Nuclear Magnetic Resonance Imaging Basic Principles

Stuart W. Young, M. D.

Nuclear Magnetic Resonance Imaging

Basic Principles

Stuart W. Young, M.D.

Department of Diagnostic Radiology
Stanford University Medical Center
Stanford, California

Raven Press ■ New York

Raven Press, 1140 Avenue of the Americas, New York, New York 10036

Library of Congress Cataloging in Publication Data

Young, Stuart W.
Nuclear magnetic resonance imaging.

Bibliography: p.
Includes index.
1. Nuclear magnetic resonance—Diagnostic use.
2. Imaging systems in medicine. I. Title.
RC78.7.N83Y68 1984 616.07'575 83-42621
ISBN 0-89004-998-X

Made in the United States of America

Second Printing, July 1984

Preface

This book has been organized to give an overview of the clinical and biological potential of nuclear magnetic resonance (NMR) imaging, and then proceeds to discuss the fundamental principles of the interaction of NMR and electromagnetic waves to generate the NMR signal on which NMR images are based. Subsequently, the components of the NMR signal, i.e., proton density, relaxation times (T_1 and T_2), and motion or flow, are introduced together with their various interpretations and effects on image contrast.

Finally, some of the potential applications of NMR are introduced as well as the types of current imaging systems available. The book concludes with a chapter that considers the hazards of NMR imaging and site planning, as well as a reference section for those desiring to do further reading in this area.

NMR imaging in all likelihood will become increasingly more important to a broad spectrum of health professionals and investigators. This book has been compiled so that a broad spectrum of readers with general imaging or NMR background or biological and physiological medical backgrounds will be able to understand the basic principles of NMR imaging and gain enough background to progress to more in-depth NMR studies in their respective medical subspecialties. Health professionals who have been previously concerned with imaging subspecialties will benefit from becoming familiar with the physical principles of NMR, and those who have a background in NMR will further gain from the sections that are devoted to imaging and anatomic correlation. Finally, other health professionals without background in imaging or NMR should find the principles, as illustrated by analogies from common experience, helpful in understanding this complex technology.

Stuart W. Young

Acknowledgments

I am indebted to Albert Macovski, Ph.D., C. Leon Partain, Ph.D., M.D., Oleg Jardetzky, M.D., Ph.D., Ronald Castellino, M.D., Leslie M. Zatz, M.D., and Dieter Enzmann, M.D. for critical review of the manuscript. I am deeply indebted to Mike Mesenbrink; University Hospitals of Cleveland, Ralph Alfidi, M.D., Cleveland Clinic Foundation, Thomas Meaney, M.D., Mickey Weinstein, M.D. and Technicare Corporation; Felix Wehrli, Ph.D. and Morry Blumenfeld, Ph.D. The Medical College of Wisconsin and the General Electric Company; Michael Brant-Zawadski, M.D. and Leon Kaufman, Ph.D., Radiologic Imaging Laboratory, University of California, San Francisco; and Raymond Damadian and Fonar, Incorporated; for permission to utilize the NMR figures presented in this book. The author gratefully acknowledges the invaluable assistance of Charlene Levering and the Medical Graphics staff of Stanford's Office of Instructual Media for their patient work in preparing the graphic illustrations. This is the first text to be done completely by computer graphics. My thanks to Marie Graham and Lynn Roussell for manuscript preparation and word processing. And finally I am indebted to William Bradley, M.D., Ph.D. and Don Plewis, Ph.D. for general background illustrations on the physics and principles of NMR imaging.

Foreword

Nuclear magnetic resonance (NMR), long an established powerful research tool of the physicist, chemist, and molecular biologist has finally caught the imagination of the practicing clinician as a noninvasive technique for medical diagnosis that has an unprecedented wealth of information, versatility, and potential in medicine. The successful combination of NMR spectroscopy with established image reconstruction techniques, pioneered by Paul Lauterbur, and the construction of stable high resolution magnets with bores large enough to accommodate the human body during the past decade have provided the main impetus for this development. With it arose the need for an introductory text on NMR and its potential medical applications for the clinician who until now had little reason to worry about the intricacies of exotic physical techniques.

Dr. Young has written a lucid introduction to the fundamentals of NMR, relating by many imaginative analogies the physical principles of the method to similar physical phenomena more familiar from everyday life. Mastery of these concepts will be indispensable not only to the researcher, but to the clinical diagnostician as well. NMR is inherently a more complicated physical phenomenon than the scattering of X-rays. As a result, a greater variety of information can be extracted from NMR observations, but there is also a far greater danger of misinterpretation and instrumental artifact. Purely empirical correlations may prove treacherous, because of the larger number of physical variables involved. To be confident of a diagnostic finding we will need to have not just density, as in X-rays, but also the chemical shift, T1, T2, and RF pulse sequences as part of our second nature. The reader of this book will be well on the way to absorbing them into his intuitive armamentarium.

Whether we enter this new field with expertise in NMR or in clinical medicine, we must however remember that we are all still beginners. We have learned how to measure chemical shifts, T1 and T2 in living systems, and we are rapidly learning how differences in these variables affect the images and the measurements we make, but we have very little understanding of the factors that determine them in normal and diseased tissues. We understand the physics, but almost not at all the chemistry of what we see. It is the access to chemical information, both in the imaging and in the spectroscopic mode that makes NMR uniquely versatile among the existing research and diagnostic methods. Therein lies the great challenge to the experimentalist and the clinician. We should meet this challenge with vigor, but also with caution, aware that we are standing before a virtually untapped treasure of new information, but also always bearing in mind that a little knowledge can be a dangerous thing.

Oleg Jardetzky

Contents

Chapter 1

Nuclear Magnetic Resonance: The Clinical Potential

Magnetic resonance medical imaging is becoming very important in the clinical management of patients. The information density in the nuclear magnetic resonance (NMR) signal is greater than that available in an imaging modality like computed tomography (X-ray CT) because the magnetic resonance signal is based on four separate components: density of the nuclear species (usually hydrogen, which is composed of a single proton—^1H), two relaxation times (T_1 and T_2), and motion or flow. The computed tomography (X-ray CT) radiographic image, by comparison, is based mainly on one tissue characteristic: electron density. The information available in nuclear magnetic resonance (NMR) images will in all likelihood be further enriched when other nuclear species such as phosphorus and carbon can be scanned in clinical NMR scanners. The signals from nuclear species other than ^1H are low, and therefore, the likely format will be to superimpose phosphorus or carbon images or spectra on hydrogen density images either by color tinting of the hydrogen image or by superimposing a black dot distribution format similar to autoradiography. Another aspect of NMR imaging that will encourage its clinical utilization is that magnetic resonance imaging does not use ionizing radiation and thus is free of the potential hazards of X-ray interaction with tissue.

The practicing physician, whether an imaging specialist or primary-care physician, may never have encountered NMR imaging and may have previously considered NMR as merely a chemical phenomenon useful for sophisticated chemical analysis. The principles of NMR were actually first described in 1946, and NMR imaging has been used since 1973. Although clinical medical applications of these imaging techniques have only recently been reported, NMR imaging has already been shown to be clearly superior to other competitive imaging modalities (e.g., CT scanning) in certain specific situations. NMR scans are free from the artifacts produced in CT scans by sharp dense bone or metallic surgical clips (i.e., aliasing and overrange artifacts). NMR is the imaging modality of choice in diagnosing multiple sclerosis, and by selecting the proper NMR imaging techniques, in determining accurately areas of edema and hemorrhage which are difficult to separate by X-ray CT. Whether a nodular density in the lung hilum is a normal pulmonary blood vessel or an abnormal tumor mass is a difficult clinical problem with CT scanning or conventional radiography; however, in NMR imaging no signal is returned from rapidly flowing blood, and a very strong signal is returned from benign or neoplastic masses. Thus, this specific clinical problem is easily resolved using NMR. Gated NMR scans appear to be excellent for imaging the myocardium because the flowing blood in the ventricle (no NMR signal) accurately outlines the cardiac muscle. At first glance NMR scans appear very much like CT scans, but there are very definite differences, as illustrated in Figs. 1.1 through 1.8. (CT/NMR scans). A careful examination reveals that the circular high-density region is the bony skull and calvarium on the CT scan with little of the subcutaneous fat and scalp tissue in evidence. However, in the NMR scan the high-density (white) ring structure corresponds to the subcutaneous fat and the bone is seen as a relatively dark or black ring inside the outer white ring of fat. Some white and gray areas within the black ring of the skull indicate the bone marrow, which has a relatively high fat content, and therefore a larger NMR signal than surrounding bone. The comparisons and contrasts between NMR and CT imaging will be expanded in the ensuing chapters.

The tempo of change in medical imaging has been accelerating, and it is continuing to accelerate at a bewildering rate even for those whose expertise is primarily in the imaging sciences. If we borrow a bit of imagery from Carl Sagan and create an imaging calendar to relate chronologically the major breakthroughs in imaging as Sagan related the major events in the development of the cosmos on a galactic calendar, spanning the events from the last big bang to the present, we find our "imaging big bang" occurs with the discovery of the roentgen ray by Wilhelm Conrad Röntgen in 1895 (Fig. 1.9). We can see that January in this imaging calendar year was truly a big bang with fluoroscopy, X-ray tubes and X-ray films, all developed in those early stages. Everything else through September of this year was really just a variation on a theme, which required a slightly different application of previously well-understood principles. How-

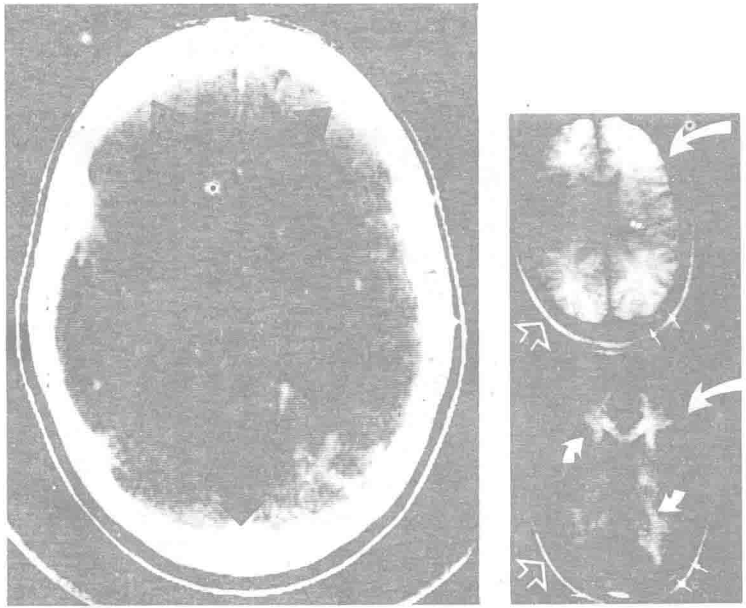

FIG. 1.1. A normal X-ray CT scan (*left*) and a normal NMR scan (*right*) using two different NMR imaging techniques, saturation-recovery (*top*) and inversion-recovery (*bottom*), obtained at the level of the lateral ventricles. Note that on the X-ray CT scan the bone of the skull is a dense white outer ring (*black arrows*) and little of the subcutaneous tissues are visualized, whereas in the NMR scan the bone is noted by its appearance as a black density around the brain (*curved arrows*) and the subcutaneous fat is seen as a dense white circumferential ring (*open white arrows*). Note also that some NMR signal is obtained from the central portion of the bony skull and this signal emanates from the fat contained in the bone marrow (*short arrows*). Also note that by changing the technique of obtaining the NMR image, different features of the tissue can be elucidated. For example, note the improvement in gray-white matter contrast resolution seen on the lower NMR image (inversion-recovery image). In this image white matter (*curved arrowheads*) appears as dense white stellate bands surrounding the lateral ventricles (3 KG, 1-cm slice thickness). (Copyright Technicare Corporation. NMR image provided by courtesy of Technicare Corporation.)

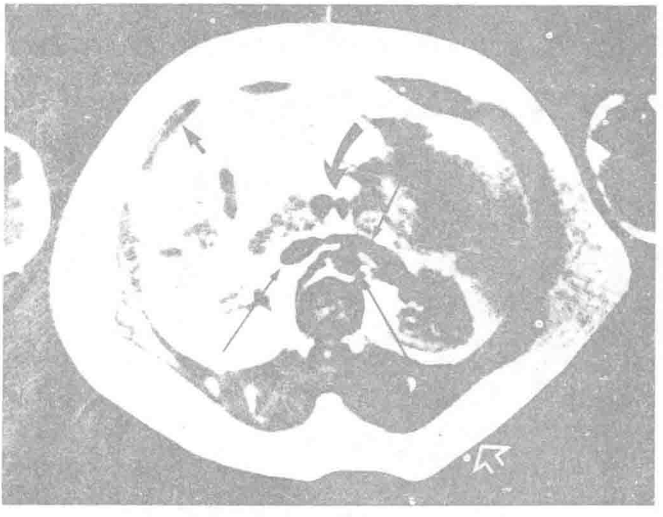

FIG. 1.2. A normal X-ray CT scan (*top*) and a normal NMR scan (*bottom*) obtained at the level of the left renal vein. As in Fig. 1.1, note the reversal in gray scale density between bone, which is white on the X-ray CT scan and black on the NMR scan (*black arrowheads*), and fat, which is black on the X-ray CT scan and white on the NMR scan (*opened white arrows*). Another interesting difference between X-ray CT and NMR scans illustrated by these body sections is the absence of NMR signal obtained from the blood vessels in the NMR scan as opposed to the soft tissue density seen on the X-ray CT scans. This absence of signal especially when juxtaposed with the high-contrast NMR signal from the fat makes the left renal vein, vena cava, and aorta (*long straight arrows*) very easy to identify as well as the superior mesenteric artery and vein (*curved arrows*). The reason for the lack of NMR signal from blood vessels is due to the absence of signal from moving structures in general (3 KG, 1-cm slice thickness). (Copyright Technicare Corporation. NMR image provided by courtesy of Technicare Corporation.)

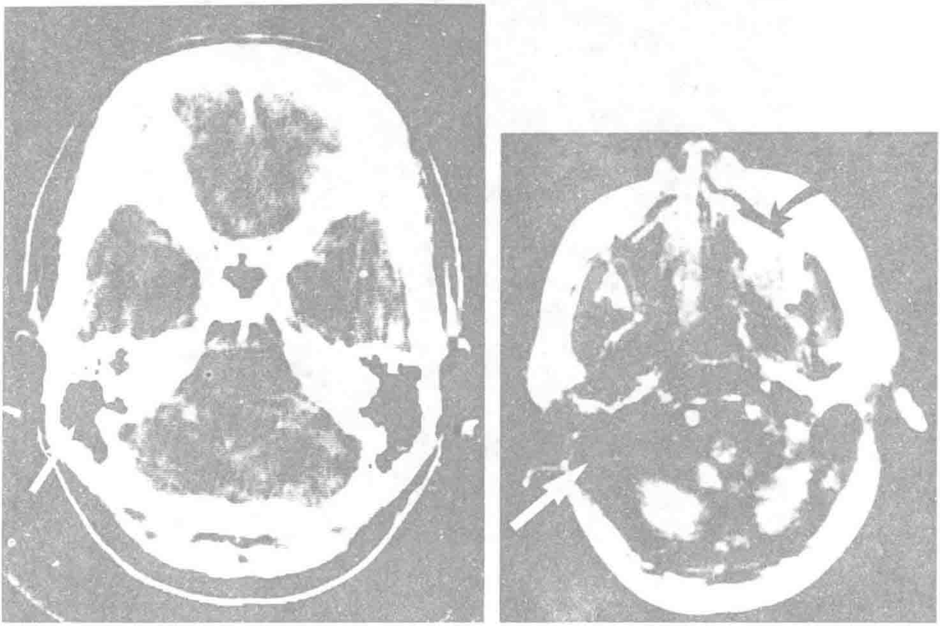

FIG. 1.3. A normal X-ray CT scan (*left*) and a normal NMR scan of the posterior fossa (*right*). Note the white streak artifacts on the CT scan, produced by the dense bone of the posterior fossa, and the absence of these artifacts on the NMR scan. No signal is obtained from the mastoid sinuses in either study (*straight arrow*), and also note opacification of the left maxillary sinus on the NMR scan due to sinusitis (*curved arrow*). (Copyright Technicare Corporation. NMR image provided by courtesy of Technicare Corporation.)

ever, in November things began to pick up with CT imaging, and an imaging "mini-bang" really exploded in December with clinical NMR imaging, digital imaging, digital subtraction angiography (DSA), laser imaging, and medical holography.

HOW TO USE THIS BOOK

For many imaging specialists who have recently become familiar with the principles, techniques, normal anatomy, and artifacts of ultrasound, CT, and digital imaging, the prospect of learning the underlying physical principles and clinical use of an entirely new technology is not considered lightly. There are always those individuals within the imaging community who take the 747 approach in the belief that you do not have to know an aileron from a gyroscope to use the

FIG. 1.4. A sagittal NMR scan of a patient with large plaques of multiple sclerosis, one of which is seen in the frontal lobe (*arrows*) as a low-density lesion on this inversion-recovery image (3 KG, 1-cm slice thickness). (NMR image provided by courtesy of Technicare Corporation and the University Hospitals of Cleveland.)

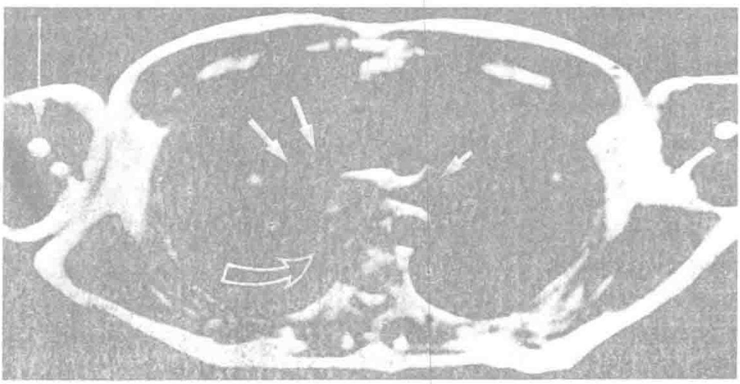

FIG. 1.5. An NMR scan at the level of the hilum demonstrating a large NMR signal from the metastatic carcinoma mass (*open arrow*) that is clearly seen as separate from the blood vessels in the same cut that are only seen because of the absence of NMR signal (*straight arrows*). Note also the bone marrow (*white*) in the humerus and cortical bone surrounding (*black ring, long arrow*) (3 KG, 1-cm slice thickness). (Copyright Technicare Corporation. NMR image provided by courtesy of Technicare Corporation and the University Hospitals of Cleveland.)

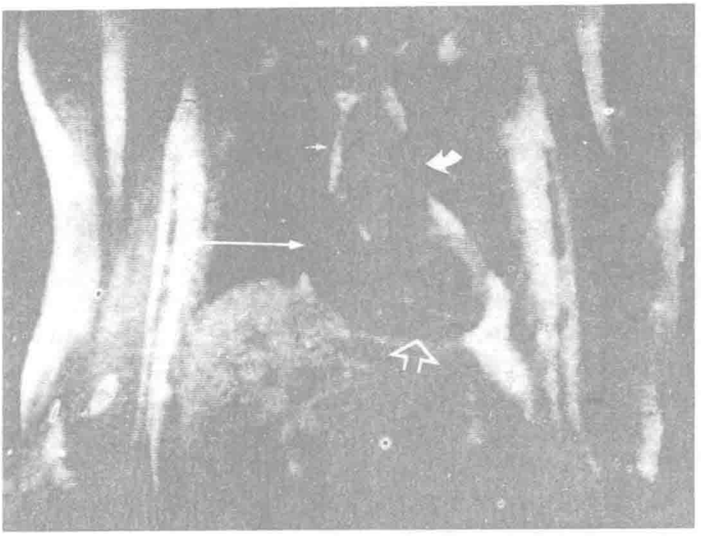

FIG. 1.6. A gated coronal NMR scan illustrating well the left ventricle (*open arrow*) as distinct from the black (lack of NMR signal) intraventricular blood and surrounding lung and fat (*white*) at the apex. Note also in this image the right atrium (*long arrow*), aorta (*short arrow*), pulmonary artery (*curved arrow*), and the proximal humerus with black cortical bone and white marrow (3 KG, 1-cm slice thickness). (Copyright Technicare Corporation. NMR image provided by courtesy of Technicare Corporation.)

747 to get from San Francisco to New York. Nevertheless, NMR will be a very important tool in medical imaging and in all likelihood will at some point exceed CT scanning as a diagnostic modality. To use these techniques, the clinician is consequently obliged to understand the basics of NMR image formation, particularly as it relates to clinical interpretation. To the clinician, magnetic resonance may seem exceptionally complex upon first encounter. However, it is the objective of this book to develop each principle and concept of NMR as if it were a fugue, using many examples from common experience. Each principle will be discussed first, by analogy with sound waves, and second, by analogy with magnetic compass needles. Finally, these analogies will be used as a foundation for the more complex explanations of NMR physics and imaging principles.

Readers of this book will undoubtedly have varying degrees of expertise and experience with magnetic resonance. Many will not need all of the fundamental analogies presented here or may wish to read the explanations in classical physics and quantum mechanics, referring to the analogies only where their understanding is somewhat

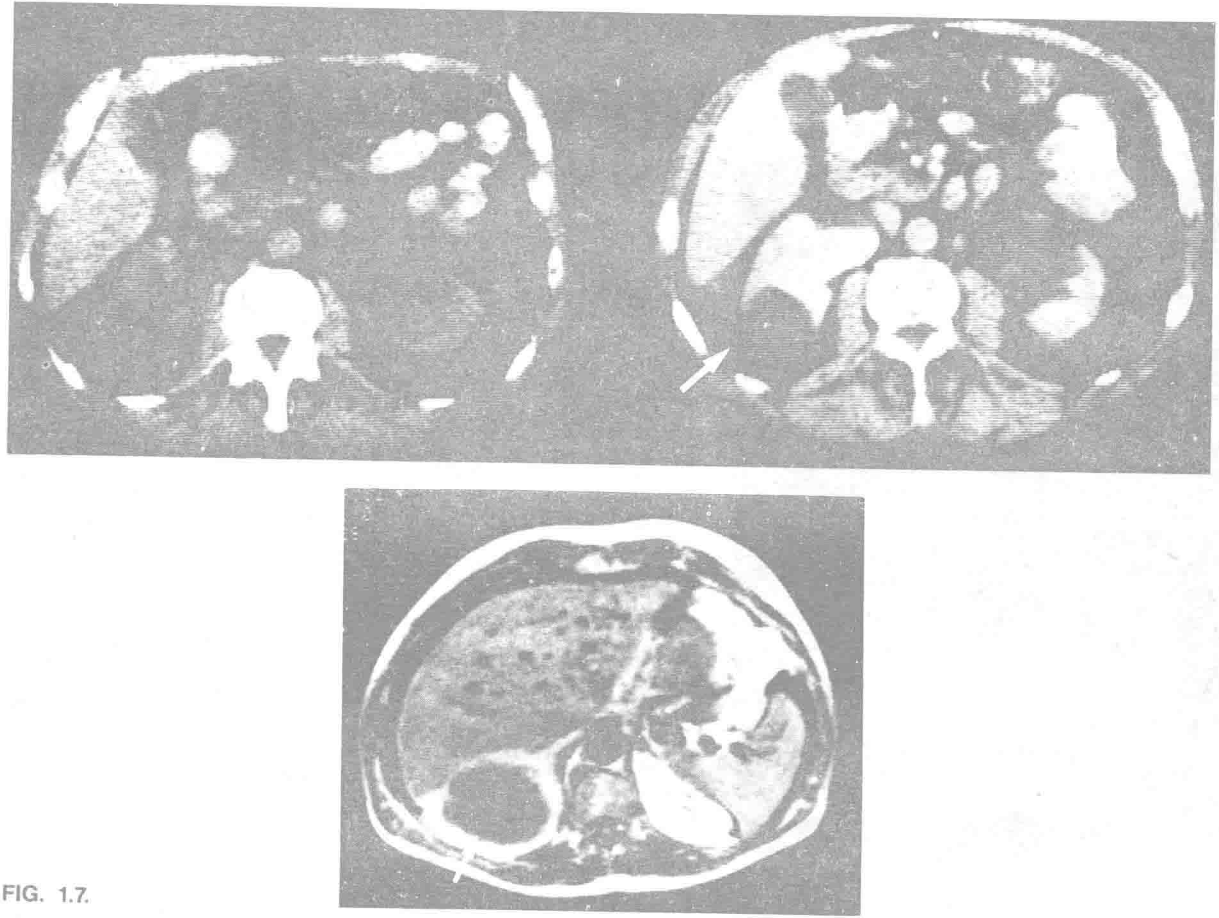

FIG. 1.7.