

Contents

Preface and acknowledgements — IX

1 Introduction — 1

- 1.1 X-ray radiography as an example — 1
- 1.2 Summary of biomedical techniques covered herein — 4

2 Digital image processing — 6

- 2.1 Image representation and point operations — 6
- 2.2 Geometric transformations and interpolation — 11
- 2.3 Convolution and filtering — 13
 - 2.3.1 Linear filters — 13
 - 2.3.2 Filtering in Fourier space — 18
 - 2.3.3 Nonlinear or rank filters — 18
- 2.4 The Hough transform — 23
- 2.5 Theory of linear imaging systems — 25
 - 2.5.1 Introduction and definitions — 25
 - 2.5.2 Point spread function (PSF) — 27
 - 2.5.3 Modulation transfer function (MTF) — 28
 - 2.5.4 Example: cosine grating and Gaussian PSF — 30
 - 2.5.5 Measurement of PSF and MTF — 31
- 2.6 Measures of image quality — 33
 - 2.6.1 Contrast — 33
 - 2.6.2 Resolution — 35
 - 2.6.3 Image noise — 39
 - 2.6.4 Power spectral density — 42
- 2.7 Fourier transformation: fundamentals — 45
 - 2.7.1 Definitions and notations — 45
 - 2.7.2 Properties and examples of Fourier pairs — 48
- 2.8 Digital data and sampling — 51
 - 2.8.1 Sampling continuous functions — 51
 - 2.8.2 The sampling theorem — 53
 - 2.8.3 Discrete Fourier transformation (DFT) — 55

References — 59

Symbols and abbreviations used in Chapter 2 — 60

3	Essentials of medical x-ray physics — 61
3.1	Electromagnetic spectrum — 61
3.2	Interactions of x-rays and matter — 62
3.2.1	Beer–Lambert law — 63
3.2.2	Differential and integral cross sections — 66
3.2.3	Photoelectric absorption — 69
3.2.4	Thomson scattering — 74
3.2.5	Compton scattering — 83
3.2.6	Pair production and annihilation — 87
3.2.7	Photonuclear reactions — 89
3.3	Generation of x-rays — 90
3.3.1	Bremsstrahlung spectrum of an x-ray tube — 92
3.3.2	Characteristic spectrum of an x-ray tube — 96
3.3.3	Synchrotron radiation — 96
3.4	Detection of x-rays — 100
3.5	Statistics of counting x-ray and gamma quanta — 103
3.6	Summary and implications for clinical applications — 105
	References — 108
	Symbols and abbreviations used in Chapter 3 — 109

4	Tomography — 111
4.1	Tomography in a nutshell — 111
4.2	Mathematical fundamentals of tomography — 120
4.2.1	Radon transformation (RT) — 120
4.2.2	Fourier slice theorem (FST) — 121
4.2.3	Backprojection operator — 123
4.2.4	General inversion formula — 124
4.2.5	Different reconstruction methods by choice of α — 125
4.2.6	Dimensionality of reconstruction and relation to the Hilbert transform — 126
4.2.7	Reconstruction as a convolution problem — 129
4.2.8	Problems of discretization and speed — 131
4.3	Reconstruction based on Chebyshev series and orthogonal polynomial expansion — 132
4.3.1	Chebyshev polynomials — 133
4.3.2	Chebyshev backprojection — 134
4.3.3	Chebyshev expansion — 136
4.4	Tomographic projection geometries — 140
4.4.1	X-ray transform, Fresnel scaling theorem and cone beam reconstruction — 142
4.4.2	Tomography based on the 3d Radon transform — 148

- 4.5 Tomography artifacts and algebraic reconstruction — **153**
- 4.5.1 Tomography artifacts and corrections — **154**
- 4.5.2 Algebraic reconstruction techniques (ART) and Helgason–Ludwig consistency conditions — **161**

References — **164**

Symbols and abbreviations used in Chapter 4 — **167**

5 Radiobiology, radiotherapy, and radiation protection — 168

- 5.1 Interactions of ionizing particles with matter — **168**
 - 5.1.1 Introductory remarks — **168**
 - 5.1.2 Energy transfer from photons to charged secondary particles — **172**
 - 5.1.3 Energy loss of charged particles in matter — **175**
- 5.2 Dose calculation and measurement — **187**
 - 5.2.1 Analytical example: proton Bragg peak — **188**
 - 5.2.2 Algorithms for external photon beams — **191**
 - 5.2.3 Principles of ionization dosimetry — **198**
- 5.3 Radiobiology — **204**
 - 5.3.1 The cell cycle — **204**
 - 5.3.2 Ionizing radiation and biological organisms — **206**
 - 5.3.3 Radiation damage to DNA — **208**
 - 5.3.4 Linear energy transfer and relative biological effectiveness — **212**
 - 5.3.5 Cell survival after irradiation: linear quadratic model — **215**
- 5.4 Fundamentals of radiotherapy — **218**
 - 5.4.1 Motivation — **219**
 - 5.4.2 Steps in radiotherapy — **219**
 - 5.4.3 Radiation modalities and treatment techniques — **221**
 - 5.4.4 Fractionation — **224**
 - 5.4.5 Tumor control and normal tissue complication probability — **227**
- 5.5 Elements of radiation protection — **230**
 - 5.5.1 Deterministic and stochastic effects — **230**
 - 5.5.2 Equivalent and effective dose — **232**
 - 5.5.3 Natural and man made radiation exposure — **237**

References — **238**

Symbols and abbreviations used in Chapter 5 — **241**

6 Phase contrast radiography — 244

- 6.1 Radiography beyond geometrical optics — **245**
 - 6.1.1 Limits of geometrical optics — **245**
 - 6.1.2 The x-ray index of refraction and phase shift in matter — **247**
- 6.2 Wave equations and coherence — **250**
 - 6.2.1 The stationary wave equation and diffraction integrals — **250**
 - 6.2.2 The optical far field and the phase problem — **258**

6.2.3	Coherence —	263
6.2.4	Paraxial wave equation (parabolic wave equation) —	270
6.2.5	Projection approximation of the object transmission function —	274
6.3	Propagation imaging —	277
6.3.1	The illumination wavefront: cone beam and plane wave —	277
6.3.2	Contrast transfer by free space propagation —	281
6.3.3	Transport of intensity equation (TIE) —	284
6.3.4	Propagation imaging in the TIE regime —	285
6.3.5	Propagation imaging in the holographic regime —	289
6.3.6	Iterative algorithms for reconstruction —	292
6.4	Grating based phase contrast —	300
6.4.1	Refraction, wavefront tilts and phase gradient —	302
6.4.2	Talbot effect and grating based x-ray phase imaging —	303
6.4.3	Talbot effect with object in the beam path —	306
6.4.4	Coded apertures —	311

References — 314

Symbols and abbreviations used in Chapter 6 — 318

7 Object reconstruction under nonideal conditions — 321

7.1	Inverse problems —	321
7.1.1	Regularization techniques for inverse problems —	321
7.1.2	Maximum likelihood approach —	325
7.1.3	Bayesian inference techniques —	328
7.2	Reconstruction of two-dimensional images —	330
7.2.1	Images as Markov random fields —	331
7.2.2	Image deconvolution by the Wiener filter —	336
7.2.3	Total variation denoising —	339

References — 341

Symbols and abbreviations used in Chapter 7 — 342

Index — 343