Magnetic Resonance Imaging
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Physical Principles and Sequence Design

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This book is dedicated to our parents:

Helena Doris Haacke
Ewart Mortimer Haacke

William James Brown
Florence Elizabeth Brown

Robert Thompson
Mary Christina Thompson

Ramasubramaniam Venkatesan
Saroja Venkatesan
Foreword

Jeffrey L. Duerk

I heard my first lecture on an emerging field in medical imaging known as Nuclear Magnetic Resonance Imaging in 1983 as an electrical engineering graduate student at The Ohio State University. I was captivated and soon moved to Cleveland, a city then considered by many to be a United States’ center for the development of MR imaging and where both Picker International and Technicare were located a few miles apart. After studying many manuscripts, books and ‘primers,’ I enrolled in a new Physics and Biomedical Engineering course at Case Western Reserve University denoted by PHYS/EBME 431: The Physics of Medical Imaging, taught by Prof. E. Mark Haacke. In large part, the present book has grown and evolved from the class notes and lectures from this course’s offering over the years.

The power of Magnetic Resonance Imaging (MRI) in the diagnostic arena of patient care is unquestionable. A multitude of books exist to assist in the training/teaching of clinicians responsible for interpreting MR images. Since joining the faculty of Case Western Reserve University almost a decade ago, I have been asked by graduate students, new industry hires, and fellow professors (from both CWRU and institutions throughout the world), if there was a book I could recommend which would provide sufficient depth in physics and MR imaging principles to serve as either a textbook or a complete tutorial for basic scientists. In my opinion, there were none which could provide the basic scientist with the tools to understand well the physics of MRI and also understand the engineering challenges necessary to develop the actual acquisitions (known as pulse sequences) which ultimately lead to the images. While there were no single sources available, I implored all to be patient. Today, I believe that patience has been rewarded as the book has arrived.

While much has changed in the field since my introduction to it in the early 1980’s (e.g., the ‘N’ in NMR Imaging and the company Technicare are both gone), the power of this book is that many central concepts in MRI are rather more permanent, and their coverage here is superb. The influence by such notable predecessors as Abragam, Slichter, and Ernst is, at times, unmistakable. Mostly, the personal descriptive and analytical teaching style of Drs. Haacke, Brown, Thompson and Venkatesan builds an understanding of new concepts while clarifying old ones from the solid foundation provided earlier in the text. Another particular advantage of this book is that the notation is consistent, and located in a single reference; the readers do not have to overcome notational differences among our predecessors or difficulties in separating fundamental concepts from advanced material. Importantly, virtually every homework problem in the text has been designed to emphasize a central concept crucial to MRI. When I page through the book, I am often able to find the same derivations in the homework questions as in my log-books from the early part of my career in MRI. Insights from the authors are present throughout the text as well as within the problems; they provide those
less experienced with glimpses (which later become illuminating flashes (no pun intended)) into how MR physics and sequences work and how they can be taken advantage of in the application to new ideas.

While I have been a co-instructor for EBME/PHYS 431 for a number of years and have used drafts of this book as the textbook, by now it bears little resemblance to the class notes of the initial offering in 1985. For that matter, the field of MRI has exploded with new techniques, new applications and far greater understanding and analysis of the innumerable aspects of the MRI hardware and software on image quality. I have benefited from my long friendships with Drs. Haacke and Brown, and the more recent ones with Drs. Thompson and Venkatesan. If you were to walk into the CWRU MRI Laboratory today, you would find no less than five drafts of this book on the shelves. The greatest tribute to these authors in their efforts to compile an important comprehensive treatise on the physics of MRI and MR sequence design can be heard in our research group’s discussions of new imaging techniques (and likely those in the future at other institutions world-wide) when someone beckons ‘Grab ‘Haacke and Brown’!’

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January 20, 1999
Foreword

Felix W. Wehrli

Haacke et al.'s new book spans a significant portion of proton MRI concerned with the design of MRI pulse sequences and image phenomenology. The work, designed for the physicist and engineer, is organized in twenty-seven chapters. The first eight chapters deal with the fundamentals of nuclear magnetic resonance, most of which is based on the classical Bloch formalism, except for a two chapter excursion into quantum mechanics. This portion of the book covers the basic NMR phenomena, and the concepts of signal detection and data acquisition. Chapters 9 and 10 introduce the spatial encoding principles, beginning with one-dimensional Fourier imaging and its logical extension to a second and third spatial dimension. Chapter 11 treats continuous and discrete Fourier transforms, followed in Chapters 12 and 13 by sampling principles, filtering and a discussion of resolution. Chapter 14 may be regarded as the opening section of the book's second part exploring more advanced concepts, beginning with treatment of non-Cartesian imaging and reconstruction. In chapter 15, the properties of signal-to-noise are dealt with in detail including a discussion of the important scaling laws, followed, in chapter 16 by a return to a more advanced treatment of rf pulses, along with such concepts as spatially varying rf excitation and spin-tagging. Chapter 17 is dedicated to the various currently practiced methods for water-fat separation, and in chapters 18 and 19, the authors delve into the ever-growing area of fast imaging techniques. Chapter 18 is entirely dedicated to steady-state gradient-echo imaging methods to which the authors have themselves contributed a great deal since the inception of whole-body MRI. Chapters 19 and 20 address echo train methods focusing on EPI, $T_2^*$ dephasing effects and the resulting artifacts, ranging from intravoxel phase dispersion to spatial distortion. Chapter 21 is a brief introduction to the physics underlying diffusion-weighted imaging and pertinent measurement techniques. Chapter 22 treats the quantification of the fundamental intrinsic parameters, spin density, $T_1$ and $T_2$. Chapters 23 and 24 deal with the manifestations of motion and flow in terms of the resulting artifacts and their remedies, followed by a broad coverage of the major angiographic and flow quantification methods. The topic of chapter 25 is induced magnetism and its various manifestations, including a discussion of its most significant application — brain functional MRI exploiting the BOLD phenomenon. In chapter 26, the authors return to pulse sequence design, reviewing the design criteria for the most important pulse sequences and discussing potential artifacts. The final chapter 27, at last, discusses hardware in terms of magnets, rf coils and gradients.

This book is the result of a monumental five-year effort by Dr. Haacke and his coauthors to generate a high-level, comprehensive graduate and post-graduate level didactic text on the physics and engineering aspects of MRI. The work clearly targets the methodology of bulk proton imaging, deliberately ignoring chemical shift resolved imaging or treatment of biophysical aspects such as the mechanisms of relaxation in tissues. Understanding the book requires college-level vector calculus. However, many of the basic tools, such as Fourier transforms and the fundamentals of electromagnetism, are elaborated upon either in dedicated chapters or appendices. The problems interspersed in the text of all chapters are a major asset and will be appreciated by student and teacher alike.

There is no doubt that the authors have succeeded in their effort to create a textbook that finally fills a need which has persisted for years. Haacke et al.'s book is, in the reviewer's assessment, the most authoritative new text on the subject, likely to become an essential
tool for anyone actively working on MRI data acquisition and reconstruction techniques, but also for those with a desire to understand MR at a more than superficial level. The work is a rare synthesis of the authors’ grasp of the subject, and their extensive practical experience, which they share with the reader through exceptional didactic skill.

The book has few flaws worth mention at all. First, not all chapters provide equal coverage of a targeted topic in that the book often emphasizes areas in which the authors have excelled themselves and thus are particularly experienced. Such a personal slant, of course, is very much in the nature of a treatise written by a single group of authors. On the other hand, the coherence in terms of depth of treatment, quality of illustrations and style, offered here, is never achievable with edited books. A case in point of author-weighted subject treatment is fast imaging, which is heavy on steady-state imaging. The following chapter on echo-train imaging almost exclusively deals with EPI and only secondarily with RARE and its various embodiments. Likewise, diffusion is treated only at its most fundamental level with little mention of anisotropic or restricted diffusion, or diffusion tensor imaging. Though the suggested reading list is helpful, a division into historic articles and those more easily accessible to the student would have been helpful since many of the historic papers cited would have to be retrieved from the library’s storage rooms provided they are available at all. Finally, an introduction to the imaging hardware earlier (rather than as the last chapter) would help the novice bridging the gap between theory and instrumentation. None of the above, however, should detract from the book’s high quality and practical usefulness.

In summary, the authors need to be congratulated on a superb product; a text vital to those concerned with MRI at a rigorous level. Magnetic Resonance Imaging: Physical Principles and Sequence Design is likely to become the daily companion of the MRI scientist and a reference standard for years to come.

Felix W. Wehrli, Ph.D.
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Editor-in-Chief, Magnetic Resonance in Medicine

February 9, 1999
Preface

The principal motivation for this book is to create a self-contained text that could be used to teach the basics of magnetic resonance imaging to both graduate students and advanced undergraduate students. Although this is not a complete research treatise on MRI, it may also serve as a useful reference text for those experienced in the field. Time and page limitations have made it impossible to include detailed discussions of exchange processes, rf penetration, k-t space, perfusion, and parametric reconstruction methods, to name a few important topics omitted. MR simulations, interactive MRI, and distance learning are other important issues that may be addressed in an expanded web-based companion volume in the future. We hope that the present text is a useful complement to the many technical details available on coil concepts in the MR technology book by Chen and Hoult and on diffusion in the microscopic imaging book by Callaghan.

To varying degrees, the chapters contain discussions of the technical details, homework problems, sequence concepts, and the resulting images. Key points are often highlighted by italicized text and single quotation marks usually signify the introduction of MR nomenclature or stylized language. Representative references appear at the end of each chapter, but only general review or introductory articles, or selected papers with which we are especially familiar, are referenced. It is beyond the scope of this book to make any attempt to present a complete bibliography.

The first fifteen chapters of the text are introductory in nature and could perhaps serve as a one-semester course. After the brief preview given in chapter one, they wend their way from the basic dynamics of nuclear magnetic moments, to the concepts of imaging, and later to the effects of reconstruction type, contrast and noise. The next eleven chapters represent the bulk of the imaging applications addressed; they could either be covered in a second semester or the basic concepts of each could be interspersed with those of the earlier chapters comprising a faster paced single-semester course (which has been our tendency). The eleven chapters begin with brief excursions into the areas of rf pulse design and chemical shift imaging, and are followed by detailed discussions on fast imaging, magnetic field inhomogeneity effects, motion, flow, diffusion, sequence design and artifacts. A unified discussion of the rf, gradient and main magnet coils is contained in the last chapter. Alternatively, we do find appealing the assimilation of coil hardware issues with material in earlier chapters where appropriate. The appendices contain review material for basic electromagnetism and statistics as well as a list of acquisition parameters for the images in the book.
Acknowledgments

Much like all major technologies, the development of magnetic resonance imaging has been a step-by-step process, building over many years on the ideas and experience of innumerable researchers in the field. The development of this book has itself been based not only on many years of our teaching magnetic resonance imaging (we are well into our second decade), but also on the efforts of numerous colleagues and collaborators, both faculty and students. Sometimes, a particular discussion or imaging result or insight has been directly due to the efforts of a single M.S. or Ph.D. student. To all those who have directly or indirectly contributed, we are indebted. Specifically, we thank the following people for reading different parts of the text and reviewing specific chapters: Gabriele Beck, Andreas Brenner, James Brookeman, Mark Conradi, Lawrence Crooks, Thomas Dixon, Jeff Duerk, Jens Frahm, Jürgen Hennig, Christopher Hess, Steve Izen, Permi Jhooti, Stephan Kannengeiser, Peter Kingsley, Uwe Klose, Zhi-Pei Liang, Michal Lijowski, Robert Ogg, John Pauly, Jean Tkach, Yi Wang, Felix Wehrli, Robert Weiskoff, Eric Wong and Ian Young. We also owe our gratitude to the following people for assisting in either the collection or processing of the data for images shown in the text: Azim Celik, Xiaoping Ding, Karthikeyan Kuppusamy, Debiao Li, Weili Lin, Yi Wang and Yingjian Yu. Special thanks are also due to Peter Kingsley for reading many of the early versions of numerous chapters, to Marinus T. Vlaardingerbroek and Jacques den Boer for incorporating some of the nomenclature into their own book on MRI, and particularly to Norman Cheng for his participation in the entire process of scrutinizing the text, solving problems, and facilitating the final editing of the book. The following students and fellow researchers need special mention for their feedback and corrections on several specific aspects of different chapters: Hongyu An, Markus Barth, Hiro Fujita, Pilar Herrero, Frank Hoogenraad, Renate Jerecic, Shantanu Kaushikkar, Weigi Kong, Song Lai, Jingzhi Liu, Jürgen Reichenbach, Jacob Willig, Yingbiao Xu and Anne Marie Yunker. Finally, our thanks to Jan Lindley for her secretarial support during the last two years of this project.

During our own tenure in this field, we have personally benefited from our involvement with both Siemens Medical Systems (Erlangen, Germany) and Picker International (Cleveland, Ohio). Many of the imaging methods have been developed thanks to a collaborative agreement with Siemens. All images presented in this text were acquired with a 1.5 T Siemens VISION scanner. We would like to thank the following people in Siemens for their support over the years: Richard Hausmann, Randall Kroecker, Gerhard Laub, Gerald Lenz, Wilfried Loeffler, Hermann Requardt, Erich Reinhardt and Franz Schmitt. We would also like to thank Gordon DeMeester, Surya Mohapatra, Michael Morich and John Patrick at Picker for longstanding support and collaboration.
Although we have played the role of teacher in giving this course, we have benefited from the entire educational experience of preparing this book. We are grateful to the many students and colleagues who have taught us in this process over and above those mentioned so far. These include: Michael Martens, Todd Parrish, Cynthia Paschal, Labros Petropoulos, Shmaryu Shvartsman, Jean Tkach, Piotr Weilopolski and Fredy Zypman.

The mistakes that remain are, of course, our responsibility alone. For these errors, we apologize in advance. We invite you to share your thoughts and to provide suggestions for improvements in the text. In this way, we can establish an updated list of corrections and additions, taking full advantage of the exciting new manner in which educational issues, open problems, and databases in MRI may now be addressed via the internet.

On a more personal note, we are most happy to finally have this chance to thank our families and friends who have supported and sustained the writing efforts over the last five years. Their patience and encouragement were crucial to the book’s completion.