

Contents in Detail

Preface	V
Introduction.	1
1 Physical and Technical Background	11
1.1 Nuclear Magnetic Resonance	12
1.1.1 Physical Principles.....	12
1.1.2 Main Magnetic Field.....	14
<i>a) Main Magnet</i>	15
<i>b) Polarization</i>	15
<i>c) Precession</i>	17
<i>d) Relaxation and the Bloch Equations</i>	18
<i>e) Rotating Frame Formalism</i>	18
1.1.3 RF Excitation.....	18
<i>a) RF-Transmit System</i>	19
<i>b) Excitation</i>	19
1.1.4 NMR Signal Detection	21
<i>a) RF-Detection System</i>	21
<i>b) Free Induction Decay</i>	21
<i>c) Signal-to-Noise Ratio</i>	23
1.2 Magnetic Resonance Imaging.....	25
1.2.1 The Gradients.....	25
1.2.2 Gradient Encoding: Signal Equation for a Single Receiver Coil.....	27
1.2.3 Slice Selection.....	32
1.2.4 Basic Imaging Sequences	33
<i>a) Gradient Echo</i>	33
<i>b) Spin Echo</i>	34
1.3 Parallel Imaging.....	35
1.3.1 RF-Receiver Array	35
1.3.2 Implications of Parallel Imaging.....	36
<i>a) Increased SNR</i>	37

b) Acceleration of MR Measurements	37
c) Further Applications	37
1.3.3 Signal Equation for Several Receiver Coils	38
2 Image Reconstruction in MRI	39
2.1 Basics of Linear Image Reconstruction	40
2.1.1 Fundamental Reconstruction Algorithms.....	40
a) Weak Matrix Approach.....	42
b) Strong Matrix Approach	45
c) Relationship Between Weak and Strong Reconstruction ...	45
d) Conclusion	47
2.1.2 Determination of the Encoding Matrix	48
a) Gradient Encoding.....	48
b) Sensitivity Encoding	48
2.1.3 Image Resolution and Aliasing Artifacts.....	50
2.1.4 Signal-to-Noise Ratio.....	52
2.1.5 SNR-Optimized Reconstructions.....	56
2.2 Image Reconstruction from a Single Receiver Coil.....	57
2.2.1 Standard Cartesian Method	58
a) Image Reconstruction	58
b) Conformity with Linear Reconstruction Theory.....	58
c) Image Properties	60
d) Conclusion	65
2.2.2 Reconstruction Methods for Radial Imaging	66
a) Direct Matrix Inversion.....	67
b) Filtered Back-Projection	68
2.2.3 Further Non-Cartesian Methods	69
2.3 Image Reconstruction from Several Receiver Coils	72
2.3.1 Image Space Reconstruction	74
a) Cartesian SENSE (<u>SENS</u> itivity <u>ENC</u> oding).....	74
b) Image Resolution and Aliasing Artifacts.....	79
c) Image Noise	80
d) Ultimate SNR.....	82
e) Superresolution Reconstruction	86
f) Non-Cartesian Methods.....	89
2.3.2 <i>k</i> -Space Reconstruction	96
a) GRAPPA (<u>Gene</u> Ralized <u>A</u> utocalibrating <u>P</u> artially <u>Parallel Acquisitions</u>).....	97

<i>b) Relationship of GRAPPA and SENSE</i>	99
3 Overview of PatLoc Imaging and Presentation of Initial Hardware Designs	103
3.1 The Concept	103
3.2 Applications	106
3.2.1 Background: New Encoding Options.....	106
3.2.2 Improved Encoding Efficiency.....	107
3.2.3 Reduction of Peripheral Nerve Stimulation	114
3.2.4 Applications Involving Nonlinear Phase Preparation ...	116
<i>a) GradLoc: Reduced Field-of-View-Imaging</i>	117
<i>b) STAGES: Dynamic Intra-Slice Shimming</i>	119
3.2.5 Summary	121
3.3 Initial Experimental Setups	121
3.3.1 Multipolar Encoding Fields	122
3.3.2 Animal System	124
3.3.3 Human System	126
Contributions of this Thesis and Current State of Research . . .	133
4 Basics of Signal Encoding and Image Reconstruction in PatLoc Imaging	135
4.1 The Fundamental Signal Model for PatLoc Imaging.....	135
4.2 Basics of Linear Image Reconstruction in PatLoc Imaging.....	140
4.2.1 A Simple 1D Example	140
4.2.2 Matrix Inversion Approaches in PatLoc.....	144
<i>a) Extension to Non-Rectilinear Reconstruction Grids</i>	146
<i>b) Nominal Voxel Volume</i>	148
<i>c) Analysis of Fundamental Image Properties</i>	151
4.2.3 Consequences of Non-Rectilinear Reconstruction Grids for Iterative Reconstruction.....	152
4.2.4 Tailoring Reconstruction to Specific Encoding Strategies: An Outline.....	153
5 Direct Reconstruction for Cartesian PatLoc Imaging	155
5.1 Direct Image Space Reconstruction	155
5.1.1 Theory	156
<i>a) General Matrix Inversion Approach</i>	157
<i>b) Cartesian PatLoc Reconstruction Algorithm</i>	160

c) <i>Equivalent Fourier Transform Approach</i>	163
d) <i>Reconstruction with Multipolar Encoding Fields</i>	165
e) <i>Basic Image Properties</i>	168
5.1.2 <i>Methods</i>	177
a) <i>Simulations</i>	177
b) <i>Experiments</i>	177
c) <i>Determination of the Encoding Fields</i>	178
5.1.3 <i>Results</i>	180
a) <i>Simulations</i>	180
b) <i>Experiments</i>	189
5.1.4 <i>Discussion</i>	191
5.1.5 <i>Conclusions</i>	194
5.2 <i>Direct k-Space Reconstruction</i>	195
5.2.1 <i>Physical Limitation: Calibration Data</i>	195
5.2.2 <i>Applicability to Subsampled PatLoc k-Space Data</i>	198
5.2.3 <i>Discussion</i>	203
5.2.4 <i>Conclusions</i>	206
6 <i>Direct Reconstruction for Radial PatLoc Imaging</i>	207
6.1 <i>Presentation of Image Reconstruction Methods</i>	209
6.1.1 <i>Signal Equation in Radial PatLoc Imaging</i>	210
6.1.2 <i>Interpretation of PatLoc Projection Data</i>	211
6.1.3 <i>Reconstruction from Projection Data with Arbitrary</i> <i>Encoding Fields</i>	213
6.1.4 <i>Reconstruction from Projection Data with Multipolar</i> <i>Encoding Fields</i>	215
a) <i>Reconstruction Algorithm</i>	215
b) <i>Image Properties</i>	218
6.2 <i>Application to Simulated and Measured Imaging Data</i>	219
6.2.1 <i>Methods</i>	219
a) <i>Simulations</i>	219
b) <i>Experiments</i>	220
c) <i>Reconstruction</i>	222
6.2.2 <i>Results</i>	223
a) <i>Radial Images with Linear and Quadrupolar Fields</i>	223
b) <i>PSF and Noise Analysis</i>	225
c) <i>Reconstruction from Undersampled Datasets</i>	226

6.3	Evaluation	227
6.3.1	Reconstruction Algorithms.....	227
	<i>a) Arbitrary Encoding Fields</i>	227
	<i>b) Multipolar Encoding Fields</i>	228
6.3.2	Influence of Field Approximations.....	229
6.3.3	Image Properties and Artifacts	229
6.3.4	Generalizations Beyond Multipolar Field Encoding and Projection Reconstruction	232
6.3.5	Conclusions.....	233
7	Iterative Reconstruction in PatLoc Imaging	235
7.1	Presentation of Image Reconstruction Methods	236
7.1.1	Reconstruction in the Time Domain	237
7.1.2	Reconstruction from Generalized Image Projections in the Frequency Domain.....	240
7.1.3	Fast Reconstruction with Non-Uniform FFT Algorithms	247
7.2	Application to Simulated and Measured Imaging Data	252
7.2.1	Methods	253
	<i>a) Reconstruction Algorithms</i>	253
	<i>b) Data</i>	254
	<i>c) Image Quality Analysis</i>	255
7.2.2	Results	255
	<i>a) Cartesian PatLoc Trajectory</i>	256
	<i>b) Radial PatLoc Trajectory</i>	259
	<i>c) Multi-Dimensional PatLoc Trajectory</i>	264
7.3	Evaluation	268
7.3.1	Image Properties: Encoding and Reconstruction	268
7.3.2	“Gold Standard”: Time-Domain Reconstruction	270
7.3.3	Methods to Accelerate Image Reconstruction	271
7.3.4	Beyond Matrix Inversion Approaches.....	273
7.3.5	Conclusions.....	275
8	Summary and Outlook	277
8.1	Summary.....	277
8.2	Ongoing and Future Research	285

A Appendix. 289

 A.1 Notation and Abbreviations 289

 A.1.1 Notation 289

 A.1.2 Abbreviations 292

 A.2 Kronecker Product 293

 A.3 On the Relationship Between GRAPPA and SENSE 294

 A.3.1 Equivalent Formulation of the Weak Reconstruction
 Condition 295

 A.3.2 Truncation of the Encoding Matrix 297

 A.4 Significance of Multipolar Magnetic Fields for Spatial
 Encoding 299

 A.5 Local k -Space: Image Resolution and Relation to PatLoc
 k -Space 303

 A.5.1 Theoretical Background Concerning Image
 Resolution 303

 A.5.2 Relation to PatLoc k -Space 305

Bibliography 307

Publications. 329

<http://www.springer.com/978-3-658-01133-8>

Magnetic Resonance Imaging with Nonlinear Gradient
Fields

Signal Encoding and Image Reconstruction

Schultz, G.

2013, XVI, 333 p. 93 illus., 27 illus. in color., Softcover

ISBN: 978-3-658-01133-8