Totally Accessible MRI
Dedicated to the memory of my grandfathers:

Samuel Parelman
Samuel B. Lipton
Meyer Light
Herman Blitz
Siegfried Rosenthal

Stature of character and ethic,
Unqualified love and support
Justifiable pride in their enduring legacy
Stand as an example for us all.

May their memory be a blessing.
Foreword

All magnetic resonance technologists and all radiologists who work with magnetic resonance (MR) technology can be divided into two subgroups: (1) those who understand the underlying physics principles and how to apply them; and (2) those who do not.

For so many patients and for so many diagnostic considerations, the difference between membership in these two groups is minimal. One can easily diagnose a vestibular schwannoma and accurately differentiate it from a cerebellopontine angle meningioma without being that well versed with many of the concepts underlying the creation of the MR images on which these tumors are depicted. One by rote can generate images of the pelvis that are quite diagnostic and aesthetically pleasing without really understanding the intricate interrelationships between the varying imaging parameters used in the generation of the obtained image contrast.

There are certain situations, however, for which a more in-depth understanding is required. For example: Seeing tissue signal disappear on a short T1 inversion-recovery sequence yet recognizing that it does not have to originate from fat but may come from methemoglobin or some other short T1 tissue may prove clinically vital for arriving at the correct diagnosis. For such circumstances, understanding the underlying principles that govern the creation of the image and the contrast contained therein is critical and sets one apart—and distinctly ahead—of the competition, who cannot make this claim.

In the two-plus decades during which I have taught my courses on MR physics entitled, "Clinical MR Physics: Understanding and Applying," I have had the good fortune to teach literally thousands of eager students. Among the most eager and most persistent was Dr. Michael Lipton. Never satisfied with a superficial understanding, he always asked for more and continually sought a deeper level of understanding of the underlying concepts in a never-ending effort to build upon and improve upon that which we already know.
With this text, Dr. Lipton attempts to impart some of his vast knowledge to one just starting out on a journey toward understanding this fascinating technology. In a clearly written and disarmingly informal style more reminiscent of conversational tone than formal lecture, Dr. Lipton breaks down many of the concepts involved in the clinical magnetic resonance imaging process into bite-sized pieces that are easy to swallow and digest. Steering clear of most mathematics and quantum mechanics and remaining firmly grounded in classical physics and explanations, Dr. Lipton sheds light on many topics that can be so difficult to so many. By so doing, he is attempting to modify the ratio of “understanders” to “rote performers” we find in our MR society today. I hold this to be quite a commendable objective, and I applaud Dr. Lipton for his efforts. You, too, are to be commended, because reading this book is clear evidence that you have taken your first steps in trying to switch camps to the “understanders” group.

With G-d’s Help and through the assistance of Michael’s pen, may you be granted the wisdom to attain your objectives and, more importantly, apply them to the benefit of the patients entrusted to your care.

Emanuel Kanal, MD, FACP, FISMRM, AANG
Pittsburgh, Pennsylvania
Why This Book?

Nam et ipsa scientia potestas est [Knowledge itself is power].
—Sir Francis Bacon (Of Heresies, 1597)

The pages that follow are, in a very large part, an outgrowth of an intensive but accessible course in the physical basis and practical use of magnetic resonance imaging (MRI) technology that I have had the privilege and pleasure to present semiannually at Montefiore Medical Center/Albert Einstein College of Medicine since 1997. It is at the urging of numerous current and former students that I finally undertook to transform the contents of the course and its syllabus into a cohesive written work. My approach in preparing this book has been to mirror the experience of the course, to the extent that is possible given the restrictions of a one-sided conversation.

The course remains oriented toward and open to anyone who wishes to understand MRI, from the ground up, as used in clinical medicine; it is not merely a crash course to review for the radiology physics examinations. When the study of physics and technology is broached among clinical radiologists, a common refrain is “why, beyond passing our exams, do we need to know it.” The fact is that most clinical radiologists, simply because of its seemingly overwhelming complexity and their heavy clinical workloads, remain largely in the dark with regard to the physical basis of the technology they wield. However, as we will see, a large part of the diagnostic power of MRI lies in understanding the physical basis of the images you examine. Further, when, inevitably, images do not turn out as they should, a modest awareness of the “inner workings” of MRI leaves the user poised to understand and perhaps remedy the problem. I maintain that everything contained in these pages has direct importance and utility in clinical imaging. Nonetheless, as a part-time scientist, I believe the material is equally useful and important for nonclinicians. The responses of several graduate students and faculty scientists who have attended the course looking for a rigorous but very approachable introduction have borne this out.

In the interest of making the material as accessible as possible to as wide an audience as possible, I assume no specific background whatsoever on
the part of my students. (Attendees range from undergraduates to full professors but are predominately radiology residents.) Although it is certainly true that mathematics is exquisitely well-suited for expression of the concepts underlying MRI, I choose to take an entirely nonmathematical approach; only one equation need be learned and recalled in order to fully absorb the information. Where I do include equations, it is for the benefit of those who find it a useful way to consolidate their understanding of concepts.

Above all, this book is intended for users of MRI; it is not an exhaustive reference work and not a pulse sequence developer's handbook. The book is designed to be read. Most importantly, however, I implore you to take the concepts detailed in the following pages with you as you review clinical images, assess abnormalities, and confront artifacts and otherwise suboptimal images. One thing I can virtually guarantee: when it comes to MRI, it is use it or lose it. Come join the users; the alternative doesn't sound very good!

*Michael L. Lipton, MD, PhD*
A User’s Guide

The scientists of today think deeply instead of clearly. One must be sane to think clearly, but one can think deeply and be quite insane.

—Nikola Tesla (Modern Mechanics and Inventions, 1934)

We are forced to live with [scientific advances] whether we want or not and try to make the best out of it.

—Richard R. Ernst (Nobel Banquet Speech, 1991)

This book was written to be read. It is not a reference book but rather a conversation of sorts that you are invited to join. Our common goal will be a clear understanding of MRI. I begin at the beginning: the only prior knowledge required is of the most basic concepts of vectors—their addition and decomposition. A concise exposition of this essential foundation topic is provided in Appendix 1. With this small bit of background in hand, the book can be approached as a self-contained narrative, in sequence, providing a comprehensive understanding of nuclear magnetic resonance (NMR) and basic and advanced MRI techniques.

Always keep clearly in view that our goal is to understand essential principles to the extent that they facilitate our understanding and enhance our application of clinically relevant imaging techniques. In order to maintain a readable narrative format, I have deliberately avoided specific literature references for the myriad concepts and applications described in these pages. It goes without saying, however, that I come as an expositor and not an originator of these concepts. As Dr. Emanuel Kanal once remarked to me (I paraphrase): As we struggle to understand this stuff, remember that someone figured it out the first time around! Those readers interested in more in-depth, specialized, or mathematical approaches may wish to consult one of the sources listed in Appendix 4 and the original research cited in those references.

I have divided the book into three parts. Part I covers the concepts of NMR, without creating an image, just an NMR signal. This part is important because it develops all of the concepts underlying image contrast that are
central to clinical imaging. In discussing the basics of the NMR phenomenon, I have not, as is customary in introductory texts, shied away from the quantum mechanical nature of this phenomenon. My rationale is simple: using analogies of classical mechanics and electromagnetism is misleading, wrong, and ultimately proves more confusing than helpful. To keep this section open and accessible, however, I have taken a qualitative approach and not delved into the mathematics. I believe the presentation is, nonetheless, a truthful description of NMR and provides a more satisfying and complete explanation than one forced using classical physics analogies.

The concepts of excitation and relaxation and the parameters T1, T2, and T2* are essential principles developed in Part I that will be referred to over and over again in subsequent chapters. Additionally, be advised that without understanding the concepts underlying the spin echo, you cannot understand spin echo or turbo spin echo imaging or magnetic susceptibility-related contrast (Parts II and III).

Part I ends with an overview of the hardware elements of the MRI scanner system. Some overall understanding of the components is extremely useful when we delve into imaging in Part II. A thorough understanding of the concept of the gradient magnetic field, however, should be considered an absolute prerequisite to understanding imaging in Parts II and III.

A word of caution: It is quite common for students who attend my course to inquire about skipping the first day and a half when basic NMR and image reconstruction concepts (Parts I and II in this book) are covered. These individuals, busy as they are, are understandably interested in attending only those sessions that address clinical imaging applications such as pulse sequences, artifacts, magnetic resonance angiography (MRA), and diffusion imaging. I always balk at these requests, generally refusing them outright. On the rare occasion when I accede to a persistent plea, it inevitably backfires. Simply put, if you are not equipped with a basic understanding of NMR, you will certainly be lost and frustrated trying to understand, say, turbo spin echo imaging. I implore you to strongly consider reading the chapters in order.

Part II encompasses the basics of imaging. In the first portion of this part, we cover the building of an MRI image from a spatially encoded NMR signal. Be advised that this part (Chapter 6) is, hands down, the most difficult material in the entire book. Keep in mind that our goal in covering this material is not to become experts in the raw physics or the design of MRI pulse sequences but rather to understand the components of an image and a pulse sequence and how choices made when selecting these elements impact image quality, imaging time, and other outcomes. Take heart! From this point on, the material will begin to “jell” as we unify our background knowledge to begin imaging. The remainder of Part II introduces our basic pulse sequence types: spin echo and gradient echo. A clear understanding of the basics of these imaging methods forms a solid foundation for our discussion of more advanced techniques in Part III. Safety
and image quality are also included in Part II precisely because they are basics.

Whereas Parts I and II form a continuous narrative that is best studied in sequence, Part III allows, perhaps, more room for discretion and selection. Each chapter explores an advanced topic in MRI. Although each chapter builds on the material presented in Parts I and II, the chapters of Part III do not specifically depend one on the other. Bear in mind that each of the topics in Part III could be the subject of an entire textbook. I have aimed to distill the essential elements of each technique and point out its practical application. Sources for further study are listed in Appendix 4.

The language of MRI is almost a field unto itself. Abbreviations and acronyms seem to propagate endlessly. Although the abundance of jargon and catchy but cryptic abbreviations presents a challenge to the newcomer, it is simply a fact of life that is not likely to change. To bridge the language barrier somewhat, Appendix 2 contains a glossary of essential MRI terms used in the book. Although each term is defined when it is introduced in the text, this one-stop reference will prove useful when reading later chapters that do not redefine each and every term. Appendix 3 contains a rather long list of MRI symbols, abbreviations, and acronyms. I have endeavored to include those items that surface throughout the book but have also listed many that are not mentioned at all. Consider this a ready reference when an unintelligible string of letters confronts you in a journal or rolls off your physicist's tongue.

It is my fervent hope, and I dare say my expectation, that anyone who reads through as outlined above will find themselves better equipped to not merely understand but also to use MRI in their day-to-day practice. Then, recalling (or looking up) the principles discussed can truly open your eyes to important nuances of your images that went unnoticed before. Constantly holding your images to this higher level of scrutiny will enhance your understanding and, as far as physics is concerned, how you will use it, not lose it!

Michael L. Lipton, MD, PhD
Acknowledgments

I have learned much from my teachers, even more from my colleagues, but I have learned the most from my students.

—Babylonian Talmud—Taanit

The Talmudic dictum is apt in considering the major forces that drove the development of this book. It is more than 10 years of teaching radiology residents and others about MRI that has honed my approach and presentation. To all of my former and current students, I owe tremendous recognition for their interest, patience, and perseverance. Their many insightful questions and demands for clarification and substantiation have been perhaps the single most important influence on my understanding of MRI and its presentation in this book. Thankfully, they have never let me get away with anything! Although the list of individual students is too long to include here, I do wish to specifically acknowledge the first small group who was willing to sit around a conference table in the original Harold G. Jacobson Library at Montefiore Medical Center and bear with my first iterations: Ginny Bakshi, Bruce Berkowitz, and Janet Spector.

My continuous tenure at Albert Einstein College of Medicine and Montefiore Medical Center is somewhat unusual by academic standards. In no small part, it has evolved this way because of the exceptional support I have received from our chairman, Steve Amis, and the exceptional and collegial faculty and staff with whom I have had the pleasure to work. The many facets of my career that have developed over the past years benefited greatly from the support, guidance, and mentoring I have been fortunate to receive from Jacqueline A. Bello, director of neuroradiology. Without her support and sacrifice, the circumstances that led to this publication would not have transpired.

I have been fortunate to tap two wellsprings in developing an understanding of MRI. Manny Kanal was my first actual teacher of MRI physics. By welcoming me not only to Pittsburgh but into their home, he and his wonderful wife, Judy, set the stage for an ongoing correspondence that has
been an invaluable resource. I am further certain that Manny's rigorous yet accessible teaching style has influenced me as well.

My position in the Center for Advanced Brain Imaging (CABI) at the Nathan S. Kline Institute for Psychiatric Research provided me immersion in MRI as well as an ongoing interaction with MR scientists and developers. To the founding director of CABI, Joe Helpern, and its current director, my mentor Craig Branch, I express my appreciation for the opportunity to benefit from the CABI and their interest and expertise. My colleagues at the CABI—David Guilfoyle, Honza Hrabe, David Lewis, Gaby Pell, Jody Tanabe, and Bob Bilder—have been a welcome influence as well.

The manuscript was read in part by Tamar Gold and Bill Gomes and has benefited from their insightful suggestions. David Lewis and David Guilfoyle each helped me with image reconstruction techniques used to generate selected figures. I am indebted to my photographic assistants Gittel, Miriam, Shmuel, and Chava and my reliable model Tamar.

My editor at Springer, Rob Albano, as well as Sadie Forrester have been extremely gracious—and patient—in allowing this project to come to fruition. Liz Corra, developmental editor for Springer, has been an absolute pleasure to work with and has provided organizational suggestions that truly enhance the user-friendliness of the book. Liz patiently waited for and promptly processed each component of the manuscript I sent her way, no matter how stale my promise may have been. I thank my dedicated assistant, Jessica Delvalle, for her prompt attention to detail.

My dear father, Dr. Arthur Lipton, spent many hours reading the entire manuscript in detail, providing numerous suggestions that have enhanced it considerably. I further owe any writing ability I wield to my father. He, more than any professional teacher of English, taught me to express myself using the written word. It is my hope that this book is in some way a testament to his efforts.

To my parents, Arthur and Judith Lipton, I, of course, owe everything. A special belated note of appreciation is due for their unending and unconditional support. In the same vein, my parents-in-law, Gary and Rose Ann Rosenthal, have been a cornerstone of support since I merited to join their family almost 19 years ago.

Gittel, Miriam, Tamar. Shmuel, Chava, Aaron, and Rafael graciously indulged the time their father devoted to the writing of this volume. Although this endeavor only added to many other time-intensive professional commitments, they nonetheless allowed me the quiet to finish the job, interrupting only to express encouragement and offer suggestions.

To my precious wife, Leah, I owe more than everything. These pages would be empty were it not for her support, encouragement, and perseverance.

Michael L. Lipton, MD, PhD
Contents

Foreword by Emanuel Kanal ........................................ vii
Why This Book? ......................................................... ix
A User’s Guide ......................................................... xi
Acknowledgments ..................................................... xv

Part I  In the Beginning: Generating, Detecting, and Manipulating the MR (NMR) Signal

1  Laying the Foundation: Nuclear Magnetism, Spin, and the NMR Phenomenon ........................................ 3
   The Overall Aim ...................................................... 3
   Where Does the MRI Signal Come From? ....................... 4
   Interaction of Protons with a Static Magnetic Field (B) ........ 10
   The Energy Configuration Approach: A Painless (Really!) Bit of Quantum Mechanics ................................. 12
   One More Thing . . . What Exactly Is the MRI Signal That We Measure? ........................................ 18

2  Rocking the Boat: Resonance, Excitation, and Relaxation ................................................................. 19
   Introduction: How Can We Find a Signal to Measure? .... 19
   Generating Net Transverse Magnetization ......................... 20

3  Relaxation: What Happens Next? .................................. 27
   What Happens When the Radiofrequency Is Shut Off? .... 27
   Separate, but Equal (Sort of): Two Components of Relaxation ................................................................. 27
   The Spin Echo .......................................................... 32

4  Image Contrast: T1, T2, T2*, and Proton Density .............. 38
   T2/T2* Contrast ..................................................... 38
   T1 Contrast ............................................................ 40
   Proton Density Contrast ............................................. 44
   Putting Things Together to Control Image Contrast .......... 45

xvii
5 Hardware, Especially Gradient Magnetic Fields ........................................... 47
  Why This Chapter? ....................................................................................... 47
  The $B_0$ Magnetic Field .............................................................................. 47
  Radiofrequency Transmission ...................................................................... 55
  The Gradient Magnetic Field ........................................................................ 55
  The RF Coils .................................................................................................. 60
  The Receiver (A2D) ....................................................................................... 65
  The Computer ................................................................................................ 66
  Shielding ........................................................................................................ 68
  The Prescan Process ...................................................................................... 71

Part II User Friendly: Localizing and Optimizing the MRI Signal for Imaging

6 Spatial Localization: Creating an Image ..................................................... 75
  What Is an Image? ......................................................................................... 75
  Understanding and Exploiting $B_0$ Homogeneity ......................................... 77
  Slice Selection Using the Gradient Magnetic Field ........................................ 78
  Localizing Signal Within the Plane of the Slice: Background for Frequency
  and Phase Encoding ....................................................................................... 82
  Frequency Encoding: The Next Stage .......................................................... 84
  Phase Encoding and the Two-dimensional Fourier Transform ...................... 90
  Some Comments Regarding k-Space ............................................................. 97

7 Defining Image Size and Spatial Resolution .............................................. 101
  How Much Area Will Be Included in the Image? .......................................... 101
  Specifying the Field of View ....................................................................... 102
  Aliasing and Its Fixes ................................................................................... 103
  Refining the Field of View .......................................................................... 107
  A Footnote Regarding Receiver Bandwidth .................................................. 109

8 Putting It All Together: An Introduction to Pulse Sequences ..................... 110
  Putting It All Together .................................................................................. 110
  What Exactly Is a Pulse Sequence? ............................................................. 110
  The Pulse Sequence Diagram ..................................................................... 111
  Building the Pulse Sequence ....................................................................... 113
  The Spin Echo Pulse Sequence: A First Example ....................................... 113
  What Happens After TE: Multiple Echoes and Multiple Slices ................. 116
  The Gradient Echo Pulse Sequence ............................................................ 119
  Contrast Modification in SE and GRE Imaging ........................................... 127
9 Understanding, Assessing, and Maximizing Image Quality
   What Is the Measure of a Good Image? ........................................... 128
   What Is Noise? .................................................................................. 129
   Signal-to-Noise Ratio: Measuring Image Quality ................................ 129
   What Affects Signal to Noise? .......................................................... 131
   Contrast-to-Noise Ratio: Measuring Diagnostic Utility ..................... 134
   Quality Assurance .............................................................................. 135

10 Artifacts: When Things Go Wrong, It's Not Necessarily All Bad
   Things Do Go Wrong ... but It's Not All Bad News .............................. 139
   Motion ............................................................................................... 139
   Undersampling (Wraparound Artifact) .............................................. 141
   Susceptibility Effects: Signal Loss and Geometric Distortion .......... 144
   Truncation (Gibbs Artifact) .............................................................. 146
   Radiofrequency Leak (Zipper Artifact) .............................................. 149
   k-Space Corruption: (Corduroy, Herringbone, and Spike Artifacts) . 150
   Chemical Shift Artifact ..................................................................... 151
   Slice Profile Interactions (Cross-Talk Artifact) ................................. 153

11 Safety: First, Do No Harm ............................................................... 154
   Who Cares? ....................................................................................... 154
   The Safety of MRI Versus Iatrogenic Injury ....................................... 154
   Types of MRI Risk ............................................................................. 155
   Keeping It Safe: S4 ........................................................................... 159

Part III To the Limit: Advanced MRI Applications

12 Preparatory Modules: Saturation Techniques ................................. 165
   Inversion-Recovery Imaging ............................................................. 165
   Spectral Saturation Techniques ....................................................... 169
   Hybrid Techniques ........................................................................... 170
   Selective Excitation .......................................................................... 170
   Spatial Saturation ............................................................................. 171
   Magnetization Transfer Contrast ..................................................... 172

13 Readout Modules: Fast Imaging ....................................................... 174
   Gradient Echo Approaches ............................................................... 174
   Steady-State Free Precession ............................................................ 177
   Manipulating k-Space ........................................................................ 177
   Hyperspace: Echoplanar Imaging ...................................................... 182
   Further Exploits in k-Space .............................................................. 185
14 Volumetric Imaging: The Three-dimensional Fourier Transform ........................................... 187
  Multislice Versus Volumetric Imaging:
    Three-dimensional Versus Two-dimensional .............. 187
  Two-dimensional Imaging: How Do We Do It? ............. 187
  Three-dimensional Imaging: How Do We Do It? .......... 188

15 Parallel Imaging: Acceleration with SENSE and SMASH ............................................. 194
  Why Another Imaging Technique? .......................... 194
  So What’s New? ............................................. 194
  Basics of Parallel Techniques ............................... 195
  Sensitivity Encoding: SENSE .................................. 197
  Simultaneous Acquisition of Spatial Harmonics:
    SMASH ..................................................... 198
  What Do We Actually Gain and at What Cost? .......... 198

16 Flow and Angiography: Artifacts and Imaging of Coherent Motion .................................. 200
  What Is Magnetic Resonance Angiography Anyway? .... 200
  Basic Principles of Flow for Students of MRI ........... 201
  Impact of Flow on the MR Signal ......................... 203
  Time-of-Flight MRA .......................................... 212
  Something Different: Contrast-Enhanced MRA .......... 221
  Don’t Forget This Pitfall! ..................................... 225
  Phase-Contrast MRA .......................................... 226
  Where Do We Go from Here? ................................. 232

17 Diffusion: Detection of Microscopic Motion ................. 233
  Introduction .................................................. 233
  What Is Diffusion? ........................................... 233
  Effect of Diffusion on the MR Signal ...................... 234
  Making the MR Image Sensitive to Diffusion ............ 234
  What Do Diffusion-Sensitized Images Look Like? ....... 236
  Quantitative Diffusion Imaging: The ADC ............... 238
  Directional Information: DTI ................................. 239

18 Understanding and Exploiting Magnetic Susceptibility .............................................. 245
  Proton-Electron Dipole Interactions: The Other Face of Paramagnetism ......................... 248
  Susceptibility-Related Effects I: Artifacts ............. 248
  Susceptibility-Related Effects II: Hemorrhage ........ 249
  Susceptibility-Related Effects III: Contrast Agents .... 254
Susceptibility-Related Effects IV: Perfusion Imaging ......... 255
Susceptibility-Related Effects V: Functional MRI ............ 259

19 Spectroscopy and Spectroscopic Imaging: In Vivo
   Chemical Assays by Exploiting the Chemical Shift .......... 263
Introduction .................................................. 263
The Chemical Basis of MRS ................................. 263
What Then Is Spectroscopy (MRS) and How Is It
   Different from MRI? ....................................... 264
Abundance, Resolution, and Detection ........................ 265
The Importance of Field Homogeneity ......................... 266
Localization: Single-Voxel Methods .......................... 267
Localization: Chemical Shift Imaging ......................... 270
Brain Chemistry: Brief Overview of
   the Proton Spectrum ..................................... 272

Appendices
Appendix 1 Understanding and Manipulating Vectors ......... 277
Appendix 2 Glossary of Terms ................................. 279
Appendix 3 Glossary of Common MRI Acronyms,
   Abbreviations, and Notations ............................. 291
Appendix 4 Resources for Reference and Further Study ....... 297

Index ............................................................ 299
Part I
In the Beginning: Generating, Detecting, and Manipulating the MR (NMR) Signal
Laying the Foundation: Nuclear Magnetism, Spin, and the NMR Phenomenon

The Overall Aim

If we bring together a group of people involved in magnetic resonance imaging (MRI) and present them with a magnetic resonance (MR) image, each will see something different in that image. Radiologists will hone in on subtle pathology, psychiatry researchers will notice minute asymmetries in cortical sulci, technologists may pick up on poor positioning, and physicists will evaluate signal-to-noise and detect artifacts. What are we all trying to achieve at the end of the day? Regardless of the type of image acquired or the purpose for which it was acquired, our single common goal in MRI is this:

Differentiate the tissue in two adjacent locations based on the way that tissue behaves in the MRI environment.

If the signal extracted from those two locations is identical, we cannot differentiate the two tissues from each other. This could be because each location does in fact contain the same tissue (e.g., two locations within the cortex of the kidney) or because the MR image was not made sensitive to the difference between the two tissues. In this latter case, a tumor could be virtually indistinguishable from the normal tissue within which it is growing.

To accomplish our goal of differentiating adjacent tissues of different composition, two tasks must be accomplished in properly designing the MRI examination: (1) resolving the tissues to unique locations in the image and (2) detecting different signal amplitude (intensity) from the two tissues.

Spatial Resolution

The image must be physically capable of resolving the two locations of interest in the tissue to distinct locations within the image; that is, the image
must have sufficient spatial resolution. An MR image represents a slice of tissue with a defined thickness. This slice is then divided into a two-dimensional array of prism-shaped pieces that we call voxels (for "volume elements"). If we are trying, for example, to differentiate a 5-mm nodule in the liver of a cancer patient from the surrounding normal liver tissue, the voxel must be close to or, preferably, smaller than 5 mm. This is because each voxel is sampled as a single MRI signal that is an average of signal arising from all of the tissue within the voxel. In our example liver nodule, if the voxel is so large, say 10 mm, that it contains more normal tissue than abnormal, the average signal we sample will be dominated by normal tissue. Because this signal is no different than that arising from adjacent voxels containing normal liver, the nodule may go undetected.

Contrast Resolution

The MRI acquisition must also elicit a different signal from each of the tissues we wish to separate. That is, the image must have sufficient contrast resolution. Even if the image has exceptional spatial resolution (i.e., very small voxels much smaller than the lesion of interest), if both the nodule and normal liver yield the same signal, we will be unable to differentiate the nodule from normal liver tissue. In an effort to maximize the difference in signal between tissues, we modulate the measured signal by adjusting the parameters of the MR acquisition.

As we progress in our understanding of MRI, do not lose sight of the fact that all we are ever trying to do is to differentiate two adjacent tissues based on their different MR signal. The same is true for any and all MRI images whether spin echo, diffusion weighted, or even functional MRI.

Where Does the MRI Signal Come From?

Before we venture into the realm of imaging, we must first understand how the MR signal is generated and measured. To keep things manageable, the following disclaimer should be kept in mind: Until further notice, we will limit our discussion to the measurement of signal from a homogeneous sample (maybe a bowl of Jell-O?). No attempt will be made, at this point, to determine where in the sample the signal comes from; the signal comes from everywhere in the entire sample.

Nuclear Magnetic Resonance

Nuclear magnetic resonance (NMR) is a physical phenomenon that occurs when certain elements interact with a magnetic field. NMR is the process by which the signal detected in MRI is generated; it is the foundation on which MRI is built. Some common elements that demonstrate NMR are...
Where Does the MRI Signal Come From?

Table 1-1. Some elements that undergo NMR.

<table>
<thead>
<tr>
<th>Element</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>H</td>
</tr>
<tr>
<td>Carbon</td>
<td>C</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>P</td>
</tr>
<tr>
<td>Fluorine</td>
<td>F</td>
</tr>
<tr>
<td>Xenon</td>
<td>Xe</td>
</tr>
</tbody>
</table>

listed in Table 1-1. In order to qualify for this list (and other elements and isotopes do qualify), the element must have a nonzero magnetic moment. It is not necessary for us to delve into what a nonzero magnetic moment is, but it will be present when either the number of protons or neutrons in an atom is odd. Thus, helium can never undergo NMR because its nucleus is composed of two protons and two neutrons. So why is it so important that the atom have an odd number of protons or neutrons? A truthful answer requires a discussion involving quantum mechanics. We will touch on this a bit in the following sections. The bottom line, however, is only those nuclei with nonzero magnetic moments demonstrate a property called spin angular momentum. The essential role of spin angular momentum in NMR will be introduced shortly.

Spin Semantics

Although many nuclei can undergo NMR, we will confine our discussion to the hydrogen nucleus (\(^1\)H). The type of sample we will be imaging and the question that we wish to answer directs the choice of nucleus to be examined. In human tissue, which is composed largely of hydrogen-containing water (H\(_2\)O), hydrogen is the most abundant of all the NMR-capable nuclei. For this reason, human MRI is focused almost exclusively on hydrogen. However, if we wished to look at energy metabolism and ATP, \(^{31}\)P would be the nucleus of choice. If we were interested in glucose metabolism, \(^{13}\)C would be best.

Because the hydrogen nucleus contains a single proton and nothing more, hydrogen nuclei are also referred to merely as

What about the electrons?

As small charged subatomic particles, electrons also demonstrate magnetism and spin. Thus, they demonstrate both magnetism and spin angular momentum. Why, then, are we ignoring them in our discussion of NMR? Because of their much smaller mass, electrons have a much higher gyromagnetic ratio and precess at frequencies in the gigahertz range; signals in this frequency range will not be detected by our detection hardware (see Chapter 5). Additionally, their resonance signal—called electron spin resonance, or ESR—is comparatively weak relative to the NMR signal. The magnetic fields expressed by electrons, however, are quite important, as they induce variability in the static magnetic field of the MRI scanner (\(B_0\)), causing the chemical shift effects so important in spectroscopy and imaging.
protons. As we will see shortly, the nucleus must have a quantum mechanical property termed nucleus, proton, and spin are interchangeable. For human MRI, the terms nuclear spin. For this reason, nuclei are also commonly referred to merely as spins. Note that in the case of NMR of nuclei other than \(^1\)H, the term proton would be incorrect, whereas the term spin would be appropriate.

Prerequisites to NMR: Nuclear Magnetism

NMR is based on the presence of two properties of the atom: (1) magnetism and (2) spin angular momentum. The protons within the nucleus of any atom contain electric charge and generate a magnetic field. Whereas it is tempting to think of such nuclear magnetism in terms of classic electromagnetic phenomena with spinning charges generating a magnetic field based on Faraday's law of induction, nuclear magnetism is in fact a quantum mechanical phenomenon, and nuclear particles do not, as currently understood, actually spin in the physical sense.

Nuclear magnetism does, nonetheless, result in a very real magnetic field that is local to the nucleus and behaves just like the magnetic field of a permanent magnet or compass needle. Magnetic field lines describe this nuclear magnetic field and are identical to those generated by a common bar-shaped permanent magnet (Fig. 1-1).

Field lines are not something magical. They are very real and a useful way to describe the strength, orientation, and homogeneity of a magnetic field (see Chapter 5). For our descriptions of nuclear magnetism, however, it will suffice to describe the magnetic field of the nucleus using a single vector. The orientation of this magnetic field vector will indicate the orientation of the nuclear magnetic field, and the length of the vector will indicate the strength of the field. In the absence of any magnetic field external to the nucleus, orientation of the nuclear magnetic field will be random. In
Where Does the MRI Signal Come From?

Figure 1-1. The proton's magnetic field. The magnetic field lines of a common bar magnet (right) are shown by the distribution of iron filings. The magnetic field of a proton (left) behaves in the same manner, exhibiting field lines and polarity identical to those produced by the bar magnet.

the presence of an externally applied magnetic field, however, the nuclear magnetic field will align with the externally applied magnetic field, much as a compass needle aligns with the earth’s magnetic field.

At this point, we have described the magnetism of the $^1$H nucleus and can see that our proton essentially behaves as a tiny magnet, aligning with an external applied magnetic field. To demonstrate NMR and be useful for MRI, however, the proton must also have spin angular momentum.

Prerequisites to NMR: Nuclear Spin Angular Momentum

Spin angular momentum is a property of certain nuclei (those that exhibit NMR). Its existence becomes apparent when we observe the interaction of such a nucleus with an externally applied magnetic field. Though not precisely applicable to the world of small particles like atomic nuclei, a real-world example can at least give us a feeling for what angular momentum is. When a figure skater crouches into a high-velocity spin, the skater may wobble. If we ask the skater what he or she felt during that spin, they will describe a centrifugal force pushing his or her body away from its vertical alignment. In fact, any Olympic hopeful skater will tell us that it takes substantial energy to resist this force and maintain the spin. Similarly, if we take a small weight, tie it to the end of a string, and whirl the string and weight overhead like a lasso, what happens? The string remains taut. Again, this centrifugal force is at work. The physical phenomenon that produces this centrifugal force is called angular momentum. The same force causes the wobble of a spinning top.

Spin angular momentum is an analogous force that is applicable to small particles such as atomic nuclei. Consider another macroscopic example. Tie a permanent magnet to a string and suspend it a few centimeters above a tabletop; the entire system will lie at rest with the string plumb to gravity. Next, place a second permanent magnet on the tabletop and slide it under the suspended magnet. What happens? The suspended magnet will begin
to swing from side to side over the magnet placed below it on the tabletop (Fig. 1-2A). The magnet below attracts the suspended magnet, causing it to move closer. Momentum of the suspended magnet causes it to overshoot the location of the magnet below. Next, the suspended magnet is drawn back toward the magnet on the tabletop. Ultimately, the suspended magnet swings back and forth in a straight line until it eventually slows and comes to rest over the magnet that was placed on the tabletop. Why does the suspended magnet stop swinging? The system comes to rest only because of friction within the suspensory mechanism. If a completely frictionless system could be developed to suspend the magnet, it would swing back and forth forever! By the way, although the direction in which the magnet swings is completely unrestricted, it will swing back and forth in a straight line.

Let's complicate the system slightly. Install a small motor at the point where the string is suspended and rotate the string at this point. Note that the string is still free to swing back and forth. What happens now? Instead of swinging back and forth in a straight line, the spinning magnet moves in a circular trajectory around the magnet lying on the table below (Fig. 1-2B). If we would map the path of the suspending string, it would delineate a cone. This change from a linear to a circular path is due only to the pres-

![Figure 1-2](image.png)

**Figure 1-2.** Spin angular momentum. (A) The magnet suspended from a universal joint is free to swing in any direction. (N and S refer to the poles of the magnet.) When a second magnet is placed underneath it, the suspended magnet will swing back and forth through a plane parallel to the magnetic field of the stationary magnet. Only because of friction at its point of attachment will the suspended magnet eventually come to rest. (B) When the point of attachment is connected to the shaft of a small motor, angular momentum is added to the system. When the second magnet is positioned underneath, the suspended magnet circles so that the string to which it is attached traces the surface of a cone.
Where Does the MRI Signal Come From?

**FIGURE 1-3. Precession.** Interaction of the magnetic field of the proton with an applied magnetic field leads to precession. The vector describing the proton’s magnetic field circles that describing the static magnetic field. Its path traces the surface of a cone.

This same phenomenon is responsible for the wobbling of a gyroscope, top, or dreidel. Because such devices have “spin,” when they interact with the earth’s gravitational field, they pursue the same conical trajectory.

Now let’s look at the same phenomenon as it pertains to nuclei. Nuclei have charge that confers nuclear magnetism. When placed in an externally applied magnetic field, they will interact with that field in much the same way as a compass needle interacts with the earth’s magnetic field: they will oscillate. If the nucleus also has spin angular momentum, it will not oscillate but will precess around the externally applied magnetic field, pursuing the same type of conical trajectory described above (Fig. 1-3).

**What Is Spin?**

The preceding description of spin angular momentum drew on examples from classical mechanics. These examples are useful but are ultimately inadequate for accurately describing the behavior of very small particles such
as nuclei. Quantum mechanics is required to fully explain the effects of spin angular momentum at the nuclear level. Although a full quantum mechanical description is beyond our scope and is not necessary for an understanding of MRI, it is worthwhile to be aware of the quantum definition of “spin” described in the box in this section. Note that nuclear spin does not imply that the nuclei actually spin in the physical sense; in the world of quantum mechanics, small particles such as nuclei exhibit angular momentum, but do not actually spin.

Based on the background we have developed thus far, the “requirements” for the NMR effect can be succinctly stated as follows:

1. Nonzero charge provides nuclear magnetism.
2. Nonzero spin provides spin angular momentum.

Both of these characteristics are central in determining the nature of the interactions of nuclei with an externally applied magnetic field, and both must be present before an MRI signal or image can be obtained.

Interaction of Protons with a Static Magnetic Field (B)

In the absence of a magnetic field external to the one exhibited by the spins, the orientation of the spins’ magnetization will be completely random such that the vector sum of their magnetization will be zero. We must
consider two consequences of the spins’ interaction with B. First, just as a compass needle will align with the earth’s magnetic field, the proton’s magnetic field will align with B. Spins tend to align parallel or antiparallel (parallel, but pointing in the opposite direction) to B. After the spins’ magnetizations align with B, the vector sum will be nonzero, yielding a net magnetic field. In this state, we say that the sample has become magnetized. The alignment of spin magnetization is in some way analogous to the preferred alignment of two permanent magnets. The “antiparallel” orientation is in fact the most likely to occur. When you press two small bar magnets together, the north pole of each will tend to align with the south pole of the other. Whereas two bar magnets will always assume this “antiparallel” alignment, the magnetization of our spins will align both antiparallel and parallel. This is because of the quantum mechanical nature of nuclear magnetism. The majority of the magnetization will yield a vector sum of zero with only a small excess vector sum detectable in the antiparallel orientation. This small excess is approximately equivalent to the magnetization of six nuclei in a sample of 10,000. That tiny net magnetization is the signal we must detect in order to make an MR image. However, we will soon see that this tiny component of magnetization cannot be detected unless we manipulate its orientation using the NMR effect. Second, because the spins precess about B they never fully assume a truly parallel orientation with respect to B. The influence of spin angular momentum leads to the proton’s magnetization vector describing a cone (Fig. 1-3). This pattern of motion is termed precession. The gyromagnetic ratio—indicated by the Greek letter $\gamma$ and expressed in units of MHz/T—is the unique value for each nucleus that allows us to determine the frequency (think of it as rate or speed) at which the nucleus will precess around a static magnetic field B. The gyromagnetic ratio in combination with the strength of B tells us the frequency of precession (i.e., the rate or “speed” at which each proton precesses around the axis of B), indicated by the Greek letter $\omega$: $\omega = \gamma B$. This is the famous Larmor equation.

In the ensuing discussions, we will, until further notice, assume a constant and perfectly homogeneous externally applied magnetic field (B), referred to from now on as $B_0$. This means that the strength and orientation of $B_0$ is exactly the same in every location, so that each and every spin “sees” the same $B_0$. Because we will be dealing with a homogeneous magnetic field $B_0$, we will speak in terms of the Larmor frequency of the nucleus at that field strength. It is termed $\omega_0$. Thus,

$$\omega_0 = \gamma B_0$$

You must know this equation, but this is the only equation that you will have to know.
Describing a Real-Life Sample: Dealing with Many Spins

In reality, whether our sample is a solution in a test tube or the human body, we never observe a single proton. Rather, billions of protons are observed as a group. The signal that we measure is the aggregate signal generated by all spins in the sample. Just as we measure the aggregate signal, in our discussions of NMR and MRI we will deal with this composite signal rather than discuss the behavior of individual spins. Although each proton is an individual, so to speak, we can describe this entire group of spins without misrepresenting the contribution of even one individual spin. The net magnetization vector (NMV), also called \( M \), gives us this "bird's-eye view" of the whole sample of spins. Here we will put vector addition into practice.

In order to find the NMV, we first decompose the vector of each spin into components parallel and perpendicular to \( B_0 \). Adding the component vectors parallel to \( B_0 \), which we call longitudinal component vectors, yields a single vector that is also parallel to \( B_0 \). This vector will be called \( M_L \). Next we will deal with the component vectors perpendicular to \( B_0 \), calling them transverse component vectors, or \( M_T \). Although all spins precess at the same rate (\( \omega \))—remember, they all "feel" the same \( B_0 \), and \( \omega = \gamma B_0 \)—they are not all at the same point in their precession about \( B_0 \). That is, the transverse components do not all point in the same direction at any one point in time. In fact, the arrangement of the spins along the path of precession is completely random. We call this random phase. Given a large sample of spins—remember that we are dealing with millions, billions, or trillions of spins—we will find a transverse component vector with orientation exactly opposite each and every component vector. These transverse component vectors yield a vector sum of zero. In other words, for each transverse component vector, there is another one pointing in the opposite direction to cancel it. Recall that the magnitude of each of these component vectors is identical because each derives from a single proton experiencing an identical \( B_0 \). Random phase means that all transverse components cancel each other.

The net magnetization is now correctly represented as a single vector parallel to \( B_0 \) with a magnitude equal to the sum of the longitudinal component vectors. Note that whereas each protons' vector demonstrates precession, the NMV is stationary because the "precessing component" of magnetization has summed to zero.

The Energy Configuration Approach: A Painless (Really!) Bit of Quantum Mechanics

Overview

Explanations of the NMR phenomenon that employ principles of classical mechanics and electromagnetism abound in introductory texts on NMR and
MRI. This approach, however, inevitably runs aground, unable to really explain what is going on. This is because classical physics is not capable of explaining the behavior of very small particles such as nuclei undergoing NMR. In order to understand what is going on during NMR, we must view the events through the lens of quantum mechanics. The problem is that a full understanding of quantum mechanics is well beyond the scope of this book and beyond what most MRI users (even MRI scientists) want and need to know. So, on the one hand we have relatively easy to understand phenomena (classical approach) that do not accurately explain NMR. On the other hand, esoteric and more difficult to understand phenomena (quantum mechanics) can elegantly explain the physical basis of NMR. It is indeed tempting to take the easy path and use the classical explanations, hoping that some hand waving will suffice where the approach fails.

Another approach for those who reject the simpler but inadequate classical physics explanations is to simply accept various tenets of the NMR phenomena as postulates or articles of faith.

Our approach, on the other hand, will be to take the “high road” and invoke quantum mechanical explanations to expose the truth of MRI. The catch is that we propose to do so without delving into the more esoteric details of quantum mechanics and certainly not into the mathematics. Although the mathematics provides the clearest and most complete delineation of these concepts, it is not necessary in order to gain adequate insight to support a very good working knowledge of MRI. Our rationale for this approach is that it affords “an explanation that actually makes sense” and allows the student of MRI to see a logic behind the apparent NMR voodoo. This understanding of basic mechanisms is not an end in itself but in turn enhances understanding of concepts such as spin relaxation and facilitates retention of important concepts and their application to other aspects of NMR and MRI.

Probability and Certainty

The world of quantum mechanics is very different from the world that we are accustomed to. First, we perceive a continuous spectrum of possibilities. Human vision, for example, does not generate images composed of individual pixels but a continuous spectrum of color and objects. Second, we are accustomed to having “certain” knowledge of the state of affairs at any moment