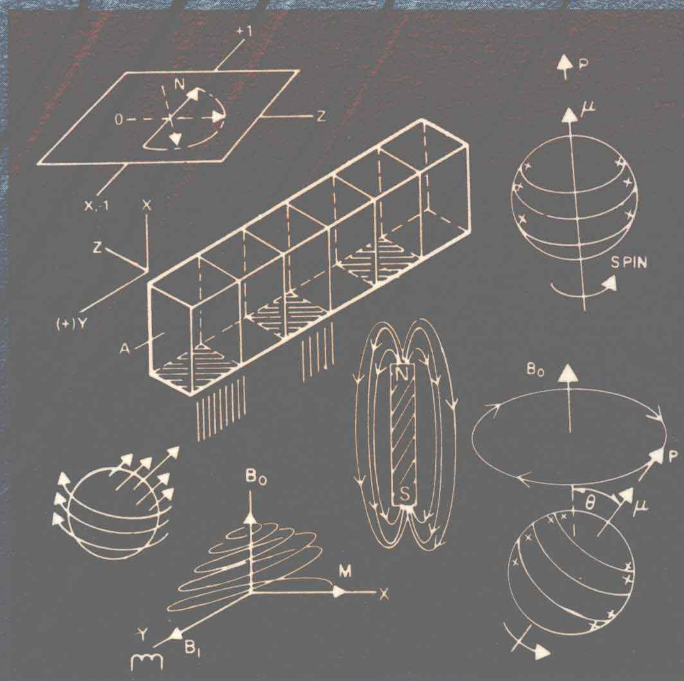
# MAGNETIC RESONANCE WORKBOOK

N.A. MATWIYOFF



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# MAGNETIC RESONANCE WORKBOOK

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# MAGNETIC RESONANCE WORKBOOK

*To Janet and Greg*

# Preface

This primer introduces the beginner to the basic concepts of proton magnetic resonance imaging (MRI) in medicine using models of the proton and tissue magnetization as ordinary magnets. These models provide direct "visual" answers to questions most frequently asked even by students who have a long clinical experience with MRI and who may have participated in a number of magnetic resonance courses. For example, exactly how is the MR signal generated and how is its frequency used to encode position? What do phase, phase coherence, and phase encoding really mean? How do MR signals "decay" and how does this decay affect contrast and intensity in the image? These questions go directly to the heart of the matter of construction and interpretation of images. The fact that they are asked so frequently by students struggling with the subject reflects the somewhat confused state of MRI education. Over the past 40 years magnetic resonance has developed rapidly as a highly sophisticated analytical and structural tool described by an equally sophisticated but difficult language grounded in the quantum mechanics of nuclear magnetic dipoles. Yet the medical magnetic resonance concepts are presented to beginners very rapidly as a potpourri of quantum mechanics, electricity, and magnetism, and often confusing analogies to everyday experience.

Of course, a complete description of the magnetic properties of small particles like the proton does require a quantum mechanical treatment, which also provides the formalism to understand and to apply the full power of nuclear magnetic resonance techniques to biomedical problems. Yet most novices come to this subject with no background in quantum mechanics and only a vague appreciation of the classical concepts of electricity and magnetism that are so important in magnetic resonance. Classical concepts *can* be used to describe the behavior of large numbers of proton dipoles. These constitute the macroscopic tissue magnetization that is manipulated in creating a proton MR image. Given the problems inherent in the "mixed" approach, I have emphasized the classical or macroscopic model in this introductory work because it is easier to understand and it allows a facile visualization of the interactions and processes taking place in proton MRI.

In Chapters 1 through 3 of the workbook I use simple, familiar, two-dimensional models to introduce the central concepts in electricity, magnetism, and MRI. The reader can demonstrate for himself many of these models using two bar magnets, a horseshoe magnet, two compasses (one having the compass needle immersed in a viscous fluid), some iron filings, and a stiff sheet of paper. In Chapters 4 through 6, I extend the treatment to three dimensions where many concepts such as pulse angles and relaxation can be treated more naturally. In Chapter 7, frequency and phase are reconsidered for the purpose of providing more insight into the individual steps of the process of image construction. The reader who does not feel comfortable with the incomplete discussion of phase in Chapter 2 might profit by proceeding directly from Chapter 2 to a preview of Chapter 4 and then Chapter 7, before continuing on to Chapter 3.

I have tried to minimize calculations and the use of equations. Nonetheless, a meaningful discussion of the origin of the variation in signal intensity and contrast encountered with the use of pulse sequences having mixed $T_1$ and $T_2$ attentuation (weighting) requires a consideration of the different forms of the exponential time dependence of the signal on the spin–spin relaxation time ($T_2$) and of equilibrium z magnetization on the spin–lattice relaxation time ($T_1$). Consequently, I "bit the bullet" and included an explicit discussion of these exponential processes in Chapter 5 and a number of closely related calculations in Chapter 6 to illustrate key aspects of the variation of signal intensity and contrast. I hope the reader will be encouraged to "bite the bullet" as well and read those sections carefully. Doing so will pay big dividends in understanding.

This introductory text is not comprehensive. It is designed as a primer on basic concepts in spin echo imaging that might be a useful companion to the physician or technologist taking one of the many MRI short courses now available. On a more permanent basis, it is intended also as a reference to facilitate the reading of the many clinically oriented reviews, references, and compendia that are being published with increasing frequency.

*N. A. Matwiyoff, Ph.D*

# Acknowledgments

I am indebted to my colleagues M. S. Brown, Ph.D., E. Fukushima, Ph.D., R. Griffey, Ph.D., and C. Haas, M.D., who read the text and provided valuable suggestions and critical comments.

I am especially grateful to Michael Brant-Zawadzki, M.D., for his advice. Without it, this text would not have been written. He was most helpful in the development of Chapters 1 through 3 offering encouragement and suggestions on improving the clarity and simplicity of the text and figures.

I am deeply grateful to my wife Janet for her support and for all her help, not only in preparing this text, but also in her many collaborating efforts in MR education.

*N. A. Matwiyoff, Ph.D.*

# Contents

# 1

# Rudiments of Proton Magnetic Resonance Imaging

## 1.1 What is a Proton Magnetic Resonance Image?

The picture shown in Fig. 1-1 is a proton magnetic resonance image (MRI) of a thin (5 mm) slice of a human brain with a resolution in plane of approximately 1 mm × 1 mm. This image of the brain was obtained at depth, noninvasively. The patient was placed in a large, strong magnet, where he acquired a very slight magnetization, so slight, in fact, that even a very sensitive compass could not detect it. The picture elements were then obtained with the aid of an antenna sensitive to the weakly magnetized areas of the patient and converted with a digital computer to an image of the brain recognizable by the eye. After the procedure the patient walked away from the magnet having immediately lost his slight magnetization and having experienced no known deleterious biological effects. The proton MRI bears a strong resemblance to an actual section of a human brain in nearly the same plane taken at autopsy (Fig. 1-2). What is remarkable about the comparison is that Fig. 1-2 is a photograph of the tangible tissue, whereas Fig. 1-1 is actually a graph of the location of the concentration (sometimes called density) of hydrogen atoms (also called protons) that are essential constituents of body water and fat.

The origin of the weak magnetization induced in the body tissue by the strong magnet is the nucleus of the hydrogen atom, which is a small mass of spinning positive charge. Magnetism is associated with the circulation of all charges, positive or negative. A familiar example is the flow of negatively charged electrons (an electrical current) in a wire that is accompanied by a magnetic field surrounding the wire (Diagrams 1-1, 1-2).

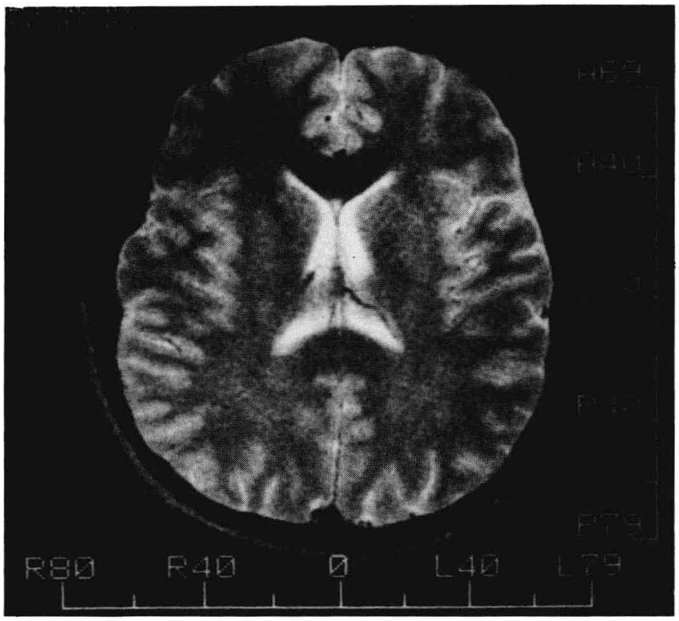



**FIG. 1-1.** A proton MRI of a human brain taken in axial section: section thickness, 5 mm, in plane resolution 1 mm × 1 mm.

**FIG. 1-2.** Section of human brain.

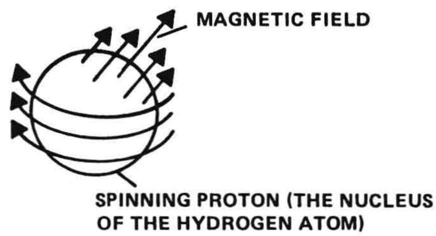



**DIAGRAM 1-1.** Spinning proton (nucleus of the hydrogen atom).

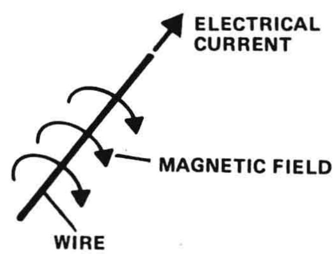



**DIAGRAM 1-2.** Flow of negatively charged electrons in a wire accompanied by a magnetic field.

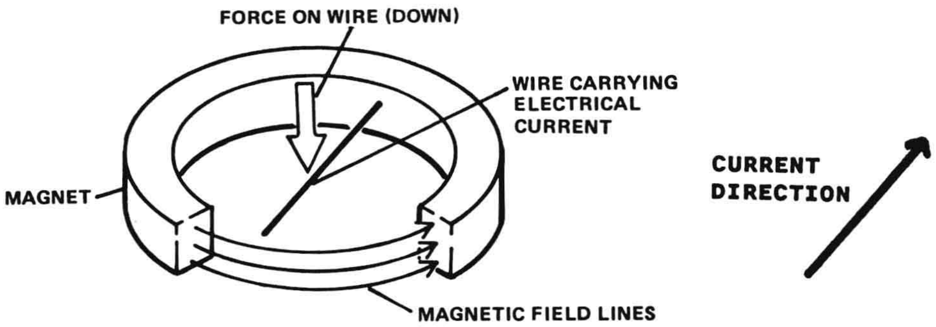



**FIG. 1-3.** A wire conducting an electrical current in the direction indicated would be pulled down into the center of the static magnetic field.

## 1.2 All Substances Interact with Strong Magnetic Fields: Very Strong Interactions Can Occur for Electrical Currents and Iron Bars

All substances become magnetized, to a greater or lesser extent, in strong magnetic fields because magnetic fields can cause charges to flow or cause moving charges to align in preferred directions. A familiar example of this force, which is the basis for electric motors and meters, is sketched in Fig. 1-3. The origin of the force is the "push" that magnetic fields exert on moving charges—for the directions of magnetic field and electrical current shown in Fig. 1-3, the magnetic field pulls the current in the same direction it is already traveling, and the wire is attracted into the center of the magnet where the field is greatest. Reversal of the current would result in a magnetic field push against the current and the wire would be repelled from the strong part of the field to reduce the effects of this push.

Another familiar example is the magnetization of a bar of iron in a strong magnetic field, as sketched in Fig. 1-4. When all the domains *that can line up are aligned*, the bar is then completely magnetized at that field strength and will stay that way unless a strong random force, such as heat or mechanical shock, forces the domains out of alignment.When taken out of the field, the bar is a permanent magnet that will attract iron filings or

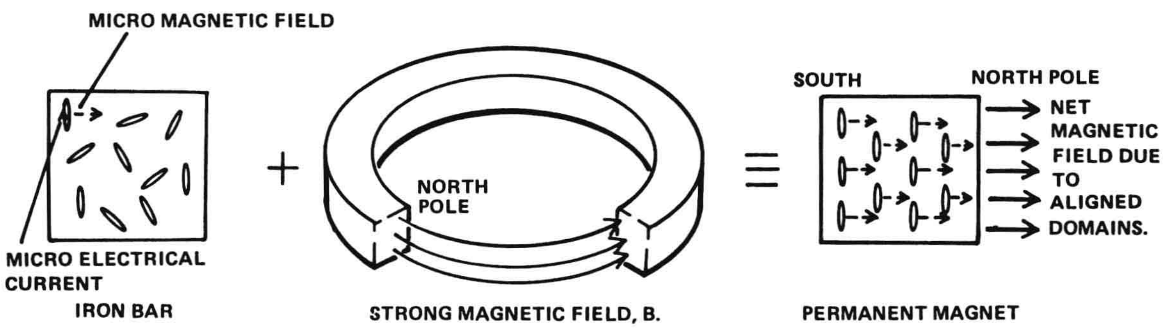



**FIG. 1-4.** This figure illustrates the alignment of magnetic domains in the iron bar. A domain is a microcrystal in the structure in which there is a net flow of electrons in a closed loop, i.e., the domain represents a microcurrent of electricity and a small magnetic field. The external magnetic field exerts a force on the flowing current, which attempts to align the domain such that its magnetic field is parallel to the external magnetic field. The domains align slowly because they are held tightly in the crystal lattice of the iron bar.

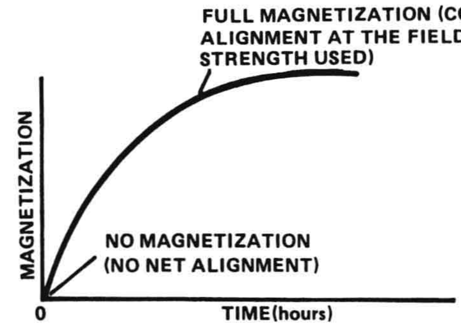



**DIAGRAM 1-3.** Exponential process required for complete magnetization. Note that *not* all domains necessarily line up, the force of the field being opposed by forces in the iron crystal lattice holding the bar together. To obtain more complete alignment, the magnetic field strength must be increased.

other bar magnets. This is an example of extremely strong magnetic interactions. The time required to achieve complete magnetization at the field strength used is very long (many hours) and follows an exponential process, as shown in Diagram 1-3.

### 1.3 The Interaction of the Spinning Proton with Magnetic Fields is Weak and the Resulting Magnetization of Tissues Containing Protons is Rapidly Established

In analogy to the forces exerted on current carrying wires and iron bars, strong magnetic fields also exert forces on the protons of tissue, forces that tend to twist the spinning charge of the nucleus so that the weak magnetic field of the spinning charge is parallel to the direction of the strong orienting field (Fig. 1-5). Without the orienting magnetic field, the protons can assume any orientation and there is no net magnetic field associated with the tissue sample. When the tissue is placed in a strong magnetic field (called $B_0$), the magnetic forces attempt to twist the spinning nuclear charges so that the proton magnetic dipoles are aligned parallel to the orienting field in a low energy state. The forces are weak, however, because the flow of charge (current) associated with the spinning proton is very small. The magnetic forces are opposed by nonmagnetic thermal forces that result in a rapid random movement of the molecules in the lattice of the tissue. These thermal forces cause some of the spinning protons to occupy a higher energy state in which the spinning nuclear charges have their magnetic dipoles antiparallel, or opposed to the $B_0$ field. The very small excess number of protons in the low energy state relative to the high energy state confers a weak net magnetization M on the tissue sample.

In contrast to the strong magnetism (magnetic forces much stronger than thermal forces) acquired by iron bars in an orienting or static field, the weak magnetization acquired by tissue containing hydrogen in fat and water molecules is acquired quickly. Depending on the tissue type, the time it requires is less than a minute. Nonetheless, an exponential process also characterizes the acquisition of magnetization, as shown in Diagram 1-4. Note that when the tissue is removed from the static magnetic field, it loses magnetization by the same exponential process and becomes de-

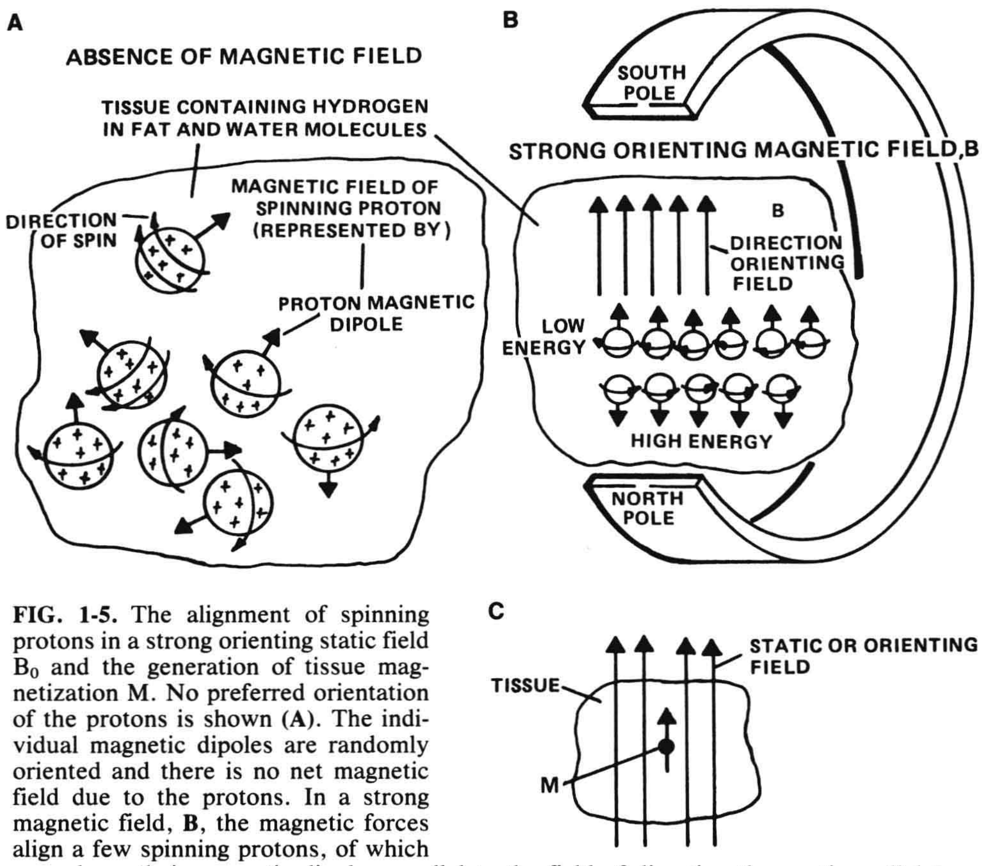



**FIG. 1-5.** The alignment of spinning protons in a strong orienting static field $B_0$ and the generation of tissue magnetization M. No preferred orientation of the protons is shown (**A**). The individual magnetic dipoles are randomly oriented and there is no net magnetic field due to the protons. In a strong magnetic field, **B**, the magnetic forces align a few spinning protons, of which more have their magnetic dipoles parallel to the field of direction than anti-parallel (opposed) to the field direction. This confers a weak net magnetization, M, on the tissue, which is depicted in **C**.

magnetized in less than a minute. In this case the thermal forces are much larger than the magnetic forces.

The strength of magnetic fields is measured in Gauss (G) or Tesla (T; 10,000 G = 1 T). As reference points, note that the strength of the average magnetic field of the earth is ~0.5 G or 0.00005 T. The field strength of an iron bar magnet that has undergone magnetization at the highest field strengths might be ~1.0 T at its north or south poles. The range of strengths of the magnets used in *most* proton MRI devices is 0.35 T to 1.5 T. The net magnetization exhibited by tissue protons outside the bore of a 1.5-T magnet is much less than the strength of the earth's magnetic field, or less than 0.001 G.

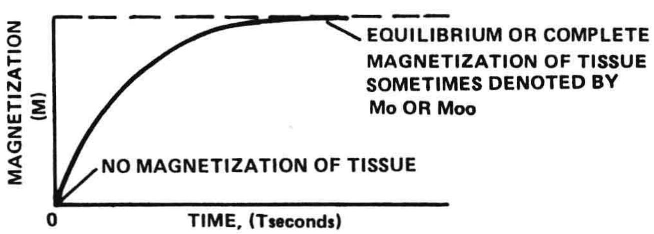
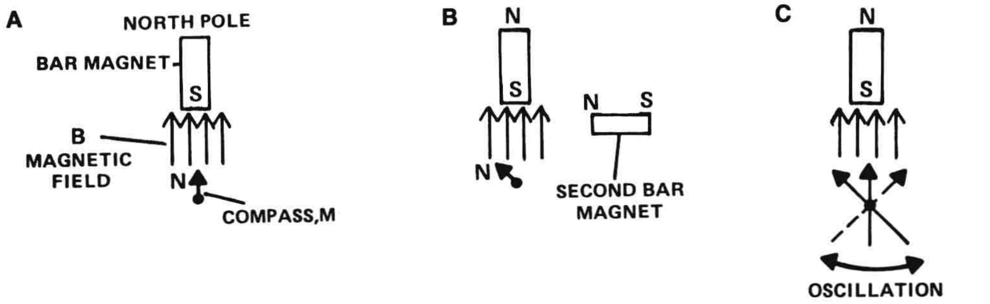



**DIAGRAM 1-4.** Exponential process in acquisition of magnetization by tissue.



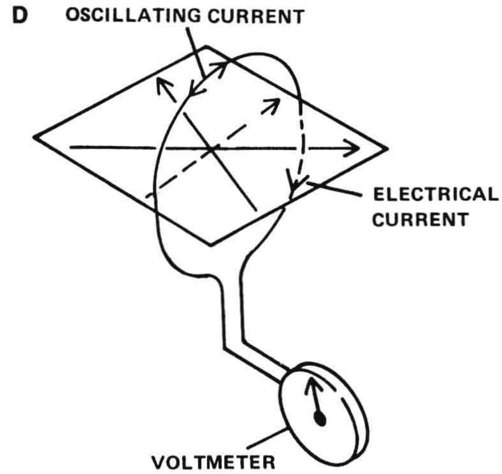




**FIG. 1-6.** A compass needle oriented in a magnetic field can be set in to oscillation by a second magnetic field. **A:** Orientation of M. **B:** Perturbation of M by a second bar magnet. **C:** Removal of second bar magnet. **D:** Detection of oscillation: an oscillating magnetic field will induce an AC current in a coil.

### 1.4 The Slight Net Magnetization of Tissue Protons in a Strong Static Magnetic Field Must be Detected with a Second Weaker Perturbing Field Which is Imposed at Right Angles to the Static Field and Which Sets the Proton Magnetization in Oscillation

The net magnetization (M) of tissue protons placed in a 1.5-T field ($B_0$) corresponds to a weak tissue magnet of strength ~0.001 G or 0.0000001 T. The detection of this weakly induced field in the presence of the much stronger static field would require measurements of nearly impossible precision, greater than 1 part in ten million ($10^{+7}$), which nonetheless have been the subject of some interesting physics experiments. Another approach to the detection of M, which is at the heart of proton MRI, is to perturb or disturb the net magnetization from its equilibrium alignment with $B_0$ and then measure the realignment of M with the static field.

A simple easy-to-test model to show how this might be accomplished is sketched in Fig. 1-6. The model consists of a compass representing the M of the proton magnetic dipoles, a strong bar magnet representing the static field $B_0$, and another bar magnet representing the second perturbing magnetic field.

In A (Fig. 1-6), the magnetization M is oriented along the field lines of a strong bar magnet. In B, a second bar magnet in the same plane as the compass and the first bar magnet is used to deflect M from its alignment, the direction of deflection arising from the repulsion of the two north poles. When the second bar magnet is suddenly removed, the compass will be