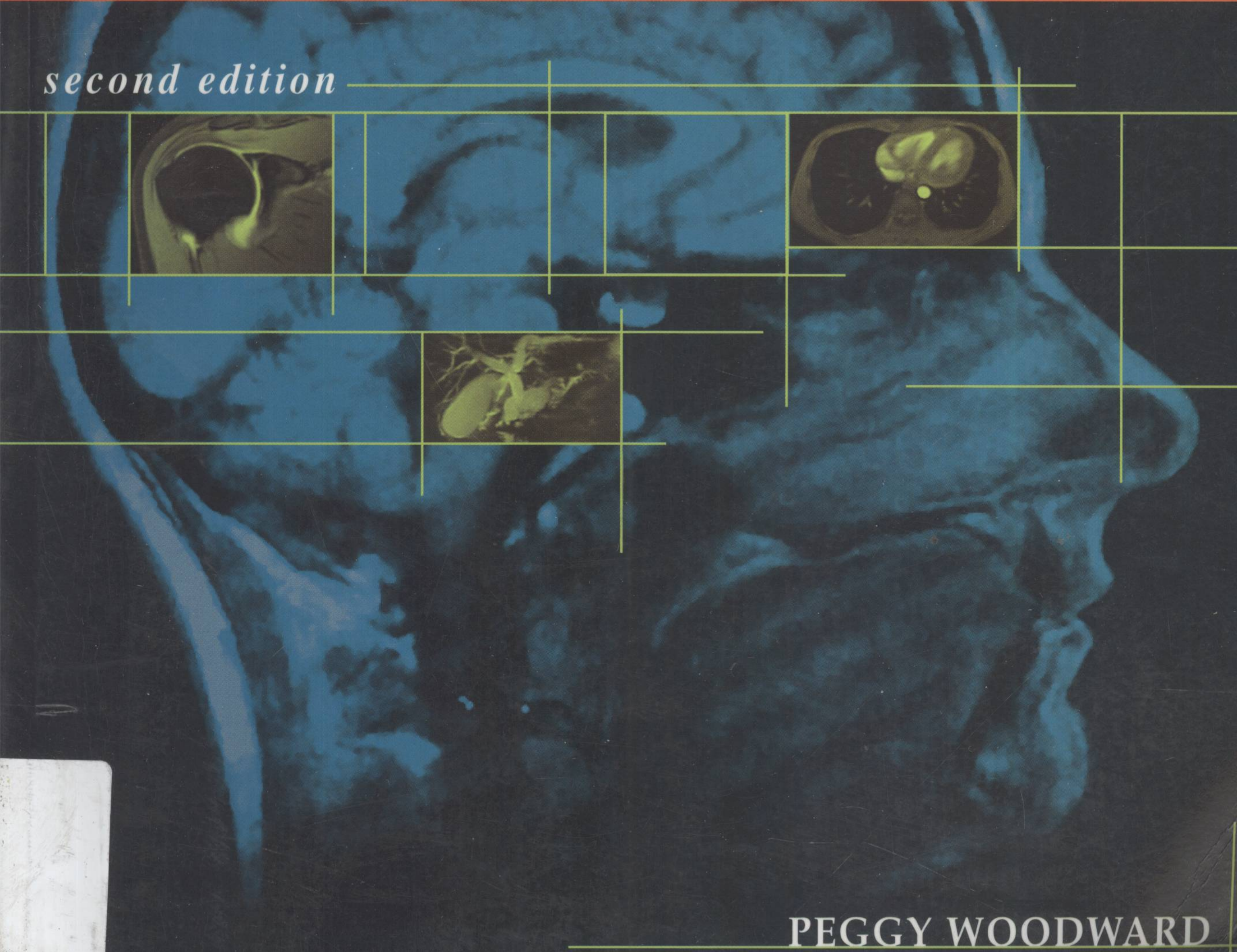
MRI *for* TECHNOLOGISTS

second edition



PEGGY WOODWARD

MRI FOR TECHNOLOGISTS

SECOND EDITION

EDITOR

Peggy Woodward, B.S., R.T.(R)(MR)

Peggy Woodward Associates, MRI Consultants, Mill Valley, California

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Contributors

Edie E. Cox, R.T.
Odessa, Florida

Luann J. Culbreth, M.Ed.
Manager, MRI Department
Baylor University Medical Center
Dallas, Texas

William Faulkner, Jr., B.S., R.T.(R)(MR)(CT)
William Faulkner & Associates
Chattanooga, Tennessee

Roger D. Freimark, R.T.(R)(MR)
Director
Northwest Imaging Forums
Eugene, Oregon

Joseph V. Fritz, Ph.D.
Senior Manager, Clinical Development
Toshiba America Medical Systems, Inc.
Tustin, California

Eric Hohenschuh, B.S.
Director, Licensing
Protarga, Inc.
Conshohocken, Pennsylvania

Yanmin Huang, Ph.D.
Engineering Scientist
Foster City, California

David M. Kramer, Ph.D.
Development Scientist
Toshiba Radiologic Imaging Laboratory
South San Francisco, California

Ralph E. Lee, M.A., R.T.(R)(MR)
Clinical Applications Specialist
Toshiba America Medical Systems, Inc.
Carlton, Texas

Bartram J. Pierce, B.S., R.T.(R)(MR)
MRI Supervisor
Corvallis, Oregon

Rodney Roemer, R.T., H.P.
River Grove, Illinois

Gary M. Schwartz, M.S.
London, England

Michael C. Sweitzer
Product Manager, Delivery Systems
Varian Medical Systems
Palo Alto, California

Alan D. Watson, Ph.D., M.B.A.
Senior Vice President,
Corporate Development
Cubist Pharmaceuticals, Inc.
Cambridge, Massachusetts

Gregory L. Wheeler, B.S., R.T.(R)(MR)
GPW Medical Imaging Consultants
Oakland, California

Preface

Since the publication of the first edition of *MRI for Technologists* in 1995, magnetic resonance imaging has enjoyed great advances in its science. Although the physics of MRI has not changed, our understanding of it has, and that insight is reflected in technological gains that are examined in both old and new chapters of the second edition.

Chapter 5, Imaging Coil Technology, has been updated to incorporate new advancements in the field. Technological progress that has been made in magnetic resonance angiography (MRA) and breast imaging is elucidated in Chapter 9, MR Angiographic Imaging, and Chapter 11, MR Imaging of the Breast. There has been a significant amount of research and subsequent development of MR contrast media since the early 1990s, and this crucial information is covered in Chapter 10, a heavily revised and comprehensive chapter. Safety issues, discussed in Chapter 16, reflect both the comfort level of the industry and the introduction of lower field strength MRI systems. Chapter 18, Evaluation of Magnetic Resonance Imaging Equipment, now includes open MR technology, which enjoys a significant portion of today's market share.

Two new chapters have been added. Chapter 8, Advanced MR Pulse Sequences, describes technologies used in today's MR field. Chapter 19, Perspectives on Future MRI Technology and Applications, gives a panoramic view of what is in store for MRI as seen by investigators and clinicians.

MRI will continue to progress at impressive speeds that will require the continued vigilance of the academics, technologists, radiologists, and clinicians involved in its growth. It is the intent of *MRI for Technologists* to provide an ongoing didactic basis from which all those associated with this field can benefit. For those who are new to MRI, the second edition will prepare you for the use of this exciting technology. For those who are seasoned advocates of MRI, the second edition will give you new perspectives. In either case, without you, this second edition would not have been conceived.

ACKNOWLEDGMENTS

Without past contributors as well as new contributors to *MRI for Technologists*, the second edition would not have been realized. Thus I would like to thank Rodney Roemer, Gary Schwartz, Edie Cox, and Jean Boyle for their contributions to the first edition. Their hard work and talent expressed in that book is gratefully acknowledged.

With appreciation for the important role of their editorial review, hearty "thanks" go to Yanmin Huang, Ph.D., and Joseph V. Fritz, Ph.D., who both contributed to the technical quality of the second edition.

And last but not least, thanks go to my husband, David Stumbos. Without his patient endurance in the scanner, many images used in this edition would not have been obtained. Thanks, David!

Peggy Woodward

Contents

CHAPTER 1

Historical Perspective on Nuclear Magnetic Resonance

Rodney Roemer

People have pondered and speculated over the basic structure of matter since the dawn of time. It was Democritus, a Greek philosopher, who in 400 B.C. was first to theorize that all matter consists of both invisible and indivisible particles, which he named atoms from the Greek root word atomos – meaning "uncut."

It was also the early Greeks who first became mystified how certain objects would be attracted or repelled by invisible forces that we now know as static electricity. They first noted and observed that a piece of amber, when rubbed by fur, would attract specific particles or objects. The word "amber" is translated as electron.

Concurrently, in the city of Magnesia in Asia Minor (Turkey), the mysteries of mass further perplexed humans when they observed that when certain rock formations were spun on their axes, they always and immediately returned to their original orientation. These magnetized structures, which are called lodestones, were used for navigational, religious, and magical purposes. The city of Magnesia is the origin of the term magnetism.

The heart of MRI mathematics that we now use to translate raw MR signals into spatial location first emerged when the brilliant Jean-Baptiste-Joseph Fourier first introduced this very complex mathematical process over 200 years ago while serving Emperor Napoleon of France [Figure 1-1].

Our early ancestors (B.C.) were the first to theorize that there was a relationship between electricity (electron flow) and magnetism (properties of the lodestone). However, its relationship remained unsolved until approximately 2000 years later. In 1819 Hans Christian Oersted accidently discovered that electricity produces magnetism when he noted that a compass needle would deflect in the presence of an electric charge.

Twelve years later, Michael Faraday [Figure 1-2] stated and successfully proved that since electricity can produce magnetism, why not

Figure 1-1. Jean-Baptiste-Joseph Fourier, born in Auxerre, France, led a very active mathematical life, which opened the doors to politics. Twice he narrowly escaped the guillotine while serving Napoleon Bonaparte during the French revolution. Among Fourier's most significant contributions to mathematics, science, and engineering are works on series, integrals, applied harmonics, sinusoidal waves, and transformation of energy. Two hundred years later we process MR images using transforms based on his original algorithm, Fourier transforms. (Courtesy of Gauthier-Villars, Dunod Editeur, Paris, France.)

the reciprocal? Why can't magnetism produce electricity? This revelation gave rise to Faraday's law of magnetic induction, which is not only the basis of MR signal detection but also is the precursor to modern-day electromechanics. Faraday discovered that magnetic fields traversed through an electrical coil at a 90-degree angle would induce a voltage/current in that coil. He further noted that in order for magnetic induction to be sustained, the magnetic field

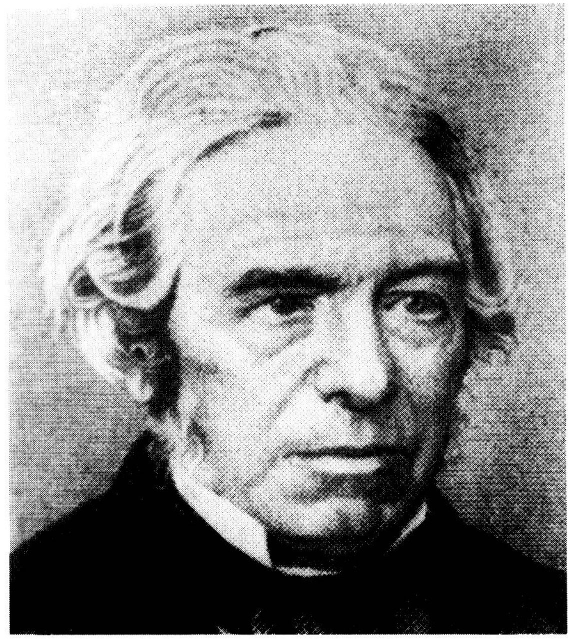

Figure 1-2. Michael Faraday, English physicist, often referred to as the Father of Electricity, postulated that if electricity produces magnetism, maybe magnetism produces electricity. He developed this idea into Faraday's Laws of Induction, one of his many contributions to physics. (Courtesy of Chicago Historical Society.)

(or current) had to be interrupted or pulsed. For this contribution, and many others, Michael Faraday is regarded by many as the father of Electricity.

Around the 1860s, Sir James Clerk Maxwell of Scotland discovered that magnetic lines of force could be mathematically expressed. Some of Maxwell's equations also proved that electrical and magnetic fields coexist at 90 degrees to each other. Also, it was noted that an induced magnetic field will spiral perpendicular to and in the opposite direction of the electron flow which produced it, and at the velocity of light – 3.0×10^6 m/s (meters per second) in a vacuum.

It was also Maxwell who calculated the velocity and propagation of electromagnetic

Figure 1-3. In November 1895 Wilhelm Roentgen, a physics professor in Würzburg, discovered mysterious penetrating rays. He called them X, after the mathematical unknown, and the name X-rays is still in use today.

waves and predicted the existence of other waves in addition to the ultraviolet and infrared regions known to his contemporaries. Eight years later, Heinrich Hertz of Germany discovered that invisible electromagnetic waves do exist and that all electromagnetic waves are identifiable by their characteristic wave frequency values. The electromagnetic spectrum, the categorical arrangement of wave energies corresponding to their properties, began to take form.

The scene was set for Wilhelm Konrad Roentgen to discover high frequency electromagnetic X-rays in 1895 [Figure 1-3] and Frédéric Joliot and Marie Curie the gamma rays (waves) in 1896. Their discoveries soon demonstrated that high frequency wave energies were identifiable, detectable, measurable, and often biologically damaging.

The opening of the twentieth century soon became synonymous with the atomic era. There are many physicists/scientists who collectively set the stage for NMR/MRI, the most significant are the following.

1905 **Albert Einstein:** Conservation law of energy ($E = mc^2$) indicates that mass and energy are one and the same.

1911 **Ernest Rutherford:** Recognized the nucleus.

1911 **J.J. Thompson:** Objective proof of electron's existence.

1913 **Niels Bohr:** Defined the electron geometric patterns and properties; opened door to quantum physics. Related the similarities of our solar system to that of the atom [Figure 1-4].

Otto Stern: Established method to measure a magnetic dipole moment.

Wolfgang Pauli: Coined the phrase nuclear magnetic resonance.

Isidor Isaac Rabi: Devised and performed the first nuclear magnetic resonance experiment.

WORLD WAR II

German/American Albert Einstein [Figure 1-5], then a relatively unknown physicist, proposed and subsequently proved that matter and energy are actually different manifestations yet are one and the same. His famous theory of relativity postulates the equivalence of mass and energy. Einstein's theory of relativity lay dormant for

Figure 1-4. Niels Bohr, Danish physicist, significantly contributed to the field of quantum physics. He received the Nobel Prize in 1922 for pioneering work in atomic physics. (Courtesy the United States Energy Research and Development Administration Technical Information Center, Oak Ridge, Tennessee, no longer in existence.)

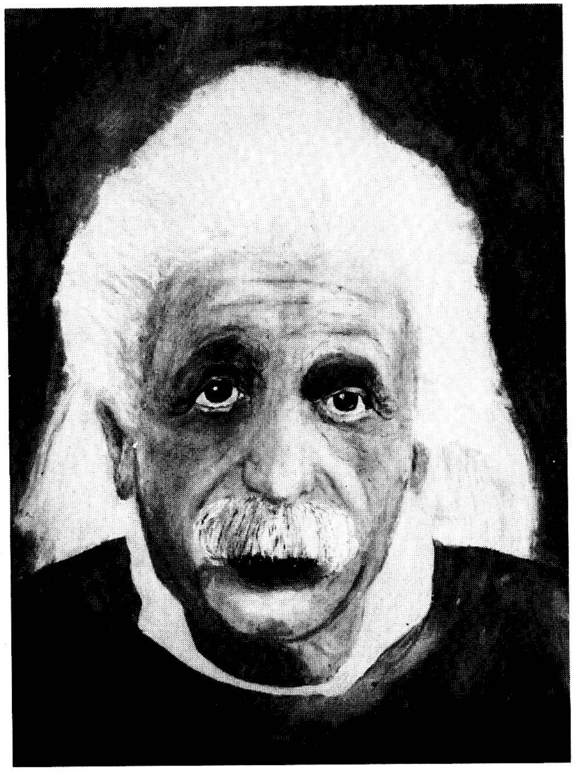

Figure 1-5. Portrait of Albert Einstein by Tom Olson. (Courtesy the artist.)

years, for there was insufficient sophistication of equipment and/or theoretical vision or knowledge to prove or disprove its authenticity. A spin-off from the conservation of energy formula, $E = mc^2$, the era of atomic energy took on an ominous dimension when Einstein wrote President Roosevelt a letter in 1939 and informed him of the awesome power of the atom. Roosevelt became a believer that a sample of uranium the size of a golf ball had an energy equivalence of several million pounds of coal, and established the Manhattan Project Committee to pursue the development of what would later be called the atomic bomb. As a result, the atomic bomb was developed and five years later it was dropped on Hiroshima, Japan, on August 6, 1945.

POST WORLD WAR II

Some of the technological advances associated with World War II laid the groundwork for utilizing sonography (submarine detection) and nuclear medicine (atomic energy) for human imaging. In 1946 two American theoretical physicists, Felix Bloch [Figure 1-6] and Edward Purcell [Figure 1-7] continued to explore the mystery of the atom. While working independently, they noted that when a test-tube

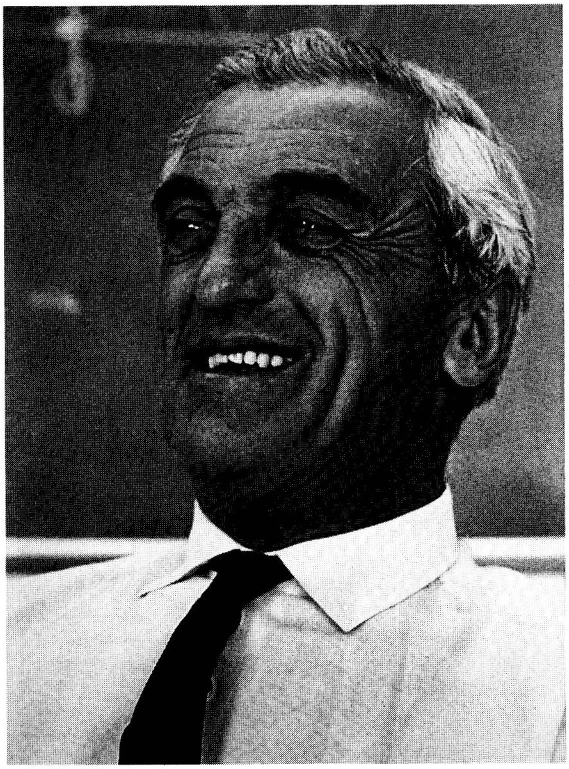

Figure 1-6. Felix Bloch shared the Nobel Prize with Edward Purcell for developing nuclear magnetic resonance (NMR) to measure the magnetic field of atomic nuclei. (Courtesy Stanford University News Service.)

Figure 1-7. Edward Purcell shared the 1952 Nobel Prize for Physics with Felix Bloch. Purcell's NMR detection method was extremely accurate and a major improvement over the atomic beam method originally devised by Isidor I. Rabi.

sample of a pure substance was magnetically energized and RF bombarded the excited atoms themselves would respond by singing their own atomic "tune." These tune signals were detected and recorded into spectroscopic images [Figure 1-8] corresponding to their frequency values. Virtually overnight nuclear magnetic resonance (NMR), the prelude to MRI, was about to be born.

Industry initially benefited from this analytical discovery, as now for the very first time, a pure substance could be analyzed into its frequency components solely from a molecular perspective. Both Bloch and Purcell were the recipients of the Nobel Prize in 1952 for their major contribution in uniquely discovering and implementing the use of atomic energy for analytical purposes.

During the next quarter of a century spectroscopy flourished; more than 1000 NMR units were manufactured and thousands of spectroscopists emerged on an international level. Researchers performed varied and sundry types of in vitro NMR analyses and experiments, but their application for human imaging was viewed as not

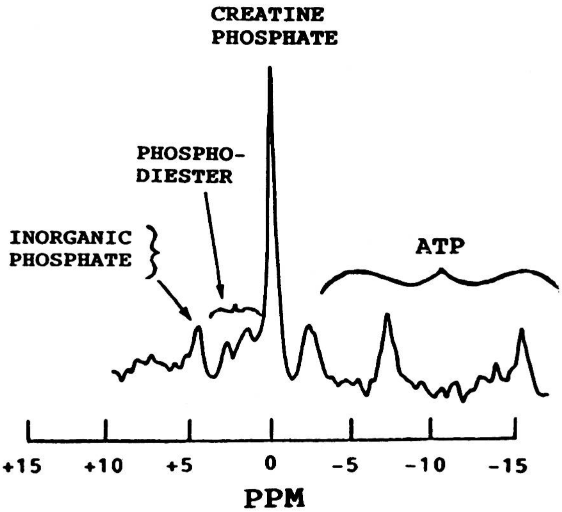

Figure 1-8. Current spectroscopic images recorded as true signals by the nuclear magnetic resonance (NMR) method discovered independently by Bloch and Purcell.

only impossible, but lunatic. This was like comparing a minnow to Moby Dick.

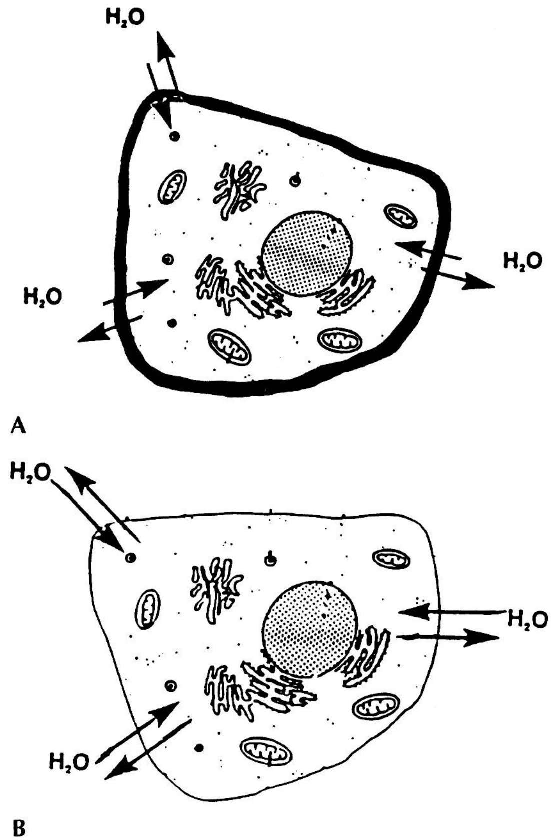

Figure 1-9. The structure of intracellular H_2O in **A** a healthy cell and **B** an unhealthy cell. The healthy cell is smaller and less pervious to the in/out flow of H_2O due to its thicker, relatively impervious membrane. The water movement is more abrupt so the relaxation rates are shorter. The resulting MR signals produce a brighter image. The unhealthy cell is larger and has a thinner membrane more pervious to H_2O. In/out H_2O flow is generally uninhibited and sluggish so the relaxation rates are longer. The resulting MR signals produce a grayer image. Although not widely accepted, the "structural" water theory continues to generate rousting conversations.

RAYMOND DAMADIAN, M.D.

The world of medical imaging was irrevocably altered when in 1970 a visionary American physician/physicist, Dr. Raymond Damadian, exclaimed to some of his close coworkers that he was going to build a scanner for whole body human imaging. Dr. Damadian suddenly was struck with the idea while performing NMR experiments on rats that he had surgically implanted with malignant cells. He readily observed that the rat tumor tissues would respond to magnetic excitation and, when bombarded by a resonant pulse, would emit two different types of signals as the torqued magnetic dipole moments relaxed to equilibrium. These signals would vary in their image contrast characteristics corresponding to whether the tissue was healthy or diseased [Figure 1-9]. It was Felix Bloch who named these two relaxation rates T1 and T2 [Figure 1-10], many years prior to Damadian's discovery.

Dr. Damadian also discovered in the early 1970s that the structure of water is the very

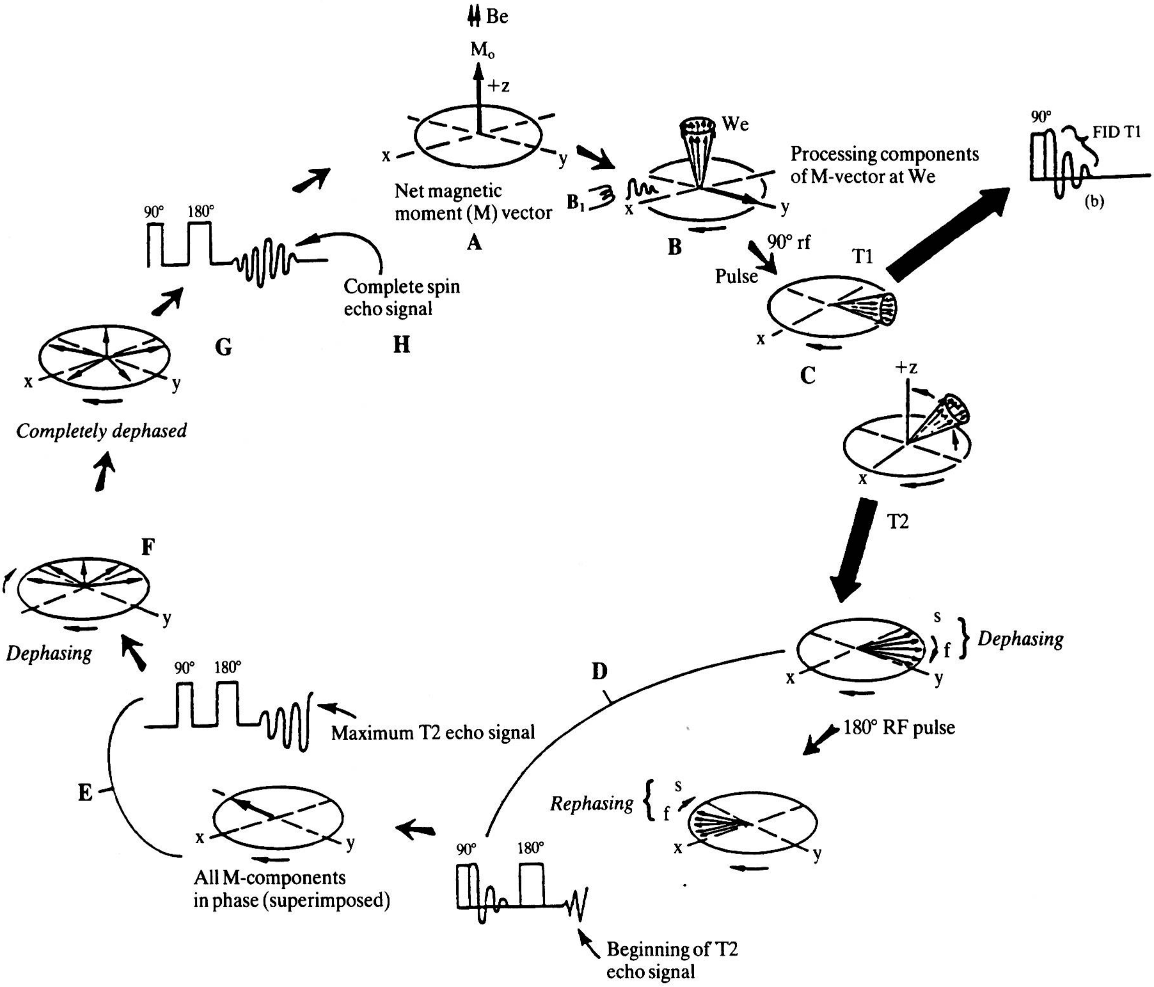

Figure 1-10. An introduction to T1 and T2 relaxation. Free induction decay (FID) is a kind of T1 decay in which the signals are produced without B_1 influence (free) and induces an MR signal in the receiver coil (induction) as a result of its characteristic relaxation decay process (decay).

essence of MRI imaging. He theorized that each water molecule contains a very intense magnetic (north/south) dipole because its hydrogens' orbiting/spinning electrons spend more time orbiting around the bonded oxygen than they spend orbiting the hydrogens [Figure 1-11]. This condition creates an intense regional source of MR signals which Damadian subsequently proved to be detectable and recordable as a characteristic image.

Damadian, like Roentgen 100 years before him, envisioned the diagnostic value of these new magnetically induced rays. He and his team spent the next seven years designing and building the very first MRI whole body scanner for whole body human imaging [Figure 1-12]. They endured

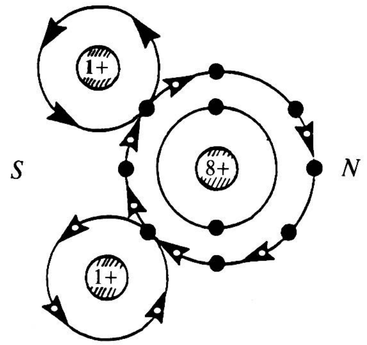

Figure 1-11. A molecule of water consists of two hydrogen atoms and one oxygen atom. Each hydrogen atom is an electron (filled circle) orbiting a proton (1+). Each oxygen atom has six valence electrons (filled circles) orbiting a nucleus of eight protons (8+) and eight neutrons (8*n*). When two hydrogens and an oxygen are covalently bonded to form a water molecule, not only does each hydrogen electron orbit its own single-proton hydrogen nucleus, it also orbits the larger oxygen nucleus. As the two orbiting electrons spend more time spinning around the larger oxygen there is less magnetic cloud around the two hydrogen atoms, thus causing $^{1}_{1}H$ it to create the most intense MR signal.

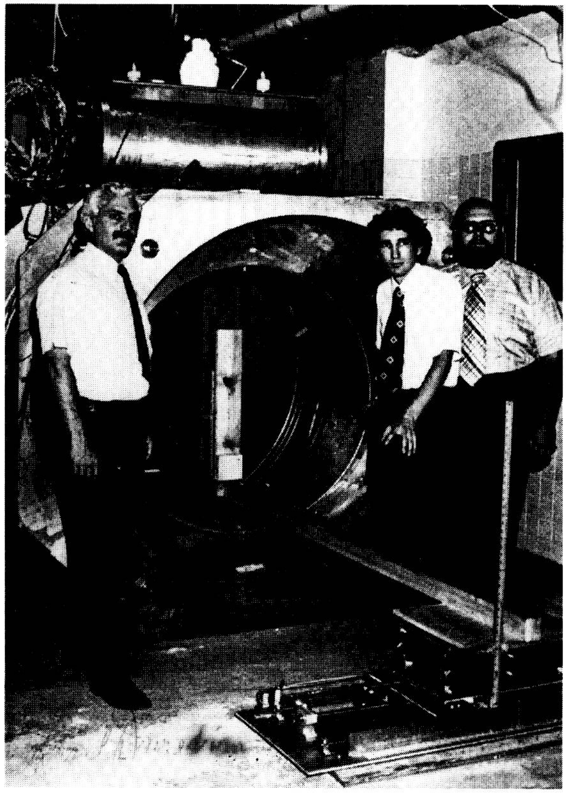

Figure 1-12. In 1977 Dr. Raymond Damadian and his associates, Dr. Larry Minkoff and Dr. Michael Goldsmith, successfully completed the construction of the world's first whole body MRI scanner. Named Indomitable to capture the spirit of its seven-year construction, it is now located at the Smithsonian Institute in Washington, D.C. (Courtesy Dr. Damadian and Fonar Corporation, Melville, New York.)

numerous setbacks and hardships: however, on July 3, 1977, they performed the first whole body transaxial proton density weighted slice image requiring 4 h 45 min [Figure 1-13]. During the scanning procedure, the patient had to be physically moved 106 times on a trambler to accomplish spatial excitation. Dr. Damadian states that only his inner religious faith and strength sustained him through those seven tumultuous years.

Dr. Damadian named his whole body scanner Indomitable, which portrays their dauntlessness, resolve, and determination in building it. The Indomitable is now located at the Smithsonian Institute of Technology in Washington, D.C.

PAUL LAUTERBUR, Ph.D.

Irrespective of his great success and fame in the field of test tube spectroscopy, Dr. Lauterbur [Figure 1-14] was not content with the fact that a substance had to be pure to obtain a spectroanalysis. He knew there must be some scientific approach utilizing the principles of NMR where selective excitation could be achieved. He agonized and deliberated over this dilemma for months.

The solution came to him one day while he sat eating at a fast-food restaurant. He theorized that by superimposing a controlled weaker magnetic gradient field onto a stronger static

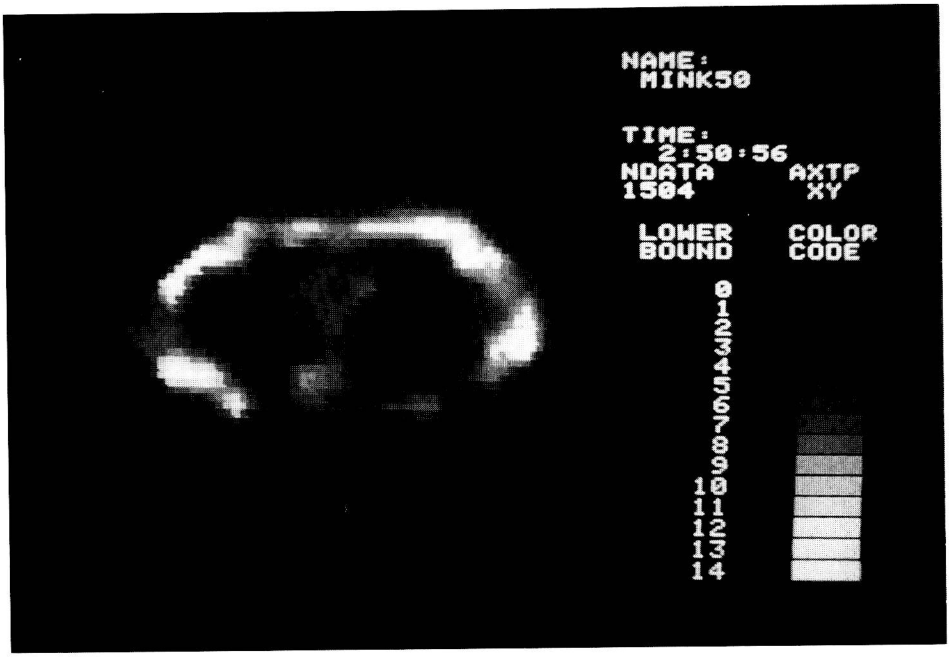

Figure 1-13. The first whole body transaxial image took 4 h 45 min to produce. Made on July 3, 1977, it shows the thoracic spine (nipple line) of Larry Minkoff, who built the Indomitable scanner with Damadian and Goldsmith. (Courtesy of Dr. Damadian and Fonar Corporation, Melville, New York.)

magnetic field going through the specimen, a magnetic tomographic region of the same frequency value could be isolated and its signals detected and transformed into an image.

Once the idea was conceived, it required many weeks of painstaking research and experimentation before Dr. Lauterbur was convinced of the following.

1. Selected NMR signals could produce a magnetic tomographic region.
2. These signals would be of sufficient magnitude for the implementation of the principles of Fourier transformation (FT) to produce a spatial image.
3. Magnets could possess sufficient magnetic homogeneity for selective image quality.

As part of the Herculean task of integrating and perfecting these three theoretical conditions, in 1973 Dr. Lauterbur astounded his peers by designing and implementing the use of G_x, G_y, and G_z gradients for selective excitation imaging of various animal and plant matter [Figure 1-15].

In 1988 President Ronald Reagan bestowed this nation's most prestigious award, the National Medal of Technology, upon Doctors Damadian and Lauterbur for their outstanding contribution to improving the well-being of the nation through the promotion of technology.

Scientists and physicists throughout the world continuously researched and expanded on the foundation and knowledge set heretofore by their predecessors. The MRI world owes considerable recognition to many. The list is long, but the most eminent certainly would include the following.

1950s **Erwin L. Hahn, Ph.D.:** currently at the University of Berkeley, for his

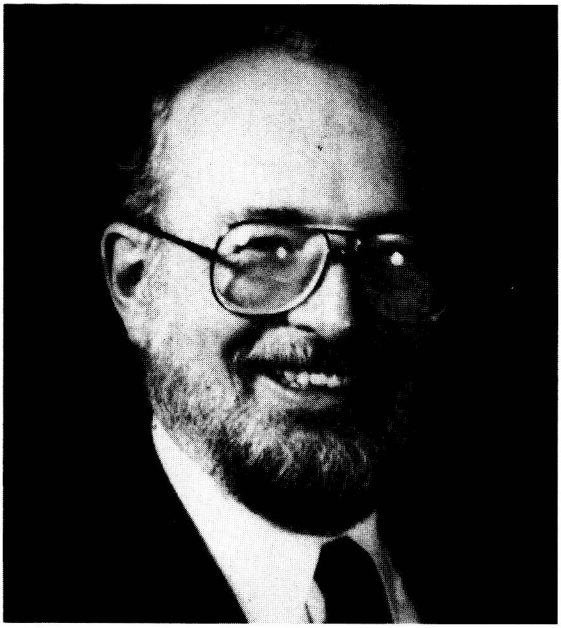

Figure 1-14. Dr. Paul Lauterbur.

discovery of the Hahn spin echo pulse sequence. At the time, his discovery (1949) was so revolutionary he could share it with no one.

1960s **Prof. Dr. R.R. Ernst:** currently at Eidgenossische Technische Hochschule, Zurich, Switzerland, for enormously increasing MRI detection sensitivity by creating the phase vs. frequency coordinates on the MR (grid) matrix and implementation of the Fourier transformation (FT) spatial imaging process. In addition, he maximized the sensitivity and balance between the flip (Ernst) angle – the essence of fast scanning imaging.

1980s **Sir Peter Mansfield:** Nottingham, England, is primarily known for his discovery of gradient echo relative to multiecho train imaging – the inevitable prelude to real-time MRI scanning. Sir Peter was knighted by Queen Elizabeth II for his considerable contribution to diagnostic MR imaging.

TODAY

Damadian and Lauterbur made believers of the previous skeptics as MRI units were being designed and manufactured at an unprecedented rate. There are close to 10,000 MR systems worldwide. Initially MRI units were only manufactured in the United States, but it did not take long for the MRI industry to expand overseas.

International MRI competition became fierce as each exporter strove to obtain the competitive edge over the others. As a result, new and confusing terms invaded the technical arena, and it was with great difficulty that the MRI operator began to immobilize the MRI language. Eventually the educational gap between industry and MRI sites widened as MRI production increased as sites were scattered throughout the United States. At best the training given to the rapidly immobilized MRI personnel, some of whom never were health career oriented, generally consisted of a 1 to 2 week crash program usually given by the manufacturer. Problems related to protocol and safety were usually answered by making a telephone call to the closest manufacturer's headquarters. Even the most adept operators had great difficulty knowing how, when, and where to override the computer during a patient's claustrophobic anxiety attack or how, when, and where to enhance image contrast for a particular lesion.

During this interim, three basic system strengths were being used: low, mid, and high; each with their own advantages and disadvantages. With the advent of FDA-approved invasive contrast media in 1988, the superconductive, high-field MRI system became the preferred method for neurological, low contrast, pathologically oriented images. Significant gains in hardware improvements at all field strengths today eliminate this preference. Newer, open architecture mid-field systems using superconductive