

Contents

ACKNOWLEDGMENTS	xvii
FOREWORD TO THE SECOND EDITION	xix
PREFACE TO THE SECOND EDITION	xxi
AUTHOR BIOGRAPHY	xxiii
01 INTRODUCTION	1
1.1 Visualization in Medicine as a Specialty of Scientific Visualization	1
1.2 Computerized Medical Imaging	3
1.3 2D and 3D Visualizations	7
1.4 Further Information	8
1.5 Organization	9
PART I ACQUISITION, ANALYSIS, AND INTERPRETATION OF MEDICAL VOLUME DATA	
02 ACQUISITION OF MEDICAL IMAGE DATA	15
2.1 Introduction	15
2.2 Medical Image Data	16
2.3 Data Artifacts and Signal Processing	19
2.3.1 Sampling Theorem	19
2.3.2 Undersampling and Aliasing	21
2.3.3 Interpolation Artifacts	22
2.4 X-Ray Imaging	24
2.4.1 Angiography	26
2.4.2 Rotational X-Ray	26
2.4.3 Discussion	28
2.4.4 Current and Future Developments of X-Ray Imaging	28
2.5 Computed Tomography	29
2.5.1 Computed Tomography Compared to X-Ray Imaging	30
2.5.2 Principle of CT Data Generation	30

2.5.3	Standardization with Hounsfield Units	31
2.5.4	Parameters of CT Scanning	32
2.5.5	Artifacts in CT Image Acquisition	35
2.5.6	Current and Future Developments of CT Scanners	37
2.5.7	Discussion	40
2.6	Magnetic Resonance Imaging	40
2.6.1	Principles of MRI	41
2.6.2	Parameters of MR Scanning	44
2.6.3	Artifacts in MRI Data	47
2.6.4	Functional MRI	48
2.6.5	Ultra-High-Field MRI	50
2.6.6	Diffusion Tensor Imaging	51
2.6.7	Discussion	52
2.7	Ultrasound	52
2.8	Imaging in Nuclear Medicine	55
2.8.1	Positron Emission Tomography—PET	56
2.8.2	Hybrid PET/CT and PET/MRI Scanners	57
2.8.3	Single Photon Emission Computed Tomography—SPECT	60
2.9	Intraoperative Imaging	61
2.9.1	CT- and MR-Guided Interventions	62
2.9.2	Fluoroscopy	63
2.9.3	Intraoperative Ultrasound	63
2.9.4	Intraoperative MRI	64
2.10	Summary	65

03	AN INTRODUCTION TO MEDICAL VISUALIZATION IN CLINICAL PRACTICE	69
3.1	Introduction	69
3.2	Diagnostic Accuracy	70
3.3	Visual Perception	73
3.3.1	Gray Value Perception	73
3.3.2	Color Spaces, Color Scales, and Color Perception	77
3.3.3	Visual Perception and Attention in the Diagnosis Of Medical Volume Data	81
3.4	Storage of Medical Image Data	81
3.4.1	Scope of Dicom	82
3.4.2	Structure of Dicom Data	82
3.5	Conventional Film-Based Diagnosis	83
3.5.1	Cooperation of Radiologists and Radiology Technicians	85
3.5.2	Tasks in Conventional Film-Based Diagnosis	85
3.6	Soft-Copy Reading	86
3.6.1	Digital Radiology Departments	86
3.6.2	Tasks in Soft-Copy Reading	88

3.6.3	Digital Hanging Protocol	92
3.6.4	Computer-Aided Detection	93
3.6.5	Diagnosis with 3D Visualizations	97
3.6.6	Guidelines for Soft-Copy Reading	100
3.7	Medical Visualization in Nuclear Medicine	101
3.8	Medical Image Data in Radiation Treatment Planning	102
3.8.1	Conformant and Intensity-Modulated Radiation Treatment	105
3.8.2	Brachytherapy	107
3.9	Medical Team Meetings	107
3.10	Concluding Remarks	109

04 IMAGE ANALYSIS FOR MEDICAL VISUALIZATION 111

4.1	Introduction	111
4.2	Preprocessing and Filtering	112
4.2.1	ROI Selection	113
4.2.2	Resampling	113
4.2.3	Histogram and Histogram Transformation	114
4.2.4	General Noise Reduction Techniques	116
4.2.5	Inhomogeneity Correction	122
4.2.6	Gradient Filtering	123
4.3	An Introduction to Image Segmentation	124
4.3.1	Requirements	125
4.3.2	Manual Segmentation	125
4.3.3	Threshold-Based Segmentation	126
4.3.4	Region Growing	128
4.3.5	Watershed Segmentation	129
4.4	Graph-Based Segmentation Techniques	132
4.4.1	Livewire Segmentation	132
4.4.2	Contour-Based Segmentation with Variational Interpolation	136
4.4.3	Graph Cuts	137
4.4.4	Random Walker Segmentation	138
4.5	Advanced and Model-Based Segmentation Methods	139
4.5.1	Active Contour Models	140
4.5.2	Level Sets and Fast Marching Methods	141
4.5.3	Statistical Shape Models	143
4.5.4	Active Appearance Models	146
4.5.5	Incorporating Model Assumptions in Region Growing Segmentation	148
4.5.6	Application: Tumor Segmentation	148
4.5.7	Verification and Representation of Segmentation Results	152
4.6	Interaction for Segmentation	153
4.6.1	General Techniques for Correcting Pre-Segmentations	155
4.6.2	Mesh-Based Correction of Segmentation Results	155
4.6.3	Interactive Morphological Image Processing	159

4.6.4	Interaction Techniques for Semi-Automatic Segmentation	160
4.7	Validation of Segmentation Methods	162
4.7.1	Phantom Studies Versus Clinical Data	162
4.7.2	Validation Metrics	163
4.7.3	Validation with Public Databases	164
4.8	Registration and Fusion of Medical Image Data	165
4.8.1	Transformation	166
4.8.2	Fitting	167
4.8.3	Model-Based Registration	169
4.8.4	Efficient Registration	170
4.8.5	Visualization	170
4.9	Summary	172

05	HUMAN-COMPUTER INTERACTION FOR MEDICAL VISUALIZATION	177
5.1	Introduction	177
5.2	User and Task Analysis	179
5.2.1	Task Analysis Methods	179
5.2.2	What has to be Analyzed?	181
5.2.3	Representations of Task Analysis	181
5.2.4	Understanding the User	189
5.2.5	Case Study: Task Analysis for Medical Team Meetings	190
5.3	Metaphors	191
5.4	Prototyping	193
5.5	User Interface Principles and User Experience	194
5.5.1	General User Interface Principles	195
5.5.2	User Interface Principles for Medical Applications	197
5.5.3	User Experience	198
5.6	3D Interaction Techniques	199
5.6.1	Selection Tasks	199
5.6.2	3D Rotation	200
5.6.3	Object Placement	202
5.6.4	Navigation	203
5.7	Input Devices	205
5.7.1	6 Dof Input Devices	207
5.7.2	Tactile Input Devices	210
5.8	HCI in the Operating Room	212
5.9	Mobile Computing	216
5.10	Evaluation	220
5.10.1	Formative and Summative Evaluations	221
5.10.2	Inspection-Based and Empirical Evaluations	222
5.10.3	Evaluation of Interactive Segmentation Techniques	222
5.10.4	Post Market Clinical Follow Up	223
5.11	Conclusion	223

PART II VISUALIZATION AND EXPLORATION OF MEDICAL VOLUME DATA

06	SURFACE RENDERING	229
6.1	Introduction	229
6.2	Reconstruction of Surfaces from Contours	230
6.2.1	Topological Problems	230
6.2.2	Neighborhood Relations in Surface Meshes	231
6.2.3	Representation of Surface Meshes	232
6.3	Marching Cubes	233
6.3.1	Marching Squares	234
6.3.2	Basic Algorithm	234
6.3.3	Discussion	237
6.3.4	Advanced Surface Extraction Methods	240
6.3.5	Hardware-Accelerated Isosurface Extraction	241
6.4	Surface Rendering of Unsegmented Volume Data	241
6.4.1	Preprocessing Volume Data for Visualization	242
6.4.2	Selection of Isovalues	244
6.4.3	Multiple and Nested Isosurfaces	245
6.4.4	Isosurface Topology Simplification	246
6.5	Surface Rendering of Segmented Volume Data	247
6.5.1	Preprocessing	248
6.5.2	Basic Mesh Smoothing	250
6.5.3	Interactive Real-Time Mesh Smoothing	254
6.5.4	Evaluation of Smoothing Approaches	257
6.6	Advanced Mesh Smoothing	258
6.6.1	Constrained Mesh Smoothing	258
6.6.2	Context-Aware Smoothing	259
6.6.3	Extracting Surfaces from Label Volumes	261
6.6.4	Evaluation of Advanced Mesh Smoothing	262
6.7	Mesh Simplification and Web-Based Surface Rendering	262
6.7.1	Mesh Simplification	263
6.7.2	Web-Based Surgical Planning	264
6.7.3	Web-Based Medical Education	265
6.8	Concluding Remarks	266
07	DIRECT VOLUME VISUALIZATION	269
7.1	Theoretical Models	269
7.1.1	Emission	270
7.1.2	Absorption	271
7.1.3	Volume Rendering Equation	271
7.2	The Volume Rendering Pipeline	273
7.2.1	Preclassified Volume Rendering Pipeline	274
7.3	Compositing	275
7.3.1	Compositing Variations: Pseudo X-Ray, MIP, CVE, and MIDA	277

7.3.2	Thin Slab Volume Rendering	279
7.3.3	Pre-Integrated Volume Rendering	281
7.4	Volume Raycasting	282
7.5	Efficient Volume Rendering	283
7.6	Direct Volume Rendering on the GPU	284
7.7	Summary	286
08	ADVANCED DIRECT VOLUME VISUALIZATION	289
8.1	Introduction	289
8.2	Volumetric Illumination	290
8.2.1	Volumetric Illumination Model	291
8.2.2	Algorithm Classification	293
8.2.3	Local Region-Based Techniques	296
8.2.4	Slice-Based Techniques	300
8.2.5	Light Space-Based Techniques	303
8.2.6	Lattice-Based Techniques	307
8.2.7	Basis Function-Based Techniques	310
8.2.8	Raytracing-Based Techniques	312
8.2.9	Perceptual Impact	313
8.2.10	Technical Considerations	314
8.3	Artificial Depth Enhancements	314
8.3.1	Color-Coding	316
8.3.2	Halos	318
8.3.3	Depth of Field	320
8.4	Concluding Remarks	321
09	VOLUME INTERACTION	323
9.1	Introduction	323
9.2	One-Dimensional Transfer Functions	324
9.2.1	Unassisted Techniques	326
9.2.2	Data-Driven Transfer Functions	327
9.2.3	Image-Driven Transfer Functions	334
9.3	Multidimensional Transfer Functions	337
9.3.1	Histograms for 2D Transfer Functions	337
9.3.2	2D Component Functions	339
9.3.3	Representation of 2D Transfer Functions	339
9.3.4	Size-Based Transfer Functions	340
9.4	Gradient-Based and LH-Based Transfer Functions	342
9.4.1	Gradient-Based Transfer Functions	342
9.4.2	Gradient Estimation and Storage	342
9.4.3	User Interfaces for Gradient-Based Transfer Functions	342
9.4.4	2D Transfer Functions Based on LH Histograms	346
9.5	Local and Distance-Based Transfer Functions	349
9.5.1	Distance-Based Transfer Functions	350

9.5.2	Local Transfer Functions	352
9.6	Advanced Picking	353
9.6.1	Contextual Picking	354
9.6.2	Visibility-Based Picking	355
9.7	Clipping	356
9.8	Virtual Resection	358
9.8.1	Virtual Resections by Drawing on Slices	359
9.8.2	Virtual Resection with a Deformable Cutting Plane	359
9.9	Cutting Medical Volume Data	365
9.9.1	High-Quality Representation of Cut Surfaces	366
9.9.2	Virtual Resection and Surgery Simulation	366
9.10	Summary	366
10	LABELING AND MEASUREMENTS IN MEDICAL VISUALIZATION	369
10.1	Introduction	369
10.2	General Design Issues	370
10.3	Interactive Measurement of Distances and Volumes	371
10.3.1	Interactive Distance Measurement	371
10.3.2	Estimation of Quantitative Values	373
10.4	Automatic Distance Measures	376
10.4.1	Bounding Volumes and Spatial Trees for Distance Computation	376
10.4.2	Efficient and Flexible Distance Computation	378
10.4.3	Clinical Examples	381
10.4.4	Measuring the Extents of Objects	381
10.5	Angular Measurements	384
10.5.1	Measurement of Angles Between Elongated Objects	384
10.5.2	Medical Applications	385
10.6	Measurements in Virtual Reality	387
10.7	Labeling 2D and 3D Medical Visualizations	387
10.7.1	Internal Labeling of 3D Medical Surface Models	390
10.7.2	External Labeling	391
10.7.3	Labeling Slice-Based Visualizations	394
10.8	Summary	397
PART III	ADVANCED MEDICAL VISUALIZATION TECHNIQUES	
11	VISUALIZATION OF VASCULAR STRUCTURES	401
11.1	Introduction	401
11.2	Enhancing Vascular Structures	402
11.2.1	Emphasis of Elongated Structures	402
11.2.2	Bone Removal	403
11.3	Projection-Based Visualization	405
11.3.1	Maximum Intensity and Closest Vessel Projection	405
11.3.2	Maximum Intensity Difference Accumulation	407

11.3.3	Curved Planar Reformation	408
11.4	Vessel Analysis	412
11.4.1	Vessel Segmentation	412
11.4.2	Skeletonization and Graph Analysis	414
11.4.3	Diameter Estimation	418
11.5	Model-Based Surface Visualization	419
11.5.1	Reconstruction with Cylinders and Truncated Cones	420
11.5.2	Visualization with Parametric and Subdivision Surfaces	424
11.5.3	Implicit Reconstruction of Vascular Trees	425
11.6	Model-Free Surface Visualization	432
11.6.1	Smoothing Surface Visualizations	432
11.6.2	Visualization with MPU Implicits	432
11.6.3	Implicit Reconstruction with Sweeping	436
11.7	Vessel Visualization for Diagnosis	438
11.7.1	Diagnosis of Cerebral Aneurysms and Arterio-Venous Malformations	440
11.7.2	Diagnosis of the Coronary Heart Disease	445
11.7.3	Multiple Coordinated Views	448
11.8	Summary	448
12	ILLUSTRATIVE MEDICAL VISUALIZATION	451
12.1	Introduction	451
12.2	Medical Applications	453
12.3	Curvature Approximation	454
12.3.1	Curvature-Related Measures	455
12.3.2	Curvature Estimation for Illustrative Visualization	456
12.4	An Introduction to Feature Lines	457
12.4.1	An Overview of Feature Lines	458
12.4.2	General Aspects of Feature Line Rendering	459
12.5	Geometry-Dependent Feature Lines	462
12.5.1	Silhouette Generation	462
12.5.2	Crease Lines	467
12.5.3	Ridge and Valley Lines	468
12.5.4	Suggestive Contours	471
12.5.5	Apparent Ridges	472
12.5.6	Streamline-Based Illustrative Rendering	474
12.6	Light-Dependent Feature Lines	476
12.6.1	Laplacian Lines	476
12.6.2	Photoc Extremum Lines	477
12.6.3	Highlight Lines	480
12.6.4	Discussion	481
12.7	Stippling	482
12.7.1	Essential Parameters of Stippling	482
12.7.2	Frame-Coherent Stippling	483
12.8	Hatching	485
12.8.1	Curvature-Guided Hatching	487

12.8.2	Model-Based Hatching of Muscles and Vascular Structures	488
12.8.3	Combination of Curvature and Preferential Direction	490
12.8.4	Hatching Volume Models	491
12.9	Illustrative Shading	492
12.9.1	Shading in Medical Textbooks	493
12.9.2	Realization of the Extended Shading	494
12.9.3	Illustrative Visualization of Vascular Trees	497
12.10	Smart Visibility	500
12.10.1	Cutaways	501
12.10.2	Ghosted Views	505
12.11	Conclusion	507
13	VIRTUAL ENDOSCOPY	509
13.1	Introduction	509
13.2	Medical and Technical Background	510
13.3	Preprocessing	513
13.3.1	Preprocessing Workflow	513
13.3.2	Path Planning	513
13.4	Rendering for Virtual Endoscopy	515
13.4.1	Indirect Volume Rendering	515
13.4.2	Direct Volume Rendering	517
13.4.3	Hybrid Rendering	518
13.4.4	Advanced Rendering	518
13.4.5	Geometry Culling	518
13.5	User Interfaces for Virtual Endoscopy	521
13.5.1	Camera Control and Navigation	522
13.5.2	Views for Interactive Virtual Endoscopy	523
13.5.3	Graphical User Interface	524
13.5.4	Input Devices	524
13.6	Applications	525
13.6.1	Virtual Colonoscopy	525
13.6.2	Virtual Bronchoscopy	529
13.6.3	Virtual Angioscopy	531
13.6.4	Virtual Endoscopy for Minimally-Invasive Neurosurgery	533
13.7	Concluding Remarks	536
14	PROJECTIONS AND REFORMATIONS (Online Chapter)	537
PART IV VISUALIZATION OF HIGH-DIMENSIONAL MEDICAL IMAGE DATA		
15	VISUALIZATION OF BRAIN CONNECTIVITY	541
15.1	Introduction	541
15.2	Acquisition of Connectivity Data	543

15.2.1	EEG and MEG	543
15.2.2	Magnetic Resonance Imaging	543
15.2.3	Diffusion MRI	545
15.2.4	Functional MRI	547
15.3	Visualization of Structural Connectivity	547
15.3.1	Scalar Reduction	548
15.3.2	Glyphs	554
15.3.3	Global Multifield	559
15.4	Visualization of Connectivity Matrices	579
15.4.1	Non-Spatial Methods	580
15.4.2	Spatial Methods	583
15.5	Summary	587
16	VISUAL EXPLORATION AND ANALYSIS OF PERFUSION DATA [Online Chapter]	589
PART V TREATMENT PLANNING, GUIDANCE AND TRAINING		
17	COMPUTER-ASSISTED SURGERY	593
17.1	Introduction	593
17.2	General Tasks	594
17.3	Visualization Techniques	595
17.3.1	Visual Representation	596
17.3.2	Interaction	598
17.3.3	Simulation	598
17.3.4	Quantitative Visualization	601
17.4	Guidance Approaches	607
17.4.1	Mental Model	608
17.4.2	Documentation	609
17.4.3	Image-Based Guidance	610
17.4.4	Mechanical Guidance	610
17.5	Application Areas	612
17.5.1	Oral and Maxillofacial Surgery	612
17.5.2	Orthopedic Surgery	614
17.5.3	Neurosurgery	616
17.5.4	Hepatic Surgery	621
17.6	Conclusions	623
18	IMAGE-GUIDED SURGERY AND AUGMENTED REALITY	625
18.1	Introduction	625
18.2	Image-Guided Surgery	627
18.2.1	Overview of IGS Applications	627
18.2.2	Medical Augmented Reality	628

18.3	Registration	630
18.3.1	Tissue Deformation and Brain Shift	631
18.3.2	Fiducial-Based Registration	631
18.3.3	Point-Based Registration	633
18.4	Calibration and Tracking	634
18.4.1	Calibrating Instruments	634
18.4.2	Camera Calibration	637
18.4.3	Optical Tracking	639
18.4.4	Electro-Magnetic Tracking	640
18.4.5	Summary	641
18.5	Navigated Control	641
18.6	Display Modes	642
18.6.1	Brief History of Medical AR	643
18.6.2	Optical See-Through Displays	644
18.6.3	Video See-Through Displays	645
18.6.4	Augmented Microscope Displays	645
18.6.5	Augmented Reality Windows	646
18.6.6	Projection-Based Medical Augmented Reality	647
18.7	Visualization Techniques for Medical Augmented Reality	648
18.7.1	The Occlusion Problem of Augmented Reality	648
18.7.2	Depth Cues in Augmented Reality	649
18.7.3	Basic Visualization in AR	650
18.7.4	Smart Visibility in AR	651
18.7.5	Illustrative Visualization in AR	653
18.7.6	Interaction in the OR	654
18.7.7	Calibrated Augmented Reality Endoscope	657
18.8	Applications	657
18.8.1	Workflow Analysis for Medical Augmented Reality	657
18.8.2	Neurosurgery	659
18.8.3	Liver Surgery	659
18.8.4	Validation and Clinical Evaluation	661
18.9	Summary	661
19	VISUAL EXPLORATION OF SIMULATED AND MEASURED FLOW DATA	665
19.1	Introduction	665
19.2	Basic Flow Visualization Techniques	666
19.2.1	Direct Flow Visualization Techniques	666
19.2.2	Feature-Based Flow Visualization Techniques	667
19.2.3	Texture-Based Flow Visualization	670
19.2.4	Geometry-Based Flow Visualization Methods	670
19.2.5	Partition-Based Flow Visualization Techniques	673
19.2.6	Evaluation of Flow Visualization Techniques	674

19.3	From Medical Image Data to Simulation Models	675
19.3.1	Segmentation and Meshing for Simulation	675
19.3.2	Requirements for Surface Meshes	676
19.3.3	Generation of Surface Meshes	678
19.3.4	Generation of Volume Grids	680
19.4	Visual Exploration of Measured Cardiac Blood Flow	684
19.4.1	Medical Background	684
19.4.2	Image Acquisition	685
19.4.3	Preprocessing Cardiac Blood Flow Data	687
19.4.4	Quantitative Analysis	688
19.4.5	Visual Exploration	689
19.4.6	Illustrative Visualization Techniques	690
19.4.7	Uncertainty Visualization	691
19.5	Exploration of Simulated Cerebral Blood Flow	692
19.5.1	Blood Flow Simulations	693
19.5.2	Extraction of Landmarks	695
19.5.3	Anatomy-Guided Flow Exploration	697
19.5.4	Lens-Based Interaction	700
19.5.5	Visualization of Vasculature and Embedded Flow	701
19.5.6	Virtual Stenting	702
19.5.7	Software Assistant	704
19.5.8	Validation	706
19.5.9	Discussion	706
19.6	Biomedical Simulation and Modeling	707
19.6.1	Biomechanical Simulation in Orthopedics	707
19.6.2	Simulation and Visualization for Planning Radio-Frequency Ablation	709
19.7	Concluding Remarks	712
20	VISUAL COMPUTING FOR ENT SURGERY PLANNING (Online Chapter)	715
21	COMPUTER-ASSISTED MEDICAL EDUCATION (Online Chapter)	717
22	OUTLOOK (Online Chapter)	719
	REFERENCES	721
	INDEX	801