Contents

1 General image characteristics, data acquisition and image reconstruction 1

1.1 Introduction 1
1.2 Specificity, sensitivity and the receiver operating characteristic (ROC) curve 2
1.3 Spatial resolution 5
1.3.1 Spatial frequencies 5
1.3.2 The line spread function 6
1.3.3 The point spread function. 7
1.3.4 The modulation transfer function 8
1.4 Signal-to-noise ratio 10
1.5 Contrast-to-noise ratio 12
1.6 Image filtering 12
1.7 Data acquisition: analogue-to-digital converters 15
1.7.1 Dynamic range and resolution 16
1.7.2 Sampling frequency and bandwidth 18
1.7.3 Digital oversampling 19
1.8 Image artifacts 20
1.9 Fourier transforms 20
1.9.1 Fourier transformation of time- and spatial frequency-domain signals 21
1.9.2 Useful properties of the Fourier transform 22
1.10 Backprojection, sinograms and filtered backprojection 24
1.10.1 Backprojection 26
1.10.2 Sinograms 27
1.10.3 Filtered backprojection 27
Exercises 30

2 X-ray planar radiography and computed tomography 34

2.1 Introduction 34
2.2 The X-ray tube 36
2.3 The X-ray energy spectrum 40

2.4	Interactions of X-rays with the body	42
	2.4.1 Photoelectric attenuation	42
	2.4.2 Compton scattering	43
2.5	X-ray linear and mass attenuation coefficients	45
2.6	Instrumentation for planar radiography	47
	2.6.1 Collimators	48
	2.6.2 Anti-scatter grids	48
2.7	X-ray detectors	50
	2.7.1 Computed radiography	50
	2.7.2 Digital radiography	52
2.8	Quantitative characteristics of planar X-ray images	54
	2.8.1 Signal-to-noise	54
	2.8.2 Spatial resolution	57
	2.8.3 Contrast-to-noise	58
2.9	X-ray contrast agents	59
	2.9.1 Contrast agents for the GI tract	59
	2.9.2 Iodine-based contrast agents	60
2.10	Specialized X-ray imaging techniques	61
	2.10.1 Digital subtraction angiography	61
	2.10.2 Digital mammography	62
	2.10.3 Digital fluoroscopy	63
2.11	Clinical applications of planar X-ray imaging	64
2.12	Computed tomography	66
	2.12.1 Spiral/helical CT	67
	2.12.2 Multi-slice spiral CT	68
2.13	Instrumentation for CT	68
	2.13.1 Instrumentation development for helical CT	69
	2.13.2 Detectors for multi-slice CT	70
2.14	Image reconstruction in CT	71
	2.14.1 Filtered backprojection techniques	71
	2.14.2 Fan beam reconstructions	73
	2.14.3 Reconstruction of helical CT data	73
	2.14.4 Reconstruction of multi-slice helical CT scans	74
	2.14.5 Pre-processing data corrections	74
2.15	Dual-source and dual-energy CT	75
2.16	Digital X-ray tomosynthesis	76
2.17	Radiation dose	77
2.18	Clinical applications of CT	80
	2.18.1 Cerebral scans	80
	2.18.2 Pulmonary disease	81
	2.18.3 Liver imaging	81
	2.18.4 Cardiac imaging	82
Exercises		83

3 Nuclear medicine: Planar scintigraphy, SPECT and PET/CT 89

3.1 Introduction 89
3.2 Radioactivity and radiotracer half-life 91
3.3 Properties of radiotracers for nuclear medicine 92
3.4 The technetium generator 93
3.5 The distribution of technetium-based radiotracers within the body 96
3.6 The gamma camera 97
3.6.1 The collimator 97
3.6.2 The detector scintillation crystal and coupled photomultiplier tubes 100
3.6.3 The Anger position network and pulse height analyzer 103
3.6.4 Instrumental dead time 106
3.7 Image characteristics 108
3.8 Clinical applications of planar scintigraphy 109
3.9 Single photon emission computed tomography (SPECT) 110
3.10 Data processing in SPECT 112
3.10.1 Scatter correction 112
3.10.2 Attenuation correction 114
3.10.3 Image reconstruction 115
3.11 SPECT/CT 116
3.12 Clinical applications of SPECT and SPECT/CT 117
3.12.1 Myocardial perfusion 117
3.12.2 Brain SPECT and SPECT/CT 120
3.13 Positron emission tomography (PET) 121
3.14 Radiotracers used for PET/CT 123
3.15 Instrumentation for PET/CT 124
3.15.1 Scintillation crystals 125
3.15.2 Photomultiplier tubes and pulse height analyzer 127
3.15.3 Annihilation coincidence detection 127
3.16 Two-dimensional and three-dimensional PET imaging 129
3.17 PET/CT 130
3.18 Data processing in PET/CT 131
3.18.1 Attenuation correction 131
3.18.2 Corrections for accidental and multiple coincidences 131
3.18.3 Corrections for scattered coincidences 133
3.18.4 Corrections for dead time 134
3.19 Image characteristics 134
3.20 Time-of-flight PET 135
3.21 Clinical applications of PET/CT 137
3.21.1 Whole-body PET/CT scanning 137

3.21.2 PET/CT applications in the brain 137
3.21.3 Cardiac PET/CT studies 139
Exercises 139

4 Ultrasound imaging 145

4.1 Introduction 145
4.2 Wave propagation and characteristic acoustic impedance 146
4.3 Wave reflection, refraction and scattering in tissue 149
4.3.1 Reflection, transmission and refraction at tissue boundaries 149
4.3.2 Scattering by small structures 152
4.4 Absorption and total attenuation of ultrasound energy in tissue 153
4.4.1 Relaxation and classical absorption 154
4.4.2 Attenuation coefficients 155
4.5 Instrumentation 156
4.6 Single element ultrasound transducers 157
4.6.1 Transducer bandwidth 159
4.6.2 Beam geometry and lateral resolution 161
4.6.3 Axial resolution 163
4.6.4 Transducer focusing 163
4.7 Transducer arrays 165
4.7.1 Linear arrays 166
4.7.2 Phased arrays 167
4.7.3 Beam-forming and steering via pulse transmission for phased arrays 168
4.7.4 Analogue and digital receiver beam-forming for phased arrays 171
4.7.5 Time-gain compensation 172
4.7.6 Multi-dimensional arrays 173
4.7.7 Annular arrays 174
4.8 Clinical diagnostic scanning modes 175
4.8.1 A-mode scanning: ophthalmic pachymetry 175
4.8.2 M-mode echocardiography 175
4.8.3 Two-dimensional B-mode scanning 176
4.8.4 Compound scanning 177
4.9 Image characteristics 178
4.9.1 Signal-to-noise 178
4.9.2 Spatial resolution 178
4.9.3 Contrast-to-noise 179
4.10 Doppler ultrasound for blood flow measurements 179
4.10.1 Pulsed wave Doppler measurements 181
4.10.2 Duplex and triplex image acquisition 182

4.10.3 Aliasing in pulsed wave Doppler imaging 184
4.10.4 Power Doppler 186
4.10.5 Continuous-wave Doppler measurements 186
4.11 Ultrasound contrast agents 187
4.11.1 Microbubbles 187
4.11.2 Harmonic and pulse inversion imaging 190
4.12 Safety guidelines in ultrasound imaging 191
4.13 Clinical applications of ultrasound 193
4.13.1 Obstetrics and gynaecology 193
4.13.2 Breast imaging 194
4.13.3 Musculoskeletal structure 194
4.13.4 Echocardiography 195
4.14 Artifacts in ultrasound imaging 196
Exercises 197

5 Magnetic resonance imaging (MRI) 204

5.1 Introduction 204
5.2 Effects of a strong magnetic field on protons in the body 205
5.2.1 Proton energy levels 206
5.2.2 Classical precession 209
5.3 Effects of a radiofrequency pulse on magnetization 211
5.3.1 Creation of transverse magnetization 212
5.4 Faraday induction: the basis of MR signal detection 213
5.4.1 MR signal intensity 214
5.4.2 The rotating reference frame 214
5.5 T_1 and T_2 relaxation times 215
5.6 Signals from lipid 219
5.7 The free induction decay 220
5.8 Magnetic resonance imaging 221
5.9 Image acquisition 223
5.9.1 Slice selection 223
5.9.2 Phase encoding 226
5.9.3 Frequency encoding 228
5.10 The k-space formalism and image reconstruction 229
5.11 Multiple-slice imaging 231
5.12 Basic imaging sequences 233
5.12.1 Multi-slice gradient echo sequences 233
5.12.2 Spin echo sequences 234
5.12.3 Three-dimensional imaging sequences 237
5.13 Tissue relaxation times 239
5.14 MRI instrumentation 241
5.14.1 Superconducting magnet design 241

5.14.2 Magnetic field gradient coils 244
5.14.3 Radiofrequency coils 247
5.14.4 Receiver design 250
5.15 Parallel imaging using coil arrays 252
5.16 Fast imaging sequences 254
5.16.1 Echo planar imaging 255
5.16.2 Turbo spin echo sequences 256
5.17 Magnetic resonance angiography 257
5.18 Functional MRI 259
5.19 MRI contrast agents 261
5.19.1 Positive contrast agents 261
5.19.2 Negative contrast agents 263
5.20 Image characteristics 264
5.20.1 Signal-to-noise 264
5.20.2 Spatial resolution 265
5.20.3 Contrast-to-noise 266
5.21 Safety considerations – specific absorption rate (SAR) 267
5.22 Lipid suppression techniques 267
5.23 Clinical applications 268
5.23.1 Neurological applications 268
5.23.2 Body applications 269
5.23.3 Musculoskeletal applications 270
5.23.4 Cardiology applications 271
Exercises 273

Index 283