
Contents

1	Introduction	1
1.1	MPI in the Context of Medical Imaging.....	1
1.2	Historical Perspective	3
1.3	Structure of the Book.....	8
2	How Magnetic Particle Imaging Works	11
2.1	Introduction	11
2.2	Magnetic Particles	12
2.2.1	Particle Concentration	12
2.2.2	Particle Magnetization	14
2.2.3	Derivative of the Magnetization Characteristic	18
2.2.4	Mean Magnetic Moment	20
2.2.5	Particle Size Distribution.....	21
2.2.6	Relaxation Effects	22
2.3	Signal Generation and Acquisition	25
2.3.1	Signal Reception.....	25
2.3.2	Direct Coupling of Excitation Field	28
2.3.3	Signal Generation.....	29
2.3.4	Signal Spectrum	32
2.3.5	Excitation Frequency and Field Strength.....	35
2.4	Spatial Encoding: Selection Field	36
2.4.1	Particle Selection	36
2.4.2	Sampling of Volumes.....	38
2.4.3	Properties of the Selection Field	39
2.5	Performance Upgrade: Drive Field	40
2.5.1	Moving the Field-Free Point	40
2.5.2	How to Move the Field-Free Point Nonmechanically	41
2.5.3	Drive-Field Waveform.....	42
2.5.4	Individual Signals	44
2.5.5	Convolution with the FFP Kernel.....	47
2.5.6	2D/3D Imaging	49
2.6	Performance Upgrade: Focus Field	58
2.6.1	Limitations of the Drive Field	59
2.6.2	Scanning Large Volumes Using the Focus Field	59

2.7	Limitations of MPI	61
2.7.1	Spatial Resolution	61
2.7.2	Sensitivity and Temporal Resolution	68
2.7.3	Detection Limit	69
3	How to Build an MPI Scanner	71
3.1	Introduction	71
3.2	Magnetic Field Generation	71
3.2.1	Electromagnetic Coils	72
3.2.2	Soft-Magnetic Iron Cores	72
3.2.3	Permanent Magnets	73
3.2.4	Skin Effect and Litz Wire	74
3.2.5	Generating Homogeneous Magnetic Fields	76
3.2.6	Generating Magnetic Gradient Fields	78
3.3	Generic MPI Coil Configuration	81
3.3.1	Generating the Selection and Focus Field	82
3.3.2	Generating the Drive Field	83
3.3.3	Receiving the Particle Magnetization	84
3.3.4	Sharing Coils	85
3.4	Generic MPI Signal Chain	86
3.4.1	Signal Separation	87
3.4.2	Overview of the 3D Signal Chain	89
3.4.3	Impedance Matching	90
3.4.4	Analog Filter	93
4	Prior to Reconstruction – The System Function	97
4.1	Introduction	97
4.2	Signal Equation in Time Space	97
4.3	Signal Equation in Frequency Space	99
4.3.1	Transfer Function	99
4.3.2	Energy of the System Function	100
4.3.3	Spatial Structure of the System Function	100
4.4	1D System Function	101
4.4.1	Ideal Particles	102
4.4.2	Langevin Particles	102
4.5	2D System Function	105
4.5.1	Spatial Structure of the 2D System Function	105
4.5.2	Energy of the 2D System Function	107
4.5.3	Nonlinear Frequency Mixing	108
4.5.4	Similarity to Tensor Products of Chebyshev Polynomials	111
4.5.5	Orthogonality	112
4.6	3D System Function	113
4.7	Discrete Signal Equation	113
4.7.1	Sampling of Time	113
4.7.2	Sampling of Space	115
4.7.3	Discretization of the Signal Equation	116

4.8	How to Determine the System Function	118
4.8.1	Measurement-Based Approach	119
4.8.2	Model-Based Approach	122
4.8.3	Comparison of Measured and Modeled System Functions ..	123
5	From Data to Images: Reconstruction	127
5.1	Introduction	127
5.2	Least-Squares Solution	128
5.2.1	Statistical Motivation	129
5.2.2	Weighted Least-Squares Solution	130
5.3	Discrete Ill-Posed Problems	131
5.4	Regularization Methods	132
5.4.1	Singular Value Decomposition	133
5.4.2	Choice of the Regularization Parameter	135
5.4.3	Complexity Analysis	137
5.4.4	Inverse Crime	139
5.5	Choosing the Weighting Matrix	139
5.5.1	Unit Weights	140
5.5.2	Row Normalization Weights	140
5.5.3	Removing Noisy Frequency Components	140
5.6	Iterative Solvers	141
5.6.1	Conjugate Gradient Normal Residual	142
5.6.2	Kaczmarz Method	144
5.6.3	Regularization by Stopping the Iteration Process	145
5.6.4	Convergence Speed of Iterative Solvers	146
5.6.5	Physical Constraints	147
6	Special System Topologies	149
6.1	Introduction	149
6.2	Single-Sided Imaging	149
6.2.1	Basic Principle	150
6.2.2	Multidimensional Imaging	153
6.2.3	Experiments	155
6.3	Field-Free Line Imaging	157
6.3.1	Static Field-Free Line Imaging	161
6.3.2	Dynamic Field-Free Line Imaging	165
6.4	MPI/MRI Hybrid Systems	169
7	Putting MPI to Use: Applications	171
7.1	Introduction	171
7.2	Cardiovascular	171
7.3	Oncology, Sentinel Lymph Node Imaging, and Hyperthermia	174
7.4	Cell Labeling and Tracking	175
7.4.1	Red Blood Cell Labeling	175
7.4.2	Stem Cell Labeling	175
7.5	Gastrointestinal and Lung Imaging	176

A	Fundamentals of Electromagnetism	177
A.1	Introduction	177
A.2	Maxwell's Equations	177
A.2.1	Constitutive Relations	179
A.2.2	Bound Currents	180
A.2.3	Quasi-static Approximation	181
A.2.4	Time-Independent Current Distribution	182
A.3	Magnetic Fields	182
A.3.1	Magnetic Vector Potential	183
A.3.2	Biot-Savart Law	185
A.3.3	Coil Sensitivity	185
A.4	Electromagnetic Induction	186
A.4.1	Single-Wire Coil	187
A.4.2	Volume Coil	188
A.4.3	Law of Reciprocity	188
A.4.4	Coil Coupling	189
	References	191
	Index	199