

Contents

Foreword to the Second Edition	xvii
Foreword to the First Edition	xxi
Preface to the Second Edition	xxvii
Preface to the First Edition	xxix
Acknowledgements	xxx
Acknowledgements to the First Edition	xxxii
1 Magnetic Resonance Imaging: A Preview	1
1.1 Magnetic Resonance Imaging: The Name	1
1.2 The Origin of Magnetic Resonance Imaging	2
1.3 A Brief Overview of MRI Concepts	3
1.3.1 Fundamental Interaction of a Proton Spin with the Magnetic Field	3
1.3.2 Equilibrium Alignment of Spin	4
1.3.3 Detecting the Magnetization of the System	5
1.3.4 Magnetic Resonance Spectroscopy	7
1.3.5 Magnetic Resonance Imaging	7
1.3.6 Relaxation Times	8
1.3.7 Resolution and Contrast	9
1.3.8 Magnetic Field Strength	10
1.3.9 Key Developments in Magnetic Resonance	12
2 Classical Response of a Single Nucleus to a Magnetic Field	19
2.1 Magnetic Moment in the Presence of a Magnetic Field	20
2.1.1 Torque on a Current Loop in a Magnetic Field	20
2.1.2 Magnet Toy Model	24
2.2 Magnetic Moment with Spin: Equation of Motion	25
2.2.1 Torque and Angular Momentum	25
2.2.2 Angular Momentum of the Proton	26
2.2.3 Electrons and Other Elements	27
2.2.4 Equation of Motion	28
2.3 Precession Solution: Phase	29
2.3.1 Precession via the Gyroscope Analogy	29
2.3.2 Geometrical Representation	31
2.3.3 Cartesian Representation	32

2.3.4	Matrix Representation	34
2.3.5	Complex Representations and Phase	34
3	Rotating Reference Frames and Resonance	37
3.1	Rotating Reference Frames	38
3.2	The Rotating Frame for an RF Field	41
3.2.1	Polarization	42
3.2.2	Quadrature	43
3.3	Resonance Condition and the RF Pulse	44
3.3.1	Flip-Angle Formula and Illustration	45
3.3.2	RF Solutions	46
3.3.3	Different Polarization Bases	47
3.3.4	Laboratory Angle of Precession	49
4	Magnetization, Relaxation, and the Bloch Equation	53
4.1	Magnetization Vector	53
4.2	Spin-Lattice Interaction and Regrowth Solution	54
4.3	Spin-Spin Interaction and Transverse Decay	57
4.4	Bloch Equation and Static-Field Solutions	60
4.5	The Combination of Static and RF Fields	62
4.5.1	Bloch Equation for $\vec{B}_{ext} = B_0\hat{z} + B_1\hat{x}'$	62
4.5.2	Short-Lived RF Pulses	63
4.5.3	Long-Lived RF Pulses	64
5	The Quantum Mechanical Basis of Precession and Excitation	67
5.1	Discrete Angular Momentum and Energy	68
5.2	Quantum Operators and the Schrödinger Equation	72
5.2.1	Wave Functions	73
5.2.2	Momentum and Angular Momentum Operators	74
5.2.3	Spin Solutions for Constant Fields	76
5.3	Quantum Derivation of Precession	77
5.4	Quantum Derivation of RF Spin Tipping	80
6	The Quantum Mechanical Basis of Thermal Equilibrium and Longitudinal Relaxation	85
6.1	Boltzmann Equilibrium Values	86
6.2	Quantum Basis of Longitudinal Relaxation	89
6.3	The RF Field	92
7	Signal Detection Concepts	95
7.1	Faraday Induction	96
7.2	The MRI Signal and the Principle of Reciprocity	99
7.3	Signal from Precessing Magnetization	101

7.3.1	General Expression	101
7.3.2	Spatial Independence	103
7.3.3	Signal Demodulation	104
7.3.4	Dependent Channels and Independent Coils	107
7.4	Dependence on System Parameters	107
7.4.1	Homogeneous Limit	107
7.4.2	Relative Signal Strength	108
7.4.3	Radiofrequency Field Effects	110
8	Introductory Signal Acquisition Methods: Free Induction Decay, Spin Echoes, Inversion Recovery, and Spectroscopy	113
8.1	Free Induction Decay and T_2^*	114
8.1.1	FID Signal	114
8.1.2	Phase Behavior and Phase Conventions	115
8.1.3	T_2^* Decay	117
8.1.4	The FID Sequence Diagram and Sampling	119
8.2	The Spin Echo and T_2 Measurements	120
8.2.1	The Spin Echo Method	120
8.2.2	Spin Echo Envelopes	123
8.2.3	Limitations of the Spin Echo	124
8.2.4	Spin Echo Sampling	125
8.2.5	Multiple Spin Echo Experiments	125
8.3	Repeated RF Pulse Structures	126
8.3.1	The FID Signal from Repeated RF Pulse Structures	127
8.3.2	The Spin Echo Signal from Repeated RF Pulse Structures	129
8.4	Inversion Recovery and T_1 Measurements	131
8.4.1	T_1 Measurement	132
8.4.2	Repeated Inversion Recovery	134
8.5	Spectroscopy and Chemical Shift	136
9	One-Dimensional Fourier Imaging, k-Space, and Gradient Echoes	141
9.1	Signal and Effective Spin Density	142
9.1.1	Complex Demodulated Signal	142
9.1.2	Magnetization and Effective Spin Density	143
9.2	Frequency Encoding and the Fourier Transform	144
9.2.1	Frequency Encoding of the Spin Position	144
9.2.2	The 1D Imaging Equation and the Fourier Transform	145
9.2.3	The Coverage of k -Space	146
9.2.4	Rect and Sinc Functions	147
9.3	Simple Two-Spin Example	147
9.3.1	Dirac Delta Function	150
9.3.2	Imaging Sequence Diagrams Revisited	151
9.4	Gradient Echo and k -Space Diagrams	151
9.4.1	The Gradient Echo	153
9.4.2	General Spin Echo Imaging	156

9.4.3	Image Profiles	158
9.5	Gradient Directionality and Nonlinearity	162
9.5.1	Frequency Encoding in an Arbitrary Direction	162
9.5.2	Nonlinear Gradients	163
10	Multi-Dimensional Fourier Imaging and Slice Excitation	165
10.1	Imaging in More Dimensions	166
10.1.1	The Imaging Equation	166
10.1.2	Single Excitation Traversal of k -Space	169
10.1.3	Time Constraints and Collecting Data over Multiple Cycles	171
10.1.4	Variations in k -Space Coverage	174
10.2	Slice Selection with Boxcar Excitations	175
10.2.1	Slice Selection	175
10.2.2	Gradient Rephasing After Slice Selection	178
10.2.3	Arbitrary Slice Orientation	180
10.3	2D Imaging and k -Space	184
10.3.1	Gradient Echo Example	184
10.3.2	Spin Echo Example	193
10.4	3D Volume Imaging	194
10.4.1	Short- T_R 3D Gradient Echo Imaging	194
10.4.2	Multi-Slice 2D Imaging	195
10.5	Chemical Shift Imaging	197
10.5.1	A 2D-Spatial 1D-Spectral Method	200
10.5.2	A 3D-Spatial, 1D-Spectral Method	204
11	The Continuous and Discrete Fourier Transforms	207
11.1	The Continuous Fourier Transform	208
11.2	Continuous Transform Properties and Phase Imaging	209
11.2.1	Complexity of the Reconstructed Image	211
11.2.2	The Shift Theorem	211
11.2.3	Phase Imaging and Phase Aliasing	212
11.2.4	Duality	215
11.2.5	Convolution Theorem	215
11.2.6	Convolution Associativity	218
11.2.7	Derivative Theorem	219
11.2.8	Fourier Transform Symmetries	220
11.2.9	Summary of Continuous Fourier Transform Properties	220
11.3	Fourier Transform Pairs	220
11.3.1	Heaviside Function	222
11.3.2	Lorentzian Form	222
11.3.3	The Sampling Function	223
11.4	The Discrete Fourier Transform	223
11.5	Discrete Transform Properties	225
11.5.1	The Discrete Convolution Theorem	226
11.5.2	Summary of Discrete Fourier Transform Properties	227

12	Sampling and Aliasing in Image Reconstruction	229
12.1	Infinite Sampling, Aliasing, and the Nyquist Criterion	230
12.1.1	Infinite Sampling	230
12.1.2	Nyquist Sampling Criterion	232
12.2	Finite Sampling, Image Reconstruction, and the Discrete Fourier Transform	237
12.2.1	Finite Sampling	237
12.2.2	Reconstructed Spin Density	239
12.2.3	Discrete and Truncated Sampling of $\hat{\rho}(x)$: Resolution	240
12.2.4	Discrete Fourier Transform	242
12.2.5	Practical Parameters	244
12.3	RF Coils, Noise, and Filtering	245
12.3.1	RF Field-of-View Considerations	245
12.3.2	Analog Filtering	245
12.3.3	Avoiding Aliasing in 3D Imaging	250
12.4	Nonuniform Sampling	250
12.4.1	Aliasing from Interleaved Sampling	250
12.4.2	Aliasing from Digital-to-Analog Error in the Gradient Specification	258
13	Filtering and Resolution in Fourier Transform Image Reconstruction	261
13.1	Review of Fourier Transform Image Reconstruction	262
13.1.1	Fourier Encoding and Fourier Inversion	262
13.1.2	Infinite Sampling and Fourier Series	263
13.1.3	Limited-Fourier Imaging and Aliasing	263
13.1.4	Signal Series and Spatial Resolution	264
13.2	Filters and Point Spread Functions	264
13.2.1	Point Spread Due to Truncation	265
13.2.2	Point Spread for Truncated and Sampled Data	266
13.2.3	Point Spread for Additional Filters	267
13.3	Gibbs Ringing	267
13.3.1	Gibbs Overshoot and Undershoot	267
13.3.2	Gibbs Oscillation Frequency	269
13.3.3	Reducing Gibbs Ringing by Filtering	270
13.4	Spatial Resolution in MRI	272
13.4.1	Resolution after Additional Filtering of the Data	277
13.4.2	Other Measures of Resolution	278
13.5	Hanning Filter and T_2^* Decay Effects	281
13.5.1	Resolution Due to the Hanning Filter	281
13.5.2	Partial Fourier T_2^* Reconstruction Effects	281
13.6	Zero Filled Interpolation, Sub-Voxel Fourier Transform Shift Concepts, and Point Spread Function Effects	283
13.6.1	Zero Padding and the Fast Fourier Transform	283
13.6.2	Equivalence of Zero Filled Image and the Sub-Voxel Shifted Image	284

13.6.3	Point Spread Effects on the Image Based on the Object Position Relative to the Reconstructed Voxels	285
13.7	Partial Fourier Imaging and Reconstruction	286
13.7.1	Forcing Conjugate Symmetry on Complex Objects	290
13.7.2	Iterative Reconstruction	290
13.7.3	Some Implementation Issues	292
13.8	Digital Truncation	293
14	Projection Reconstruction of Images	297
14.1	Radial k -Space Coverage	298
14.1.1	Coverage of k -Space at Different Angles	299
14.1.2	Two Radial Fourier Transform Examples	300
14.1.3	Inversion for Image Reconstruction	301
14.2	Sampling Radial k -Space and Nyquist Limits	302
14.3	Projections and the Radon Transform	308
14.4	Methods of Projection Reconstruction with Radial Coverage	310
14.4.1	X-Ray Analog	310
14.4.2	Back-Projection Method	311
14.4.3	Projection Slice Theorem and the Fourier Reconstruction Method	313
14.4.4	Filtered Back-Projection Method	314
14.4.5	Reconstruction of MR Images from Radial Data	316
14.5	Three-Dimensional Radial k -Space Coverage	317
14.6	Radial Coverage Versus Cartesian k -Space Coverage	320
14.6.1	Image Distortion Due to Off-Resonance Effects: Cartesian Coverage Versus Radial Sampling	321
14.6.2	Effects of Motion	323
14.6.3	Cartesian Sampling of Radially Collected Data	323
15	Signal, Contrast, and Noise	325
15.1	Signal and Noise	326
15.1.1	The Voxel Signal	326
15.1.2	The Noise in MRI	328
15.1.3	Dependence of the Noise on Imaging Parameters	328
15.1.4	Improving SNR by Averaging over Multiple Acquisitions	331
15.1.5	Measurement of σ_0 and Estimation of SNR	333
15.2	SNR Dependence on Imaging Parameters	334
15.2.1	Generalized Dependence of SNR in 3D Imaging on Imaging Parameters	334
15.2.2	SNR Dependence on Read Direction Parameters	336
15.2.3	SNR Dependence on Phase Encoding Parameters	340
15.2.4	SNR in 2D Imaging	341
15.2.5	Imaging Efficiency	342
15.3	Contrast, Contrast-to-Noise, and Visibility	342
15.3.1	Contrast and Contrast-to-Noise Ratio	343
15.3.2	Object Visibility and the Rose Criterion	343
15.4	Contrast Mechanisms in MRI and Contrast Maximization	345

15.4.1	Three Important Types of Contrast	347
15.4.2	Spin Density Weighting	347
15.4.3	T_1 -Weighting	349
15.4.4	T_2^* -Weighting	353
15.4.5	Summary of Contrast Results	355
15.4.6	A Special Case: T_1 -Weighting and Tissue Nulling with Inversion Recovery	356
15.5	Contrast Enhancement with T_1 -Shortening Agents	358
15.6	Partial Volume Effects, CNR, and Resolution	363
15.7	SNR in Magnitude and Phase Images	365
15.7.1	Magnitude Image SNR	365
15.7.2	Phase Image SNR	367
15.8	SNR as a Function of Field Strength	368
15.8.1	Frequency Dependence of the Noise in MRI	369
15.8.2	SNR Dependence on Field Strength	370
16	A Closer Look at Radiofrequency Pulses	375
16.1	Relating RF Fields and Measured Spin Density	376
16.1.1	RF Pulse Shapes and Apodization	378
16.2	Implementing Slice Selection	381
16.3	Calibrating the RF Field	383
16.3.1	Checking the RF Profile	384
16.4	Solutions of the Bloch Equations	387
16.4.1	Low Flip Angle Excitation and Rephasing Gradients	388
16.4.2	Dephasing and Rephasing at Large Flip Angles	390
16.5	Spatially Varying RF Excitation	393
16.5.1	Two-Dimensional 'Beam' Excitation	394
16.5.2	Time Varying Gradients and Slice Selection	397
16.5.3	An Example of Spatially Selective Excitations in the Low Flip Angle Limit	398
16.6	RF Pulse Characteristics: Flip Angle and RF Power	400
16.6.1	Analysis of Slice Selection Parameters	401
16.7	Spin Tagging	405
16.7.1	Tagging with Gradients Applied Between RF Pulses	405
16.7.2	Multiple RF and Gradient Pulses for Tagging	407
16.7.3	Summary of Tagging Applications	410
17	Water/Fat Separation Techniques	413
17.1	The Effect of Chemical Shift in Imaging	413
17.1.1	Fat Shift Artifact	414
17.2	Selective Excitation and Tissue Nulling	420
17.2.1	Fat Saturation	420
17.2.2	Selective Excitation	421

17.2.3	Tissue Nulling with Inversion Recovery	425
17.3	Multiple Point Water/Fat Separation Methods	428
17.3.1	Gradient Echo Sequence for Water/Fat Separation	428
17.3.2	Single-Echo Separation	433
17.3.3	Spin Echo Approach	436
17.3.4	Two-Point Separation	437
17.3.5	Three-Point Separation	440
18	Fast Imaging in the Steady State	447
18.1	Short- T_R , Spoiled, Gradient Echo Imaging	448
18.1.1	Expression for the Steady-State Incoherent (SSI) Signal	450
18.1.2	Contrast-to-noise efficiency for small changes in T_1	456
18.1.3	Approach to Incoherent Steady-State	460
18.1.4	Generating a Constant Transverse Magnetization	463
18.1.5	Nonideal Slice Profile Effects on the SSI Signal	465
18.2	Short- T_R , Coherent, Gradient Echo Imaging	468
18.2.1	Steady-State Free Precession: The Equilibrium Signal	472
18.2.2	Approach to Coherent Steady-State	476
18.2.3	Utility of SSC Imaging	479
18.3	SSFP Signal Formation Mechanisms	481
18.3.1	Magnetization Rotation Effects of an Arbitrary Flip Angle Pulse	481
18.3.2	Multi-Pulse Experiments and Echoes	484
18.4	Understanding Spoiling Mechanisms	498
18.4.1	General Principles of Spoiling	498
18.4.2	A Detailed Discussion of Spoiling	499
18.4.3	Practical Implementation of Spoiling	504
18.4.4	RF Spoiled SSI Sequence Implementation	508
19	Segmented k-Space and Echo Planar Imaging	511
19.1	Reducing Scan Times	512
19.1.1	Reducing T_R	512
19.1.2	Reducing the Number of Phase/Partition Encoding Steps	512
19.1.3	Fixing the Number of Acquisitions	514
19.1.4	Partial Fourier Data Acquisition	514
19.2	Segmented k -Space: Phase Encoding Multiple k -Space Lines per RF Excitation for Gradient Echo Imaging	514
19.2.1	Conventional Multiple Echo Acquisition	515
19.2.2	Phase Encoding Between Gradient Echoes	518
19.3	Echo Planar Imaging (EPI)	522
19.3.1	An In-Depth Analysis of the EPI Imaging Parameters	525
19.3.2	Signal-to-Noise	528
19.4	Alternate Forms of Conventional EPI	530
19.4.1	Nonuniform Sampling	531
19.4.2	Segmented EPI	531
19.4.3	Angled k -Space EPI	534

19.4.4	Segmented EPI with Oscillating Gradients	539
19.4.5	Trapezoidal Versus Oscillating Waveforms	541
19.5	Artifacts and Phase Correction	543
19.5.1	Phase Errors and Their Correction	543
19.5.2	Chemical Shift and Geometric Distortion	545
19.5.3	Geometric Distortion	546
19.5.4	T_2^* -Filter Effects	548
19.5.5	Ghosting	549
19.6	Spiral Forms of EPI	549
19.6.1	Square-Spiral EPI	549
19.6.2	Spiral EPI	553
19.7	An Overview of EPI Properties	556
19.7.1	Speed of EPI	556
19.7.2	Contrast Mechanisms	559
19.7.3	Field-of-View and Resolution in the Phase Encoding Direction	559
19.7.4	EPI Safety Issues	560
19.8	Phase Encoding Between Spin Echoes and Segmented Acquisition	560
19.9	Mansfield 2D to 1D Transformation Insight	563
19.9.1	Application of the Fourier Transform Shift Theorem	563
19.9.2	Collapsing the 2D Problem to a 1D Problem	566
20	Magnetic Field Inhomogeneity Effects and T_2^* Dephasing	569
20.1	Image Distortion Due to Field Effects	570
20.1.1	Distortion Due to Background Gradients Parallel to the Read Direction	570
20.1.2	Distortion Due to Gradient Perpendicular to the Read Direction	575
20.1.3	Slice Select Distortion	578
20.2	Echo Shifting Due to Field Inhomogeneities in Gradient Echo Imaging	580
20.2.1	Echo Shift in Terms of Number of Sampled Points	583
20.2.2	Echo Shift Due to Background Phase/Partition Encoding Gradients	585
20.2.3	Echo Shift Due to Background Gradients Parallel to the Slice Select Direction	586
20.2.4	Echo Shift Due to Background Gradients Orthogonal to the Slice Select Direction	587
20.3	Methods for Minimizing Distortion and Echo Shifting Artifacts	587
20.3.1	Distortion Versus Dephasing	587
20.3.2	High Resolution and Phase Dispersion	589
20.3.3	2D Imaging	591
20.3.4	2D Imaging with Variable Rephasing Gradients	593
20.3.5	3D Imaging	594
20.3.6	Phase Encoded 2D and 3D Imaging with Single-Point Sampling: A Limited Version of CSI	599
20.3.7	Spectrally Resolved 2D and 3D Imaging	601
20.3.8	Understanding the Recovered Signal with Spectral Collapsing	601

20.4	Empirical T_2^*	603
20.4.1	Arbitrariness of T_2^* Modeling of Gradient Echo Signal Envelopes . . .	603
20.4.2	The Spin Echo Signal Envelope and the Magnetic Field Density of States	604
20.4.3	Decaying Signal Envelopes and Integrated Signal Conservation	605
20.4.4	Obtaining a Lorentzian Density of States: A Simple Argument	609
20.4.5	Predicting the Effects of Arbitrary Field Inhomogeneities on the Image	610
20.5	Predicting T_2^* for Random Susceptibility Producing Structures	611
20.6	Correcting Geometric Distortion	615
21	Random Walks, Relaxation, and Diffusion	619
21.1	Simple Model for Intrinsic T_2	620
21.1.1	Gaussian Behavior for Random Spin Systems	620
21.1.2	Brownian Motion and T_2 Signal Loss	621
21.2	Simple Model for Diffusion	622
21.3	Carr-Purcell Mechanism	624
21.4	Meiboom-Gill Improvement	626
21.5	The Bloch-Torrey Equation	628
21.5.1	The Gradient Echo Case for a Bipolar Pulse	629
21.5.2	The Spin Echo Case	629
21.5.3	Velocity Compensated Diffusion Weighted Sequences	631
21.6	Some Practical Examples of Diffusion Imaging	632
22	Spin Density, T_1, and T_2 Quantification Methods in MR Imaging	637
22.1	Simplistic Estimates of ρ_0 , T_1 , and T_2	638
22.1.1	Spin Density Measurement	639
22.1.2	T_1 Measurement	639
22.1.3	T_2 Measurement	640
22.2	Estimating T_1 and T_2 from Signal Ratio Measurements	640
22.2.1	T_1 Estimation from a Signal Ratio Measurement	640
22.2.2	T_2 Estimation	646
22.3	Estimating T_1 and T_2 from Multiple Signal Measurements	647
22.3.1	Parameter Estimation from Multiple Signal Measurements	647
22.3.2	T_1 Estimation	648
22.3.3	T_2 and T_2^* Estimation	649
22.4	Other Methods for Spin Density and T_1 Estimation	649
22.4.1	The Look-Locker Method	650
22.4.2	T_1 Estimation from SSI Measurements at Multiple Flip Angles	653
22.5	Practical Issues Related to T_1 and T_2 Measurements	657
22.5.1	Inaccuracies Due to Nonideal Slice Profile	657
22.5.2	Other Sources of Inaccuracies in Relaxation Time and Spin Density Measurements	661
22.5.3	Advanced Sequence Design for Relaxation Time and Spin Density Measurements	663

22.5.4	Choice of Number of Signal Measurement Points	664
22.6	Calibration Materials for Relaxation Time Measurements	665
23	Motion Artifacts and Flow Compensation	669
23.1	Effects on Spin Phase from Motion along the Read Direction	670
23.1.1	Spin Phase Due to Constant Velocity Flow or Motion in the Read Direction	670
23.1.2	Effects of Constant Velocity Flow on the Image	673
23.2	Velocity Compensation along the Read and Slice Select Directions	675
23.2.1	Velocity Compensation Concepts	676
23.2.2	Velocity Compensation along the Slice Select Direction	681
23.3	Ghosting Due to Periodic Motion	683
23.3.1	Ghosting Due to Periodic Flow	683
23.3.2	Sinusoidal Translational Motion	683
23.3.3	Examples of Ghosting from Pulsatile Flow	687
23.4	Velocity Compensation along Phase Encoding Directions	688
23.4.1	Effects of Constant Velocity Flow in the Phase Encoding Direction: The Misregistration Artifact	688
23.4.2	Phase Variation View of the Shift Artifact	691
23.4.3	Velocity Compensating Phase Encoding Gradients	693
23.5	Maximum Intensity Projection	698
24	MR Angiography and Flow Quantification	701
24.1	Inflow or Time-of-Flight (TOF) Effects	702
24.1.1	Critical Speeds	702
24.1.2	Approach to Equilibrium	703
24.1.3	2D Imaging	704
24.1.4	3D Imaging	707
24.1.5	Understanding Inflow Effects for Small Velocities	709
24.2	TOF Contrast, Contrast Agents, and Spin Density/ T_2^* -Weighting	711
24.2.1	Contrast Agents	711
24.2.2	Suppressing Signal from Inflowing Blood Using an Inversion Pulse . .	714
24.2.3	Suppressing Signal from Inflowing Blood Using a Saturation Pulse . .	717
24.3	Phase Contrast and Velocity Quantification	719
24.3.1	Phase Subtraction and Complex Division for Measuring Velocity . . .	723
24.3.2	Four-Point Velocity Vector Extraction	729
24.4	Flow Quantification	730
24.4.1	Cardiac Gating	733
25	Magnetic Properties of Tissues: Theory and Measurement	739
25.1	Paramagnetism, Diamagnetism, and Ferromagnetism	740
25.1.1	Paramagnetism	740
25.1.2	Diamagnetism	741
25.1.3	Ferromagnetism	742
25.2	Permeability and Susceptibility: The \vec{H} Field	744

25.2.1	Permeability and the \vec{H} Field	744
25.2.2	Susceptibility	744
25.3	Objects in External Fields: The Lorentz Sphere	745
25.3.1	Spherical Body	747
25.3.2	Infinite Cylindrical Body	749
25.3.3	Local Field Cancellation via Molecular Demagnetization	751
25.3.4	Sphere and Cylinder Examples Revisited: The Physical Internal Fields	752
25.4	Susceptibility Imaging	755
25.4.1	Phase Measurements	755
25.4.2	Magnitude Measurements	758
25.5	Brain Functional MRI and the BOLD Phenomenon	760
25.5.1	Estimation of Oxygenation Levels	763
25.5.2	Deoxyhemoglobin Concentration and Flow	764
25.5.3	Functional MR Imaging (fMRI): An Example	765
25.6	Signal Behavior in the Presence of Deoxygenated Blood	766
25.6.1	The MR Properties of Blood	767
25.6.2	Two-Compartment Partial Volume Effects on Signal Loss	768
26	Sequence Design, Artifacts, and Nomenclature	779
26.1	Sequence Design and Imaging Parameters	780
26.1.1	Slice Select Gradient	780
26.1.2	Phase Encoding Gradient	783
26.1.3	Read Gradient	784
26.1.4	Data Sampling	785
26.2	Early Spin Echo Imaging Sequences	785
26.2.1	Single and Multi-Echo Spin Echo Sequences	785
26.2.2	Inversion Recovery	788
26.2.3	Spin Echo with Phase Encoding Between Echoes	789
26.3	Fast Short T_R Imaging Sequences	791
26.3.1	Steady-State Incoherent: Gradient Echo	791
26.3.2	Steady-State Incoherent: Spin Echo	793
26.3.3	Steady-State Coherent Imaging	793
26.3.4	Pulse Train Methods	796
26.3.5	Magnetization Prepared Sequences	797
26.4	Imaging Tricks and Image Artifacts	798
26.4.1	Readout Bandwidth	799
26.4.2	Dealing with System Instabilities	801
26.4.3	DC and Line Artifacts	806
26.4.4	Noise Spikes and Constant-Frequency Noise	809
26.5	Sequence Adjectives and Nomenclature	812
26.5.1	Nomenclature	812
26.5.2	Some Other Descriptive Adjectives and Some Specific Examples	817
27	Introduction to MRI Coils and Magnets	823
27.1	The Circular Loop as an Example	824

27.1.1	Quality of Field	826
27.2	The Main Magnet Coil	827
27.2.1	Classic Designs	827
27.2.2	Desirable Properties of Main Magnets	833
27.2.3	Shielding	836
27.2.4	Shimming	837
27.3	Linearly Varying Field Gradients	838
27.3.1	Classic Designs	838
27.3.2	Calculating Linearly Varying Fields	840
27.3.3	Desirable Properties of Linear Gradient Coils	841
27.3.4	Eddy Currents and dB/dt	842
27.3.5	Active Shielding	844
27.3.6	'Linearly Varying' Magnetic Fields	844
27.4	RF Transmit and Receive Coils	846
27.4.1	Transmit Coils	847
27.4.2	Receive Coils or RF Probes	848
27.4.3	Classic Designs	849
27.4.4	RF Shielding	854
27.4.5	Power Deposition	854
28	Parallel Imaging	859
28.1	Coil Signals, Their Images, and a One-Dimensional Test Case	860
28.1.1	Continuous and Discrete Pairs of Transforms for Multiple Coils	861
28.1.2	Supplanting Some Gradient Data with RF Coil Data: A Preview	862
28.1.3	A Two-Step Function Example	863
28.1.4	Aliasing for the Two-Step Function Example	863
28.2	Parallel Imaging with an x -Space Approach	865
28.2.1	Perfect Coil Sensitivities	866
28.2.2	More Realistic Sensitivities and SENSE	867
28.3	Parallel Imaging with a k -Space Approach	873
28.3.1	Known Sensitivities and SMASH	873
28.3.2	Unknown Sensitivities: AUTO-SMASH and GRAPPA	877
28.4	Noise and the g -Factor	885
28.4.1	SNR and g -Factor Derivation	885
28.4.2	g -Factor Example	887
28.5	Additional Topics in Acquisition and Reconstruction	888
28.5.1	Parallel Transmit Coils	888
28.5.2	Interpolation, Extrapolation, and Randomization	889
A	Electromagnetic Principles: A Brief Overview	893
A.1	Maxwell's Equations	894
A.2	Faraday's Law of Induction	894
A.3	Electromagnetic Forces	895
A.4	Dipoles in an Electromagnetic Field	896

A.5	Formulas for Electromagnetic Energy	896
A.6	Static Magnetic Field Calculations	897
B	Statistics	899
B.1	Accuracy Versus Precision	899
	B.1.1 Mean and Standard Deviation	900
B.2	The Gaussian Probability Distribution	901
	B.2.1 Probability Distribution	901
	B.2.2 z-Score	901
	B.2.3 Quoting Errors and Confidence Intervals	902
B.3	Type I and Type II Errors	902
B.4	Sum over Several Random Variables	904
	B.4.1 Multiple Noise Sources	905
B.5	Rayleigh Distribution	906
B.6	Experimental Validation of Noise Distributions	907
	B.6.1 Histogram Analysis	907
	B.6.2 Mean and Standard Deviation	909
C	Imaging Parameters to Accompany Figures	913
	Index	923