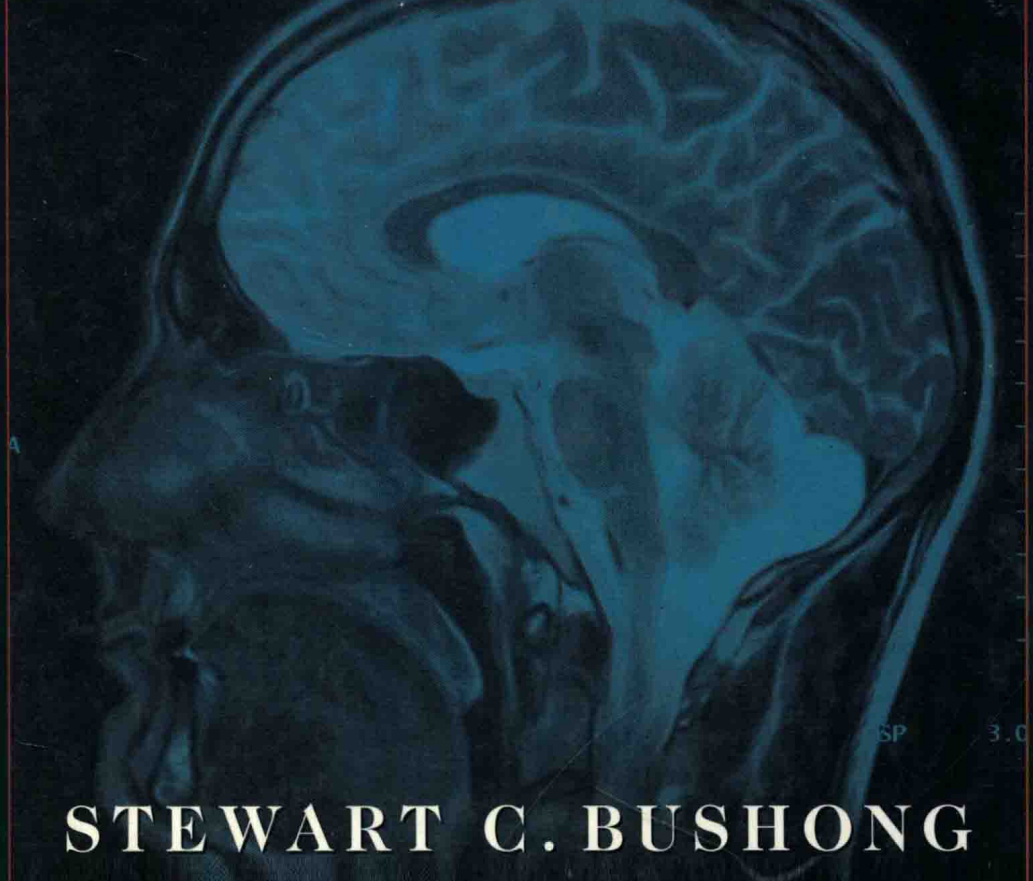
SECOND EDITION

MAGNETIC RESONANCE IMAGING

Physical and Biological Principles



STEWART C. BUSHONG

MAGNETIC RESONANCE IMAGING

Physical and Biological Principles

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SECOND EDITION
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MAGNETIC RESONANCE IMAGING

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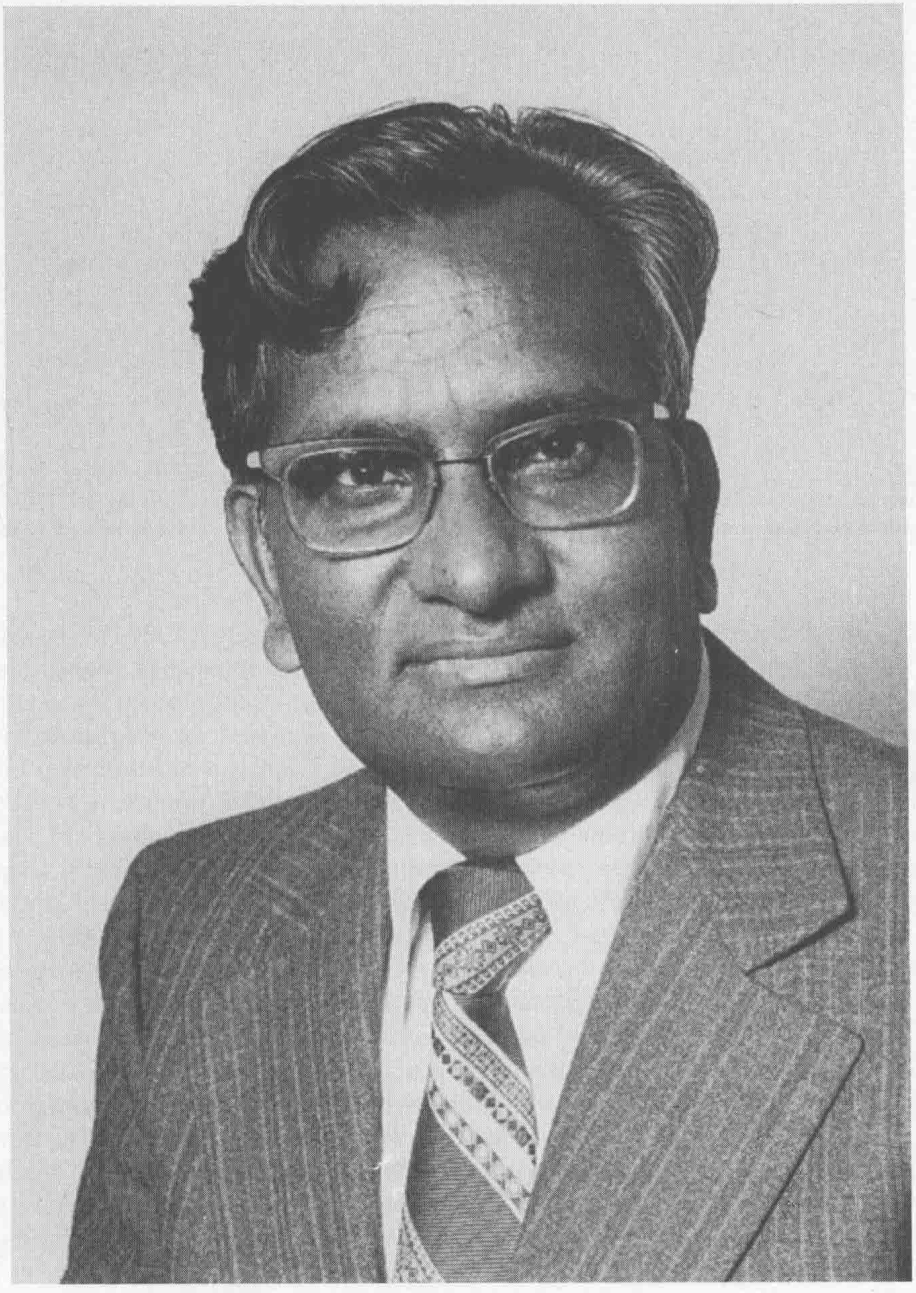
Dedicated to



Naresh Prasad, PhD
1939-1993

Preface

In the early 1980s, magnetic resonance imaging burst onto the scene as a diagnostic imaging tool with even more intensity than computed tomography in the 1970s. Its similarities to computed tomography are somewhat obvious, but the underlying physical principles are new and challenging to imaging physicians and technologists. Whereas computed tomography is an extension of x-ray imaging, whose basic physics has been well integrated into radiography training programs, the physical basis for magnetic resonance imaging (MRI) is different. Formal courses are only now being developed. The person using an MR imager or interpreting the end result must fully understand the basic principles of how this powerful modality works in order to obtain the highest quality information possible.

This second edition strives to present the fundamentals of conventional MRI and to help readers develop an understanding of the fast imaging techniques currently available. As in the first edition, concepts continue to be presented in a way that is easily understood by students, technologists, and physicians who have little or no background in math and physics. Interested readers will find a more complex mathematical development in Appendix A.

In the 7 years since the first edition of this book a wealth of advancements and changes have occurred in this fast-moving field. This accounts for the extensive revision, including 11 new chapters and hundreds of new illustrations.

The text begins with an overview and an introduction of the fundamentals of electricity and magnetism. This is followed by an in-depth explanation of how MRI works. The third part of the text discusses the latest imaging methods, as well as MRI anatomy and physiology. The final section covers personnel and patient safety and administration issues.

Reflecting state-of-the-art advances, Chapters 18 through 21 deal with timely developments in imaging strategy, which includes spin echo techniques; gradient echo techniques; magnetization prepared rapidly acquired gradient echo (MPRAGE) sequences; echo planar imaging; motion, flow, MR angiography; and echo planar imaging. At the time of the first edition, fast MR imaging was just beginning, and it was largely an unknown and misunderstood subject. This new edition fully covers the fundamentals of fast imaging, which allows for an understanding of the subject that was not possible in the past. Readers will also find descriptive chapters on Fourier transformations and MRI flow phenomena, which is information not readily available from other sources.

Now that it is possible to become certified in MRI by passing the advanced exam offered by the American Registry of Radiologic Technologists, students and technologists will find that this text presents all the essential information needed for that exam. In addition, the *Magnetic Resonance Imaging Study Guide and Exam Review* was developed to serve a dual purpose of enhancing the learning of the concepts presented in the book and acting as a study guide for those taking the certification exam. This study guide offers worksheets and mock exams that test and measure comprehension of the material.

By the way, a significant error was purposely introduced in the first edition. This error was Figure 2-5, which showed no cars on the freeway and a space shuttle resting on its launch pad as part of the downtown skyline—neither is possible in Houston! The following people were the first to report this "error," and they received a commemorative wall plaque with an outstanding illustration for their effort:

Dennis L Atwater, Warren, PA
Judy Baron, Chicago, IL
William Jan Boeve, Netherlands
Loretta Bogan, Washington, D.C.
Mark Brendt, Willoughby Hills, OH
Penny Brinkman, Centralia, IL
Ron Brociner, Lake Jackson, TX
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Kathy Webb, Rapid City, SD
Michael Williams, Tuscalosa, AL
Bob Wisniewske, Maywood, IL
Michael Wood, Boston, MA
Dennis O. Wright, Botte, MN

As anticipated, a similar "error" has been hidden in this second edition, too. The first 25 readers to report this to the author will be appropriately honored and memorialized.

This volume continues efforts to make medical imaging understandable and medical physics fun.

Stewart C. Bushong

Acknowledgements

In 1982, Baylor College of Medicine installed its first MR imager. After gaining experience with that initial system, Baylor College of Medicine offered week-long programs combining lectures and laboratory sessions for physicians, scientists, and engineers and 2-day courses for technologists. Of these courses, 80% were devoted to the physics of MRI.

The first edition of this book was an outgrowth of these courses. It represented the combined efforts of many members of the faculty in the department of radiology at Baylor College of Medicine, especially the work of the following:

R. Nick Bryan, MD, PhD, Professor of Radiology
Michele A. Gable, RT, Technical Director of MRI
John E. Madewell, MD, Vice Chairman and Professor of Radiology
Marilyn H. Sackett, RT, Technical Director of Radiology
Nicholas Schneiders, MS, Research Assistant Professor of Radiology
Susan W. Weathers, MD, Research Assistant Professor of Radiology
Richard E. Wendt, III, PhD, Research Assistant Professor of Radiology
Robert L. Wilcott, PhD, Adjunct Professor of Radiology

In preparing this second edition, I have incorporated the ideas and suggestions of many users and educators, who were kind enough to communicate with me directly. The following people were especially helpful: Barb Brown, South Bend, IN; Karen Brown, Phoenix, AZ; Luann Culbreth, Dallas, TX; William Faulkner, Chattanooga, TN; Roger Freimarch, Eugene, OR; Cathy Nathanson, Hollywood, FL; Bernadette Quinn, Fairfield, CA; Rodney Roemer, Triton College, IL; Helen Schumpert, Jackson, MS; Euclid Seeram, British Columbia; Glen Wilbert, Grand Prairie, TX.

Several of my colleagues have been especially helpful with this second edition, too. Nick Schneiders, from Lake Charles, LA provided the ideas and initial draft for the chapter on Fourier transformation. Wolfgang Nitz from Germany and Richard E. Wendt from Houston, TX provided most of the material and illustrations for Chapters 18 through 21. John Hazel from Houston, TX, expanded the information contained in chapters 11 and 12, which deal with the magnets of an MR imager.

Richard E. Wendt also authored Chapter 22: Motion, Flow, and Magnetic Resonance Angiography. I am especially grateful for his many suggestions, reviews, and contributions throughout this book.

I am also deeply indebted to Judy Matteau Faldyn for her patient help in the assembly and processing of this manuscript. Crystal Fisher and her FAX created the illustrations for this edition. Her talents and clever ideas added sense where concepts were sometimes difficult to express.

Contents

1

An Overview of Magnetic Resonance Imaging

HISTORICAL TRAIL

If someone wanted to make an image of a patient 100 years ago, what could have been done? Actually, not much of anything. At that time only photography or hand-drawn images were available. Both types of images use the narrow band of the electromagnetic spectrum called the **visible light** region (Figure 1-1). Electromagnetic radiation can be characterized by any one of three parameters: energy, frequency, and wavelength. Although people can only sense electromagnetic radiation in the visible light region, they know that the range of such radiation extends over many orders of magnitude.

How does photography work? Visible light reflects off an object, and the photons of light are captured by something that is sensitive to that kind of radiation, such as a photographic emulsion. Therefore a photograph is made with **reflected electromagnetic radiation** and a suitable receptor. Nineteenth-century physicists studying visible light detailed its wavelike properties according to how it interacted with matter (i.e., reflection, diffraction, and refraction). Consequently, visible light has always been characterized by its wavelength.

When Wilhelm Konrad Roentgen discovered x-rays in 1895, there was suddenly another equally narrow region of the electromagnetic spectrum from which medical images could be made. In 1901, Roentgen received the first Nobel Prize in Physics for his discovery. One reason Roentgen received this award was that within 6 months, he had conducted a number of cleverly designed experiments allowing him to describe x-rays pretty much as they are known today. Some of his experiments indicated that this "**x-light**" interacted as a particle, not as a wave. As a result, x-ray emissions are

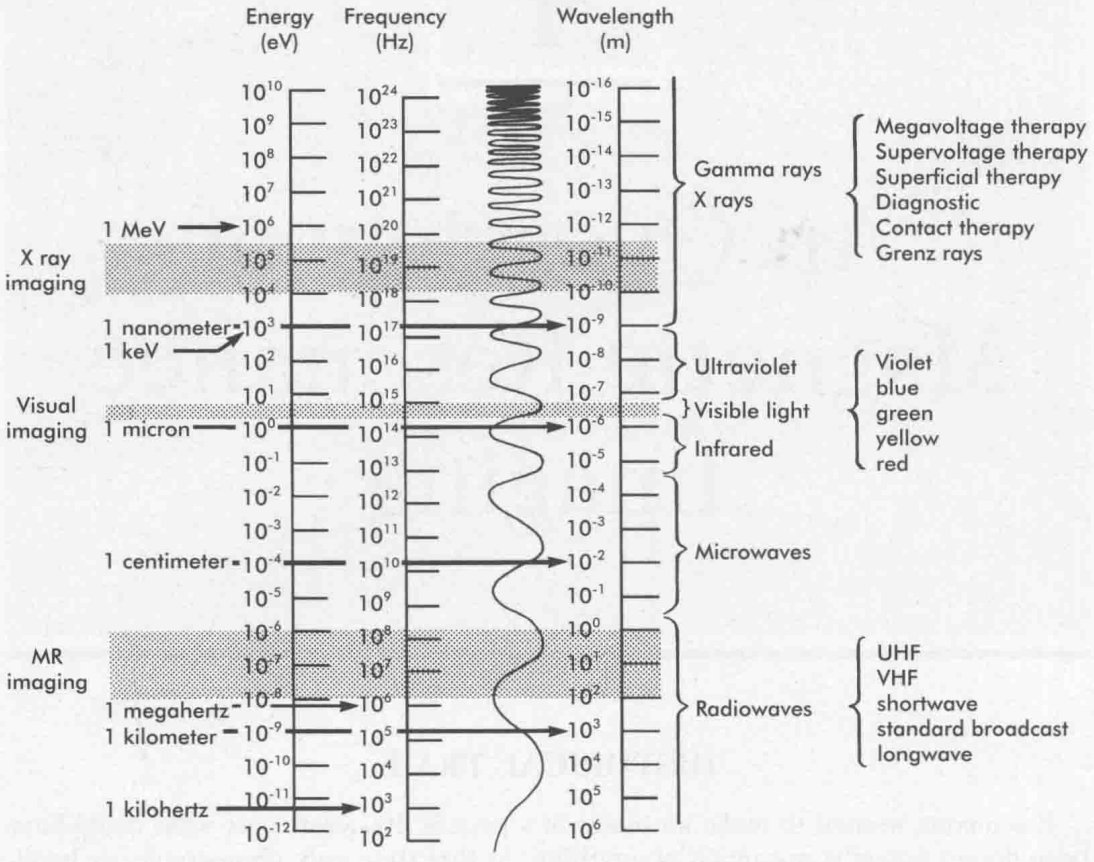

Figure 1-1 The electromagnetic spectrum showing the imaging windows of visible light, x-rays, and radiowaves.

identified according to their energy. Although people refer to kilovolt peak (kVp), it is more accurate to use kiloelectron volt (keV) to identify x-radiation.

How is an x-ray image made? A source of electromagnetic radiation (i.e., an x-ray) shines on a patient. Some of the radiation is absorbed; some of it is transmitted through the patient to an image receptor. This results in a shadowgram, like one that children make with their hands. However, the x-ray shadowgram results from the **transmission of electromagnetic radiation**, not from a reflection.

During the latter part of the nineteenth century, after Edison's early work, engineers and physicists worked to develop radio communications. Electrons need to oscillate in a conductor to create a radio emission. This requires the construction of an electronic circuit called an **oscillator**. The oscillator is the basis for radio electronics. The electromagnetic radiation produced by the oscillator is called a **radiofrequency (RF)** emission. Physicists identify this radiation according to the frequency of oscillation.

Commercial broadcast, such as AM radio, FM radio, and television (TV), are similarly identified. The AM RF band ranges from 540 to 1640 KHz, and the FM RF band ranges from 88 to 108 MHz. TV broadcast ranges from 54 to 806 MHz, which includes both VHF and UHF. Magnetic resonance images are made with RF in the range from

about 1 to 80 MHz. Each of these RF emissions can be identified by their energy or wavelength (Figure 1-1).

Contemporary medical imaging's use of the RF region of the electromagnetic spectrum to produce an image is especially spectacular. This is called **nuclear magnetic resonance (NMR), magnetic resonance imaging (MRI),** or **magnetic resonance imaging and spectroscopy (MR).** Some of the leaders in radiology were concerned about using the word *nuclear* around patients. As a result, they dropped the term early in the development of MRI.

How is an MR image made? For a visible image, radiation is reflected from the body. For an x-ray image, radiation is transmitted through the body. For an MR image, the body is stimulated so that **electromagnetic radiation** is emitted from the body. Through the use of some clever methods, the emitted signal is then detected, interpreted, and used to produce an image (Figure 1-2).

Felix Bloch

Magnetic fields associated with atoms and nuclei were described before World War II. Otto Stern and Isador Rabi each received a Nobel Prize in Physics for their work on atomic and nuclear magnetism. Rabi coined the term *nuclear magnetic resonance*.

In 1946, Felix Bloch at Stanford and Edward Purcell at Harvard independently described NMR in a solid. They shared the 1952 Nobel Prize in Physics for this work. Bloch continued extensive studies with the NMR of water, thereby laying the groundwork for later developments leading to MRI.

Bloch, therefore, is to MRI what Roentgen is to x-ray imaging. As a theoretical physicist, Bloch proposed some novel properties for the atomic nucleus. Bloch proposed that the nucleus behaves like a small magnet. He described this nuclear magnetism by what is now called **Bloch equations** (see Appendix A).

Bloch's equations explain that a nucleus, because it spins on an imaginary axis, has an associated magnetic field. This field is called a **magnetic moment.** Nucleons that have charge (e.g., protons) and that spin have even stronger magnetic fields.

Experimental verification for the Bloch equations did not come until the early 1950s. By 1960, several companies began producing analytical instruments called **NMR spectrometers.** During the 1960s and 1970s, NMR spectroscopy became widely used in academic and industrial research. Such use of NMR enabled investigators to determine the molecular configuration of a material from the analysis of its NMR spectrum.

Damadian and Lauterbur

In the late 1960s, engineer-physician Raymond Damadian worked with NMR spectroscopy. First he showed that malignant tissue has a different NMR spectrum from that of normal tissue. Furthermore, he showed that the parameters associated with NMR (i.e., spin density, spin lattice relaxation time, and spin-spin relaxation time) differ between normal and malignant tissue. Because of his unique academic background, Damadian produced a crude NMR image of a rat tumor in 1974. This image appeared on the cover of *Science* magazine. He accomplished his first body image in 1976. The image took almost 4 hours to produce.

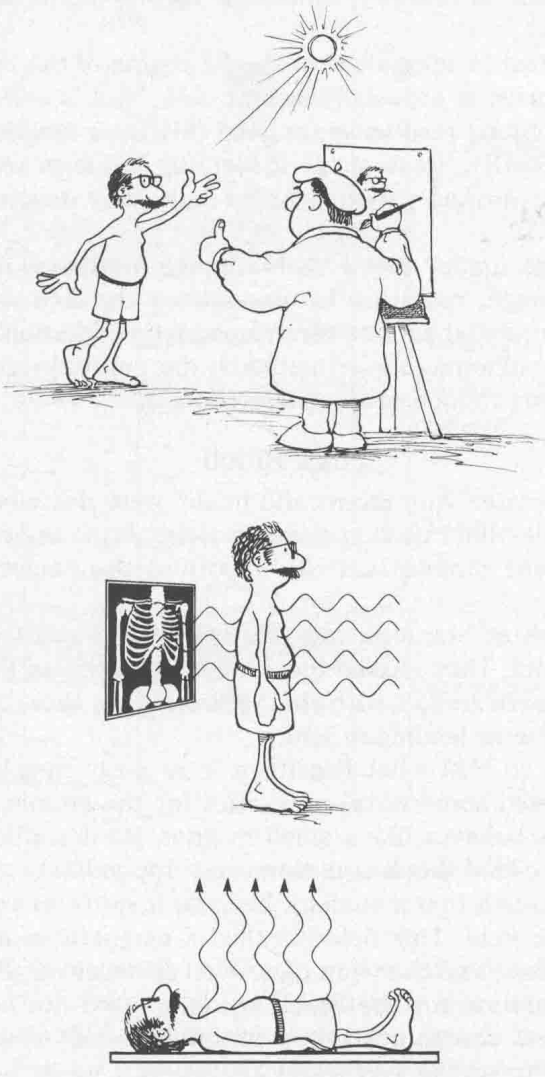

Figure 1-2 How images are made using the three regions of the electromagnetic spectrum.

At this time, Paul Lauterbur was engaged in similar research. There is considerable discussion as to whether Damadian or Lauterbur should receive recognition for developing MRI. Both will probably share this recognition in the future.

WHY DO MAGNETIC RESONANCE IMAGING?

When a plain radiograph of the abdomen is placed on a view box for interpretation, what can be seen? Not much. The image is gray and flat and shows little detail. A conventional tomogram or an angiogram may be done to enhance the image's detail. These radiographic examinations enhance the contrast of the image, improving the visualization of structures.

Contrast Resolution

If such an image is unsatisfactory, what else can be done? A computed tomography (CT) scan can be requested. The advantage of CT imaging over radiographic imaging is superior **contrast resolution**. The **spatial resolution** of CT scanning is worse than that of radiographic imaging. Likewise, the spatial resolution of MRI is worse than that of radiography. However, the contrast resolution or the resolution of low-contrast objects is even better with MRI than with CT. Contrast resolution is the *principal advantage* of MRI.

Spatial resolution refers to the ability of a process to identify small, dense objects such as metal fragments and microcalcifications. Contrast resolution allows visualization of low-density objects with similar soft tissue characteristics, such as liver-spleen or white matter–gray matter. Table 1-1 shows representative values of spatial resolution and contrast resolution for various medical imaging devices.

In x-ray imaging, spatial resolution is principally a function of the geometry of the system. Two important geometric considerations include focal spot size and source to image receptor distance (SID). In x-ray imaging, the amount of scatter radiation present limits the contrast resolution. X-ray beam collimation and the use of radiographic grids reduce scatter radiation, which improves the contrast resolution.

CT has superior contrast resolution because it uses a finely collimated x-ray beam and a small detector, unlike radiography. This results in high rejection of scattered x-rays.

In x-ray imaging, the x-ray attenuation coefficient determines the differential x-ray absorption in body tissues. In turn, the x-ray attenuation coefficient depends on the energy of the x-ray beam and the atomic number of the tissue being imaged. The basis for the MR image is different. It is a function of several intrinsic properties of the tissue being imaged. The three most important properties include **spin density (SD)**, **spin lattice relaxation time (T1)**, and **spin-spin relaxation time (T2)**. Secondary properties include motion, magnetic susceptibility, paramagnetism, and chemical shift.

In the production of a radiographic image, two principal controls cover technique selection. These controls are kVp and milliampere-second (mAs). By carefully selecting kVp and mAs, radiographers can optimize the contrast resolution of an image without compromising the spatial resolution.

Table 1-1 **Spatial and contrast resolution characteristics of several medical imaging procedure**

	Radioisotope Imaging	Ultrasound	Radiography	Computed Tomography	Magnetic Resonance Imaging
Spatial resolution (mm)	5	2	0.1	0.5	0.5
Contrast resolution (mm at 0.5% tissue difference)	20	10	10	4	1

MRI does not work that way. Many combinations exist regarding how the RF emissions **(RF pulses)** and magnetic field gradients are sequenced to maximize contrast resolution. The four principal pulse sequences include **partial saturation, inversion recovery, spin echo** and **gradient refocused echo.** Each sequence has a large selection of timing patterns for the RF pulses and magnetic field gradients. The timing of the RF pulses determines the appearance of the image. Precise RF pulse sequencing may be associated with the optimal visualization of various disease states.

Multiplanar Imaging

A second advantage to MRI is the ability to obtain direct transverse, sagittal, coronal, and oblique plane images. Conventional radiographs show superimposed anatomy regardless of the plane of the image. In CT imaging, sagittal and coronal images are reconstructed from a set of contiguous images. With MR images a large data set can be obtained. All of the data can be acquired during a single imaging sequence. With proper data processing, any anatomic plane can be reconstructed for display.

Viewing images obtained from various anatomic planes requires a different kind of knowledge on the part of physicians and technologists. During residency training, radiologists spend 4 years studying image recognition. Except for CT images, most images are parallel to the long axis of the body. The MRI interpreter may view anatomic planes that have not been imaged before. The required interpretive skills come with experience.

When students enroll in a radiologic technology program, the curriculum focuses on **technique selection** and **positioning.** Patient positioning in radiography is important to ensure that the structure being imaged is parallel and close to the image receptor. MRIs are directly available as projections in any plane, without attention to patient positioning. The operator may need to know a little trigonometry, but all planes are easily acquired because of the design of the operating console and software.

Magnetic Resonance Spectroscopy

Another advantage to MRI is the possibility of doing in vivo spectroscopy. It is possible to make an MR image, see a suspicious lesion, put the cursor on that lesion, and encompass it within a **region of interest (ROI).** Then the radiologist could retrieve the NMR spectrum from the lesion for analysis. An interpretation of the NMR spectrum would then tell whether the tissue is normal or abnormal. If the tissue appears abnormal, the NMR would reveal the molecular nature of the abnormality.

Sensitivity describes how well an imaging system can detect subtle abnormalities. **Specificity** refers to the ability to precisely identify an abnormality. MRI has excellent sensitivity. MR spectroscopy should provide increased specificity.

Increased specificity may come to pass, although development has progressed more slowly than initially anticipated. Furthermore, unless imaging physicians become organic chemists they will be unable to read NMR spectra. If in vivo NMR spectroscopy becomes a clinical reality, an organic chemist may need to be present in the reading room with the radiologist.