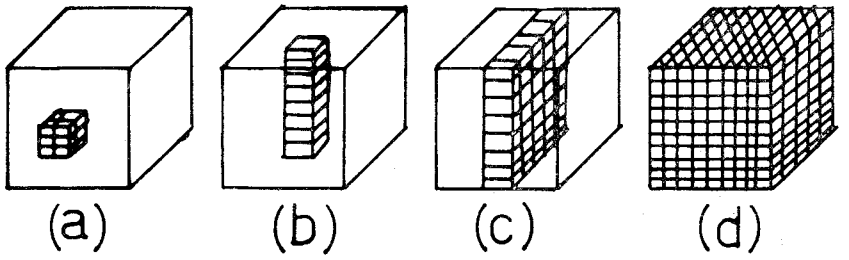

Fig. 5. Data acquisition units in NMR imaging methods: (a) Sequential point measurement. (b) Sequential line measurement. (c) Sequential plane measurement. (d) Simultaneous volume measurement.

volume. That is called the "imaging regime" in the literature. Assuming a spherical volume to be NMR imaged, the scales of regimes are "large" for 20 cm, "intermediate" for 5 cm, "small" for 1 cm, and "microscopic" for $\leq$ 0.1 cm radii.

Mathematical aspects of NMR image formation are handled with different approaches: "Projection reconstruction", "selective excitations", "sensitive point and sensitive line", "direct Fourier imaging" and "FONAR" approaches are the main ones. A tabulation of well-know methods of NMR imaging is presented in Table 1.

Table 1. A Summary of NMR İmaging methods.

Name of the Method	Regime of Data Acquisition	Dimensions used	Proposed by
Projection Reconstruction	Sequential Plane, simultaneous Volume	2D, 3D	Lauterbur 1973
Selective Excitations	Sequential line and Sequential Plane	1D, 2D	Mansfield 1974
Sensitive Point and Sensitive line	Sequential Point and and Sequential Line	0D, 1D	Hinshaw 1974
Fourier Imaging	Sequential Plane and Simultaneous volume	2D, 3D	Kumar et al. 1975
Focussed NMR (FONAR)	Sequential Point	0D	Damadian et al. 1976

a) Projection Reconstruction Method:

This method was proposed by Lauterbur (1973) in 1973. In this technique the image is reconstructed from a sufficient number of projections of the nuclear spin density contained in the sample. In this method to obtain a projection of the three-dimensional spin density onto a straight line, a strong magnetic field gradient is applied along the chosen direction. Nuclear spins in a plane perpendicular to this direction will all contribute to resonance at the same frequency. The signal intensity is thus a measure for the projected spin density. This logic of the NMR signal strength projections of the spin density distributions corresponding to three different equimagnetic field strength is shown in Fig. 6.

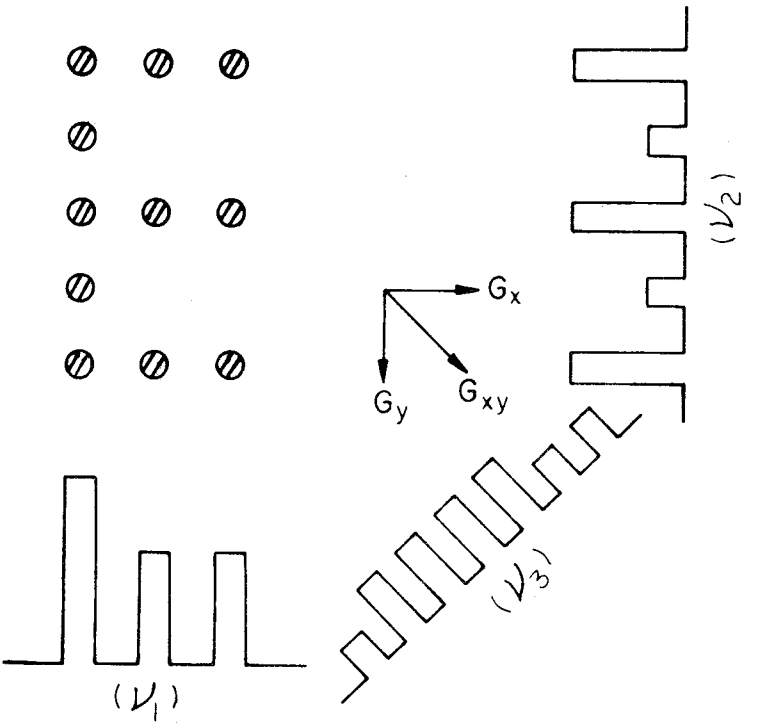

Fig. 6. The NMR spectral strength projections of a spin density distribution in the from of the letter E. The spectral projections are corresponding to three different equimagnetic field strengths at frequencies υ_1, υ_2 and υ_3. Here G_x, G_y, and G_{xy} are showing the components of the field gradient.

b) Selective excitation Methods:

These methods were introduced by Mansfield and his co-workers (1974–1976). In these techniques selective excitations are utilized to simplify the data processing. Selective excitation is applied as a line scan, a planar imaging or a multiplanar imaging.

c) Sensitive Point and Sensitive Line Methods:

This method was proposed by Hinshaw (1974). In this method three orthogonal linear field gradients, each modulated with a different field gradients, are applied on the sample and a single point in the specimen which is unmodulated is selected for the response signal. By moving the center of the field gradients, it is possible to move the "sensitive point" arbitrarily through the sample. The sensitive point method utilizes the steady-state free precession technique to generate a steady

transverse magnetization at the sensitive point. In the case of "sensitive line" method two modulated time varying gradients and one static gradient are applied on the sample. This scheme selects a single line of points as the "sensitive line".

d) Fourier Imaging Methods:

This method was proposed by Kumar et al (1975). By this method, the 2D or 3D Fourier transform of the image is recorded directly. The technique, called Fourier imaging, utilizes a sequence of switched gradients and has the advantage that reconstruction of the image can be performed by a straight forward 2D or 3D Fourier transformation. Nalcıoğlu (1984) gives an excellent comparison of projection reconstruction and Fourier techniques.

e) FONAR – Method:

FONAR is an acronym derived from, field focussed nuclear magnetic resonance. FONAR – method was proposed by Damadian et al. (1976). The method is also called "Focussed NMR". In this method the static magnetic field is suitably shaped such that a homogeneous field exists at only a single point. This method also permits one to single out the response of a single "sensitive point".

For the mathematics of NMR imaging techniques, it is worthed here to site the book editted by Nalcıoğlu and Cho (1984) which is an invaluable account on the subject.

MEDICAL AND NON-MEDICAL APPLICATION OF NMR

Medical specimens exhibiting malignant pathology can be diagnosed by NMR methods. NMR studies of biological tissues are going on all over the world. Cancer detection by NMR method made the subject so popular. Not only the cancer tumors but also all kinds of malignant tumors can be examined by NMR methods. Kautcher et al. (1978) introduced the concept of malignancy indexes for tumors. Damadian (1981) and his coworkers define the malignancy index of a tumor as:

$$\text{Malignancy Index} = \frac{(T_1)_i}{(\overline{T_1})_n} + \frac{(T_2)_i}{(\overline{T_2})_n}$$

where $(T_1)_i$ and $(T_2)_i$ are respectively spin-lattice and spin-spin relaxation times of the ith specimen, and $(\overline{T_1})_n$ and $(\overline{T_2})_n$ are the mean values of the same tissues normal specimen population. It is clear from the

equation above that, if the ith specimen is also normal (non-pathological) then the value of the malignancy index is 2.0. The majority of malignancies have indexes around 3.0. Damadian (1981) gives a very preliminary NMR classification of animal tissues. Damadian (1981) and others measured T_1 and T_2 values of malignant tumors and normal tisues surgically removed from rats or human. They all have noticed that both relaxation times of pathological tissues are longer than the corresponding relaxation times of normal tissues. Because diseases increase the viscosity of fluids in living organisms. This is why the lower limit for the malignancy index of tumors is 2.0. Besides tumors and tissues, human biological fluids like the blood, urine even the bones can be the subjects of NMR diagnosis of diseases.

In parallel to NMR relaxation time diagnosis, the NMR imaging came about as a modality to CT x-ray in the past decade. NMR methods can give all the information one may get with a CT x-ray device. NMR method is more sensitive to pathology of tissues and tumors and it is hazardless compared to x-ray exposures of intact cells. It has never been shown so far that static magnetic fields, even to high field strengths, greater and of longer duration than that used for conventional NMR are hazardous. Scientist are so confident to the harmlessness of the magnetic field that they use their own bodies as an object in NMR tests (Damadian 1981). Though there are some side effects of rf electromagnetic fields (Presman, 1970). The harmful effects of rf fields are greater at higher fields. Thus it is favorable that biomedical NMR studies in frequency are definitely below the microwave range where some damages have been shown to occur. Another favorable aspect of the pulsed NMR is that the average power expended is low. Indeed in case (whenever needed) special shielding could be used to protect nearby parts from the rf radiation. The subject of biomagnetic effects are studied by various authors recently (Davis et. al., 1962, Beisher, 1962, Budinger 1979, Llaurada et al., 1975).

Due to the presence of motion in living bodies it is desirable to obtain an NMR image of the required resolution and signal- to-noise ratio in the possible minimum time. Considering the imaging of human body as an example, the important body motion and their durations are the followings:

a) Breathing motions with periods $\cong$ 5 sec.

b) Peristaltic motions with periods $\cong$ 3 sec.

c) Cardiac motions with periods $\cong$ 1 sec.

So, one should obtain the NMR image as fast as possible. But various limitations on NMR imaging make it slower than CT x-ray scanning and at present this seems as the main disadvantage of MRI spectrometer compared to CT x-ray scanning device. On the other hand there are many advantages of MRI spectrometers and prototypes of them are already being used as shown in Fig. 7 (Mansfield and Morris, 1982). Real NMR images obtained at various research centers by numerous authors are in literature (Crooks, 1984; Damadian 1981; Mansfield and Morris 1982).

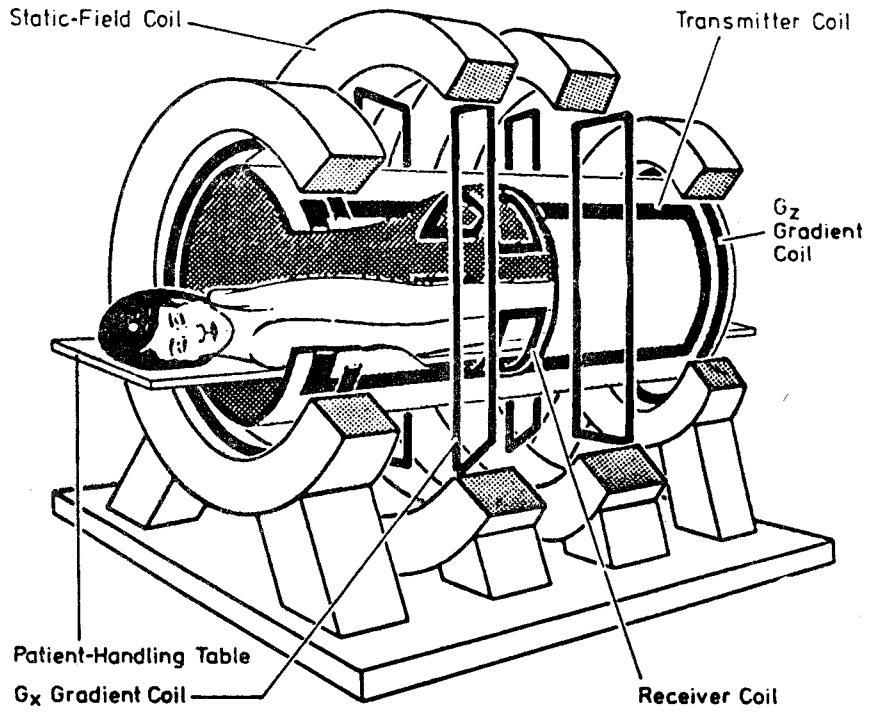

Fig. 7. Cut away sketch of whole-body NMR imaging equipment showing patient disposition (Mansfield and Morris, 1982).

NMR imaging method is promising for non-medical applications as well. Because NMR permits information about the dynamics and environment of the water molecules in living organisms, by means of the magnetization of the protons of the hydrogen atoms contained in the sample-stuff. Water content of foodstuffs (fruits, bread and so on)

and of the woodstuffs can be checked by NMR methods. National and international standardization institutions can use NMR to check the water contents of such stuffs in near future. NMR is going to be in the service of technology as well as it is for medicine.

CONCLUSION

After going through the literature, one feels that NMR imaging will find wider applications in areas other than the study of morphology of human body. Also we noticed that in the very near future commercial machines capable of producing medical images for hospital use and clinical evaluation will be available. New application of computer controlled NMR imaging spectrometers continue to be developed. Data acquisition and data processing suggest that one can expect still more innovation in NMR experiments. Especially with the developments of high-speed imaging techiques, there is now a strong possibility that in the near future one may see moving pictures constructed by NMR images, of parts of bodies of human, animals or living plants.

Authors agree that recent improvements in NMR image quality have surpassed all earlier expectations and could soon lead to a reassesment of the role of NMR as a diagnostic imaging modality.

ACKNOWLEDGMENT

We would like to express our profound thanks to Prof. Dr. Orhan Nalcıoğlu from the Irvine Medical Center of Univ. Calif. U.S.A., for his private communication.

REFERENCES

ABRAGAM A., 1961. "The Principles of Nuclear Magnetism", Oxford Univ. Press (Clarendon) London and New York.

BEİSHER D.E., 1962. Astronautics, 7, 24.

BLOCH F., 1946, Phys. Rev. 70, 460.

BLOCH F., HANSEN W.N. and PACKARD M., 1946, Ibid., 70, 474.

BRENER H., 1965, Sci. Instrum. 36, 1666.

BRUNNER, P. and ERNST R.R., 1979, J. Magn. Reson. 33, 83.

BUDİNGER T.F., 1979, IEEE Trans. Nuclear Sci. *NS*–26, 2821.

CHO Z.H. and NALCIOĞLU O., 1984, IEEE Trans. Nucl. Sci. *NS*–31, No: 4, 983 (Special Issue on Physics).

CROOKS L.E., 1984, IEEE Trans. Nucl. *NS*–31, No: 4, 1006.

DAMADİAN R., 1971, Sci. 171, 1151.

DAMADİAN R., 1981, "NMR Medicine", Springer-Verlag, Berlin, Heidelberg, New York.

DAMADİAN R., MİNKOFF L., GOLDSMİTH M., STANFORD M. and KONTCHER J., 1976, Sci. 194. 1430.

DAVİS L.D., PAPPAJOHN K., and PLAVNİEK I.M., 1962, Fed. Prof. Fed. Am. Soc. Exp. Biol. 21, (Suppl. 12) No: 5, Pt 11.

ERNST R.R., 1966, Adv. Reson. 2, 1.

GARROWAY A.N., GRANNEL P.K. and MANSFİELD P., 1974, J. Phys. C; 7, L 457

HİNSHAW W.S., 1974, Phys. Lett. A48, 87.

HOULT D.I. and RİCHARDS R.E., 1976, J. Magn. Reson. 24, 71.

KOUTHER J.A., GOLDSMİTH M. and DAMADİAN R., 1978, Cancer, 41, 174.

KUMAR A., WELTİ D. and ERNST R.R., 1975, J. Magn. Reson. 18, 69.

LAUTERBUR P., 1973, Nature, 242, 190.

LIAURADO J,G., SANCES A. and BATTOCLETTİ J.H., 1975, "Biological and Clinical Effects of Low Frequency Magnetic and Electric Fields",

THOMAS, Springfield, Illinois,

MANSFİELD P. and GRANNEL P.K., 1973, Solid State Phys. 6, L422.

MANSFİELD P., MAUDSLEY A.A. and BAİNES T., 1976, J. Phys. E; 9, 271.

MANSFİELD P. and MORRİS P.G., 1982, "NMR Imaging in Biomedicine", Academic Press, New York, London, Tokyo.

MAUDSLEY A.A., HİLAL S.K. and SİMON H.E., 1984, IEEE Trans. Nucl. Sci. *NS*–31, No: 4, 1086.

NALCIOĞLU O., 1984, IEEE Trans. Nucl. Sci. NS-31, No. 4, 983.

NALCİOĞLU O., and CHO Z.H., 1984, "Lecture Notes in Medical Informatics" Vol. 23: Selected Topics in Image Science Sipringer – Verlag, Berlin, Heidelberg, New York, Tokyo.

ODBERG G. and ODBERG L., 1974, J. Magn. Reson. 16, 342.

PRESMAN A.S., 1970, "Electromagnetic Fields and Life", Translated from Russia by Sinclair F.L., Plenum Press, New York, London.

SLİCHTER C.P., 1978, Principles of magnetic Resonnance", Springer Verlag, Berlin, New York.

TANNER I.E., 1976, Rev. Sci. Instrum. 36, 1086.

WELLS P.N.T., 1972, "Ultrasonic in Clinical Imaging", Churchill, London.

WİLLİAMS J.E.C., 1984, IEEE Trans. Nucl. Sci. *NS*–31, No: 4, 994.