

## Contents

### Preface XV

### Part One 1

|          |                                    |           |
|----------|------------------------------------|-----------|
| <b>1</b> | <b>Structure and Function</b>      | <b>3</b>  |
| 1.1      | Anatomy of the Human Eye           | 4         |
| 1.2      | Retina: The Optical Sensor         | 10        |
| 1.2.1    | Retinal Structure                  | 10        |
| 1.2.2    | Functional Areas                   | 12        |
| 1.3      | Recommended Reading                | 14        |
|          | References                         | 14        |
| <br>     |                                    |           |
| <b>2</b> | <b>Optics of the Human Eye</b>     | <b>15</b> |
| 2.1      | Optical Imaging                    | 15        |
| 2.1.1    | Entrance and Exit Pupils           | 17        |
| 2.1.2    | Cardinal Points                    | 19        |
| 2.1.3    | Eye Axes                           | 20        |
| 2.1.4    | Accommodation                      | 21        |
| 2.1.5    | Resolution                         | 23        |
| 2.1.6    | Adaption                           | 26        |
| 2.1.7    | Stiles–Crawford Effect             | 28        |
| 2.1.8    | Depth of Field                     | 29        |
| 2.1.9    | Binocular Vision                   | 30        |
| 2.1.10   | Spectral Properties                | 32        |
| 2.2      | Schematic Eye Models               | 33        |
| 2.2.1    | Paraxial Model: The Gullstrand Eye | 34        |
| 2.2.2    | Finite Wide-Angle Models           | 38        |
| 2.2.3    | Applications of Eye Models         | 44        |
| 2.3      | Color Vision                       | 45        |
| 2.4      | Recommended Reading                | 47        |
|          | References                         | 47        |

|          |                                                              |           |
|----------|--------------------------------------------------------------|-----------|
| <b>3</b> | <b>Visual Disorders and Major Eye Diseases</b>               | <b>49</b> |
| 3.1      | Refractive Errors                                            | 49        |
| 3.1.1    | Axial-Symmetric Ametropia: Myopia and Hyperopia              | 51        |
| 3.1.2    | Astigmatism                                                  | 51        |
| 3.1.3    | Notations of Spherocylindrical Refraction in Astigmatic Eyes | 53        |
| 3.1.4    | Anisometropia                                                | 54        |
| 3.1.5    | Distribution of Refractive Errors                            | 54        |
| 3.1.6    | Refractive Errors Caused by Diseases                         | 55        |
| 3.2      | Cataract                                                     | 56        |
| 3.3      | Glaucoma                                                     | 57        |
| 3.4      | Age-Related Macular Degeneration                             | 60        |
| 3.4.1    | ARM                                                          | 60        |
| 3.4.2    | Dry AMD                                                      | 60        |
| 3.4.3    | Wet AMD                                                      | 61        |
| 3.5      | Diabetic Retinopathy                                         | 64        |
| 3.6      | Retinal Vein Occlusions                                      | 65        |
| 3.7      | Infective Eye Diseases                                       | 66        |
| 3.7.1    | Trachoma                                                     | 66        |
| 3.7.2    | Onchocerciasis                                               | 67        |
| 3.8      | Major Causes for Visual Impairment                           | 67        |
| 3.9      | Major Causes of Blindness                                    | 68        |
| 3.10     | Socio-Economic Impact of Eye Diseases                        | 70        |
| 3.11     | Recommended Reading                                          | 72        |
|          | Problems to Chapters 1–3                                     | 72        |
|          | References                                                   | 76        |

## Part Two 79

|          |                                                          |           |
|----------|----------------------------------------------------------|-----------|
| <b>4</b> | <b>Introduction to Ophthalmic Diagnosis and Imaging</b>  | <b>81</b> |
| 4.1      | Determination of the Eye's Refractive Status             | 82        |
| 4.2      | Visualization, Imaging, and Structural Analysis          | 82        |
| 4.3      | Determination of the Eye's Functional Status             | 85        |
| 4.3.1    | Global Functional Status                                 | 85        |
| 4.3.2    | Local Functional Status                                  | 86        |
| 4.4      | Light Hazard Protection                                  | 86        |
|          | References                                               | 87        |
| <b>5</b> | <b>Determination of the Refractive Status of the Eye</b> | <b>89</b> |
| 5.1      | Retinoscopy                                              | 91        |
| 5.1.1    | Illumination Beam Path                                   | 92        |
| 5.1.2    | Observation Beam Path                                    | 93        |
| 5.1.3    | Measurement Procedure                                    | 96        |
| 5.1.4    | Accuracy in Retinoscopy                                  | 98        |
| 5.1.5    | Applications                                             | 99        |

|          |                                                                     |            |
|----------|---------------------------------------------------------------------|------------|
| 5.2      | Automated Objective Refractometers (Autorefractors)                 | 100        |
| 5.2.1    | Common Characteristics of Autorefractors                            | 100        |
| 5.2.2    | Measuring Methods                                                   | 102        |
| 5.2.3    | Measurement Accuracy and Limitations of Automatic Refractometers    | 120        |
| 5.3      | Aberrometers                                                        | 121        |
| 5.3.1    | Fundamentals of Aberrometry                                         | 121        |
| 5.3.2    | General Measurement Principles for Aberrometers                     | 126        |
| 5.3.3    | General Remarks on Aberrometry                                      | 127        |
| 5.3.4    | Hartmann–Shack Wavefront Aberrometer (Outgoing Light Aberrometer)   | 127        |
| 5.3.5    | Ingoing Light Aberrometers                                          | 131        |
| 5.3.6    | Commercial Aberrometers                                             | 133        |
| 5.4      | Wavefront Reconstruction and Wavefront Analysis                     | 133        |
| 5.4.1    | From Wavefront to Refraction (Wavefront Analysis)                   | 135        |
| 5.4.2    | Applications of Wavefront Analysis                                  | 140        |
| 5.5      | Excursus: Refractive Correction with Eye Glasses and Contact Lenses | 141        |
| 5.6      | Recommended Reading                                                 | 143        |
| 5.7      | Problems                                                            | 143        |
|          | References                                                          | 144        |
| <b>6</b> | <b>Optical Visualization, Imaging, and Structural Analysis</b>      | <b>147</b> |
| 6.1      | Medical Magnifying Systems                                          | 147        |
| 6.1.1    | Optics of a Single Loupe                                            | 148        |
| 6.1.2    | Medical Loupes                                                      | 149        |
| 6.2      | Surgical Microscopes                                                | 151        |
| 6.2.1    | Requirements for Surgical Microscopes                               | 152        |
| 6.2.2    | Functional Principle                                                | 154        |
| 6.2.3    | Modular Structure of Surgical Microscopes                           | 160        |
| 6.2.4    | Prospects                                                           | 176        |
| 6.3      | Reflection Methods for Topographic Measurements                     | 177        |
| 6.3.1    | Keratometer                                                         | 178        |
| 6.3.2    | Placido Ring Corneal Topographer                                    | 187        |
| 6.4      | Slit Lamp                                                           | 200        |
| 6.4.1    | Functional Principle                                                | 201        |
| 6.4.2    | Modular Structure                                                   | 202        |
| 6.4.3    | Types of Illumination for Various Applications                      | 205        |
| 6.4.4    | Accessories for Other Examinations and Measurements                 | 208        |
| 6.4.5    | Prospects                                                           | 212        |
| 6.5      | Scanning-Slit Projection Devices                                    | 212        |
| 6.5.1    | Lateral Scanning-Slit Projection Techniques                         | 213        |
| 6.5.2    | Scheimpflug Imaging of Rotating-Slit Projections                    | 217        |
| 6.5.3    | Clinical Relevance and Applications                                 | 223        |
| 6.6      | Ophthalmoscope                                                      | 225        |

|          |                                                                                              |            |
|----------|----------------------------------------------------------------------------------------------|------------|
| 6.6.1    | Functional Principle                                                                         | 226        |
| 6.6.2    | Direct Ophthalmoscope                                                                        | 227        |
| 6.6.3    | Indirect Ophthalmoscope                                                                      | 230        |
| 6.7      | Fundus Camera                                                                                | 236        |
| 6.7.1    | Requirements for a Fundus Camera                                                             | 237        |
| 6.7.2    | Functional Principle                                                                         | 238        |
| 6.7.3    | Field of View and Magnification                                                              | 241        |
| 6.7.4    | Wide-Field Imaging                                                                           | 241        |
| 6.7.5    | Color and Monochrome Imaging                                                                 | 241        |
| 6.7.6    | Fluorescence Angiography                                                                     | 242        |
| 6.7.7    | Fundus Autofluorescence                                                                      | 244        |
| 6.7.8    | Stereoscopic Imaging and Analysis                                                            | 246        |
| 6.7.9    | Equipment Solutions                                                                          | 248        |
| 6.7.10   | Prospects                                                                                    | 248        |
| 6.8      | Scanning-Laser Devices                                                                       | 249        |
| 6.8.1    | Confocal Scanning-Laser Ophthalmoscope                                                       | 250        |
| 6.8.2    | Confocal Scanning-Laser Tomograph                                                            | 259        |
| 6.8.3    | Scanning-Laser Polarimeter                                                                   | 261        |
| 6.9      | Recommended Reading                                                                          | 267        |
| 6.10     | Problems                                                                                     | 267        |
|          | References                                                                                   | 273        |
| <b>7</b> | <b>Optical Coherence Methods for Three-Dimensional Visualization and Structural Analysis</b> | <b>277</b> |
| 7.1      | Introduction to Optical Coherence Tomography                                                 | 278        |
| 7.2      | Development of OCT and LCI as an Example of Modern Medical Technology Innovation             | 280        |
| 7.2.1    | Academic Research – Conception of OCT (until 1993)                                           | 281        |
| 7.2.2    | First Generation of Commercial OCTs (1993–2002)                                              | 281        |
| 7.2.3    | Second Generation of OCTs – ZEISS Stratus OCT (2002–2006)                                    | 283        |
| 7.2.4    | Third Generation of OCTs – Frequency-Domain OCT (2007–current)                               | 283        |
| 7.3      | Principles of Low-Coherence Interferometry and Optical Coherence Tomography                  | 285        |
| 7.3.1    | Michelson Interferometry with Coherent Light                                                 | 285        |
| 7.3.2    | Michelson Interferometry with Low-Coherence Light                                            | 286        |
| 7.3.3    | Time-Domain OCT                                                                              | 289        |
| 7.3.4    | Frequency-Domain OCT                                                                         | 291        |
| 7.3.5    | Swept-Source OCT                                                                             | 295        |
| 7.3.6    | Overview and Comparison of OCT Systems                                                       | 297        |
| 7.4      | Elements of OCT Theory                                                                       | 300        |
| 7.4.1    | Theory of Time-Domain OCT – Axial Resolution                                                 | 301        |
| 7.4.2    | Theory of Frequency-Domain OCT                                                               | 304        |
| 7.4.3    | Effect of Group Velocity Dispersion in OCT Systems                                           | 309        |
| 7.4.4    | Sensitivity and Signal-To-Noise Ratio in TD-OCT and FD-OCT                                   | 311        |

|       |                                                        |     |
|-------|--------------------------------------------------------|-----|
| 7.5   | Device Design of OCTs                                  | 313 |
| 7.5.1 | Light Sources                                          | 313 |
| 7.5.2 | Commercial Systems                                     | 315 |
| 7.6   | Ophthalmic Applications of OCT                         | 316 |
| 7.6.1 | Posterior Segment of the Eye                           | 317 |
| 7.6.2 | Anterior Part of the Eye                               | 320 |
| 7.7   | Optical Biometry by Low-Coherence Interferometry       | 324 |
| 7.7.1 | Dual-Beam Low-Coherence Interferometry                 | 327 |
| 7.7.2 | Applications of Optical Biometry                       | 329 |
| 7.8   | Prospects                                              | 334 |
| 7.9   | Recommended Reading                                    | 338 |
| 7.10  | Problems                                               | 338 |
|       | References                                             | 341 |
| <br>  |                                                        |     |
| 8     | <b>Functional Diagnostics</b>                          | 345 |
| 8.1   | Visual Field Examination                               | 346 |
| 8.1.1 | Physiological Aspects and Functional Principles        | 346 |
| 8.1.2 | Basic Perimeter Design                                 | 351 |
| 8.1.3 | Alternative Perimetric Concepts                        | 357 |
| 8.1.4 | Prospects                                              | 362 |
| 8.2   | Metabolic Mapping                                      | 363 |
| 8.2.1 | Microcirculation Mapping                               | 363 |
| 8.2.2 | Fluorophore Mapping                                    | 366 |
| 8.2.3 | Prospects                                              | 367 |
| 8.3   | Recommended Reading                                    | 367 |
| 8.4   | Problems                                               | 368 |
|       | References                                             | 368 |
| <br>  |                                                        |     |
|       | <b>Part Three</b>                                      | 371 |
| <br>  |                                                        |     |
| 9     | <b>Laser-Tissue Interaction</b>                        | 373 |
| 9.1   | Absorption                                             | 374 |
| 9.2   | Elastic Scattering                                     | 375 |
| 9.2.1 | Rayleigh Scattering                                    | 376 |
| 9.2.2 | Mie Scattering                                         | 376 |
| 9.3   | Optical Properties of Biological Tissue                | 376 |
| 9.4   | Interaction of Irradiated Biological Tissue            | 378 |
| 9.4.1 | Photochemical Response                                 | 379 |
| 9.4.2 | Photothermal Response                                  | 380 |
| 9.4.3 | Photoablation                                          | 383 |
| 9.4.4 | Plasma-Induced Ablation and Photodisruption            | 384 |
| 9.5   | Propagation of Femtosecond Pulses in Transparent Media | 391 |
| 9.5.1 | Self-Focusing                                          | 392 |
| 9.5.2 | Self-Phase Modulation                                  | 392 |

|           |                                                                          |            |
|-----------|--------------------------------------------------------------------------|------------|
| 9.5.3     | Group Velocity Dispersion                                                | 393        |
| 9.6       | Ophthalmic Laser Safety                                                  | 394        |
| 9.6.1     | Laser Classes                                                            | 396        |
| 9.6.2     | Safe Use of Ophthalmic Laser Systems                                     | 399        |
| 9.7       | Recommended Reading                                                      | 401        |
| 9.8       | Problems                                                                 | 402        |
|           | References                                                               | 403        |
| <b>10</b> | <b>Laser Systems for Treatment of Eye Diseases and Refractive Errors</b> | <b>405</b> |
| 10.1      | Laser Systems Based on Photochemical Interactions                        | 406        |
| 10.1.1    | Basics of Photodynamic Therapy                                           | 408        |
| 10.1.2    | Technical Equipment Concepts                                             | 409        |
| 10.1.3    | Treatment Procedure                                                      | 411        |
| 10.1.4    | Prospects                                                                | 411        |
| 10.2      | Laser Systems Based on Photothermal Interactions                         | 412        |
| 10.2.1    | Functional Principle                                                     | 412        |
| 10.2.2    | Process Parameters                                                       | 412        |
| 10.2.3    | Treatment Modes                                                          | 415        |
| 10.2.4    | Technical Equipment Concepts                                             | 418        |
| 10.2.5    | Clinical Applications                                                    | 426        |
| 10.2.6    | Prospects                                                                | 430        |
| 10.3      | Laser Systems Based on Photoablation                                     | 431        |
| 10.3.1    | Basics of Photoablation Treatments                                       | 432        |
| 10.3.2    | Technical Equipment Concepts                                             | 441        |
| 10.3.3    | Surgical Ablation Techniques                                             | 446        |
| 10.3.4    | Prospects                                                                | 450        |
| 10.4      | Laser Systems Based on Photodisruption with Nanosecond Pulses            | 450        |
| 10.4.1    | Functional Principle                                                     | 451        |
| 10.4.2    | Process Parameters                                                       | 451        |
| 10.4.3    | Technical Equipment Concepts                                             | 454        |
| 10.4.4    | Clinical Applications                                                    | 457        |
| 10.4.5    | Prospects                                                                | 460        |
| 10.5      | Laser Systems Based on Plasma-Induced Ablation with Femtosecond Pulses   | 460        |
| 10.5.1    | Functional Principle                                                     | 460        |
| 10.5.2    | Process Parameters                                                       | 461        |
| 10.5.3    | Technical Equipment Concepts                                             | 463        |
| 10.5.4    | Clinical Applications                                                    | 466        |
| 10.5.5    | Prospects                                                                | 472        |
| 10.6      | Recommended Reading                                                      | 473        |
| 10.7      | Problems                                                                 | 473        |
|           | References                                                               | 476        |

## Appendix A Basics of Optics 481

|     |                                      |     |
|-----|--------------------------------------|-----|
| A.1 | Geometric Optics and Optical Imaging | 482 |
|-----|--------------------------------------|-----|

|       |                                                              |     |
|-------|--------------------------------------------------------------|-----|
| A.1.1 | Refraction and Dispersion                                    | 483 |
| A.1.2 | Imaging by Spherical Surfaces                                | 486 |
| A.1.3 | The Ray Tracing Approach to Paraxial Optical Systems         | 492 |
| A.1.4 | Aperture Stops, Field Stops, and Pupils                      | 496 |
| A.1.5 | Limitations of the Paraxial Beam Approximation               | 499 |
| A.1.6 | Aberrations                                                  | 501 |
| A.1.7 | Wavefront Aberration and Image Quality                       | 506 |
| A.1.8 | Classification and Expansion of the Wave Aberration Function | 510 |
| A.1.9 | Chromatic Aberration                                         | 518 |
| A.2   | Wave Optics                                                  | 518 |
| A.2.1 | Monochromatic Harmonic Waves                                 | 519 |
| A.2.2 | Paraxial Solutions of the Wave Equation                      | 530 |
| A.2.3 | Monochromatic Superposition of Harmonic Waves                | 535 |
| A.2.4 | Polychromatic Superposition of Waves                         | 537 |
| A.3   | Recommended Reading                                          | 543 |
| A.4   | Problems                                                     | 543 |
|       | References                                                   | 547 |

## **Appendix B Basics of Laser Systems 549**

|       |                                                      |     |
|-------|------------------------------------------------------|-----|
| B.1   | Einstein's Two-Level Model of Light-Atom Interaction | 550 |
| B.1.1 | Absorption                                           | 551 |
| B.1.2 | Spontaneous emission                                 | 551 |
| B.1.3 | Stimulated emission                                  | 551 |
| B.1.4 | Relation of Einstein Coefficients                    | 552 |
| B.2   | Light Amplification by Stimulated Emission           | 552 |
| B.2.1 | Conditions for Population Inversion                  | 553 |
| B.2.2 | Multilevel Optical Pumping                           | 555 |
| B.3   | Laser Oscillator                                     | 558 |
| B.3.1 | Inversion Threshold                                  | 558 |
| B.3.2 | Standing Wave Condition                              | 561 |
| B.4   | The Gaussian Oscillator                              | 563 |
| B.4.1 | Resonator Stability Condition                        | 563 |
| B.4.2 | Divergence                                           | 565 |
| B.4.3 | Polarization                                         | 566 |
| B.4.4 | Pulsed Laser Operation                               | 567 |
| B.5   | Technical Realization of Laser Sources               | 571 |
| B.5.1 | Gas Lasers                                           | 572 |
| B.5.2 | Semiconductor Lasers                                 | 577 |
| B.5.3 | Solid-State Lasers                                   | 580 |
| B.6   | Recommended Reading                                  | 583 |
| B.7   | Problems                                             | 583 |
|       | References                                           | 588 |

## **Appendix C Summary of Used Variables and Abbreviations 591**

|     |              |     |
|-----|--------------|-----|
| C.1 | Chapters 1-3 | 591 |
|-----|--------------|-----|

|     |                   |            |
|-----|-------------------|------------|
| C.2 | Chapters 4 and 5  | 593        |
| C.3 | Chapter 6         | 594        |
| C.4 | Chapter 7         | 597        |
| C.5 | Chapter 8         | 599        |
| C.6 | Chapters 9 and 10 | 600        |
| C.7 | Appendix A        | 603        |
| C.8 | Appendix B        | 605        |
|     | <b>Index</b>      | <b>607</b> |