Ocular Imaging

LECTURES IN OPTICS

Volume 5

By the Author

Lectures in Optics, Vol. 1, Introduction to Optics

Lectures in Optics, Vol. 2, Geometrical Optics

Lectures in Optics, Vol. 3, Wave Optics

Lectures in Optics, Vol. 4, Visual Optics

Lectures in Optics, Vol. 5, Ocular Imaging

Ocular Imaging

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Volume 5

George Asimellis

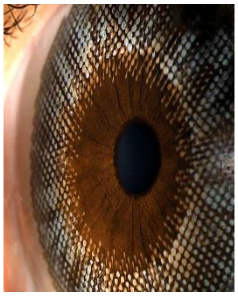
SPIE PRESS
Bellingham, Washington USA

Library of Congress Cataloging-in-Publication Data

Names: Asimellis, George, 1966- author.
Title: Ocular imaging / George Asimellis.
Description: Bellingham, Washington : SPIE, [2023] | Series: Lectures in optics ; vol. 5 | Includes bibliographical references and index.
Identifiers: LCCN 2021021274 | ISBN 9781510622654 (paperback) | ISBN 9781510622661 (pdf)
Subjects: LCSH: Eye--Imaging.
Classification: LCC RE79.I42 A85 2021 | DDC 616.07/545--dc23
LC record available at https://lccn.loc.gov/2021021274

Published by
SPIE
P.O. Box 10
Bellingham, Washington 98227-0010 USA
Phone: +1 360.676.3290
Fax: +1 360.647.1445
Email: books@spie.org
Web: http://spie.org

Printed in the United States of America.
First Printing.
For updates to this book, visit http://spie.org and type "PM297" in the search field.



COVER IMAGE:

A COLOR ENHANCING CONTACT LENS FITTED ON A HUMAN CORNEA (PHOTO VIA SLIT LAMP CAMERA) EMPHASIZES THE DOME-LIKE SHAPE OF THE CORNEA.

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FOREWORD BY J. BRADLEY RANDLEMAN, MD

What an exciting time it is to be working in the space of ocular sciences and eyecare! With the advent of multiple devices and procedures that correct optical error in ways heretofore impossible, advanced eyecare has never achieved greater success and patient satisfaction than it can offer today. Patients benefit greatly from advanced contact lens materials that improve visual quality and comfort as well as customized optics that improve upon simply spherocylindrical error correction. Surgically, advanced intraocular lenses (IOLs) at the time of cataract surgery and corneal refractive procedures with advanced ablation patterns and techniques have brought newfound safety, efficacy, and patient satisfaction to the vast majority of eyes we treat primarily. We now also have the ability to correct eyes that did not obtain satisfactory outcomes from past treatments. We can repair optical zone decentrations and induced irregular astigmatism, halt corneal ectasias, and avoid operating on less-than-ideal candidates. But, all of these advances rely on the utilization of advanced corneal imaging technologies, and more importantly, on the reviewer’s ability to understand and get the most out of each technology they use in practice.

The topic of optics can baffle the most astute student and seems to turn off many practitioners, who instead focus on the medical aspects of eye care and trudge forward with only a rudimentary understanding of the optical principles that guide eyecare and vision correction. This approach has many shortcomings for patients and practitioners alike and is often driven by the way the principles of optics are presented; this series aims to change that!

The fifth, last, and my personal favorite in a series of topics under the heading *Lectures in Optics*, this book on ocular imaging has it all! This book covers each aspect of clinical imaging, providing a comprehensive explanation for the process and principles involved in each modality we use in clinics and why we use them. The approach is balanced between being comprehensive and adequately covering the most important technologies available today. This approach is warranted; there are simply too many technologies available to cover everything in complete depth; yet those devices we use most often deserve the depth of coverage they have received.

So, enjoy this great, comprehensive text. But, take the time necessary to understand the scientific principles, technologies, and techniques presented in this text; as professor Asimellis rightly points out, our technologies are only as useful as the knowledge base of their users allows.

J. Bradley Randleman, MD
Professor, Department of Ophthalmology,
Cleveland Clinic Lerner College of Medicine of Case Western Reserve University
Staff, Ophthalmology, Cole Eye Institute, Cleveland Clinic
Editor-in-Chief, Journal of Refractive Surgery

FOREWORD BY CLIFFORD SCOTT, OD, MPH

Although the fields of optics and eye care have always been intertwined, for most of the last millennium they have been constrained by the technology of the day, in both instrumentation and suitable optical materials. The past fifty years have been marked by a cascade of scientific discoveries and inventions that fostered major advancements in diagnosing ocular conditions, ocular imaging, and light-based therapeutic techniques. Advances in other scientific fields and disciplines have created new applications for enhancing visual performance, both preventive and restorative. We are now on the cusp of applying computer-age knowledge from technical fields that intersect with human vision.

George Asimellis' academic experience in particle physics, his rigorous application of scientific principles, and his intimate understanding of the complex interactions of light within various natural and human-made media have credentialed him as a bona fide scientist. His close association with eyecare practitioners and his skill in telling the story of light and imaging magnify the impact of his achievements.

I learned about the optics of the eye and lenses from textbooks full of formulas and line drawings, passed my tests, and began a half century of providing vision care to patients. Only after I was in practice did I start to acquire an appreciation of the human miracle of transforming visible light into sensory information.

I wish that there had been a version of this book available when I was a student and fledgling practitioner. My acquired fascination with light and the eye would have been stimulated by these stories and examples rather than having evolved from the world of formulas and diagrams.

Make no mistake—this is a scientific book. But its format and presentation entice you to appreciate the underlying principles and formulas. All of us who care about vision and desire to maintain proficiency in optical correction will enjoy delving into Ocular Imaging.

Clifford Scott, OD, MPH
President Emeritus
New England College of Optometry
Boston, Massachusetts

PREFACE

Historically, the fields of medicine and technology often seem to ride a plateau; the changes implemented in these fields are evolutionary rather than revolutionary. The mid-1990s were a very interesting time. That period was in many aspects quite a revolutionary one when it comes to the fields of Ophthalmology and Optometry. The crucible moment was perhaps the introduction of laser use in the refractive correction of the eye.

Suddenly, millions of spectacle wearers were given a new option, a permanent correction to their chronic need to wear spectacles or contact lenses. The news was noteworthy, but publicity is usually not a good thing. And laser procedures got a lot of publicity. Among the good, came the bad. Night vision troubles, undesired onset of ectasia… What was wrong with that?

At the same time, the field of Astronomy was facing the conundrum of the 'lets-say-it-politely' dissatisfactory image quality received by the celebrated space Hubble telescope. The answer to this problem came from two apparently unrelated developments: the understanding of wave aberrations expressed via the Zernike polynomials and the avalanche of advanced imaging developments. This is just an example of how theoretical understanding and technology can together transform the potential of diagnostic and therapeutic facility to vastly expand the spectrum of what and how ocular care can advance vision and therapy.

Corneal topography, optical coherence tomography (both anterior and posterior segment), optical low-coherence interferometry, Scheimpflug imaging, and advances in corneal biomechanics are just some of the imaging modalities that emerged around the same time. Certainly, other technological breakthroughs were ripe at the time, such as the development of digital imaging sensors and the proliferation of computers capable of handling highly demanding computational tasks; but perhaps more important was the rise to prominence of a new generation of optical and electrical engineers who worked to develop diagnostic and biometric devices for the eye.

All the above happened rather miraculously in the mid-1990s. Suddenly, eye care professionals could not only perform diagnosis, surgery, and therapy using tools not even imagined just 10 years before but were also faced with the increasing educational demand to comprehend and harness these technological tools.

I am personally fascinated by the role technology plays in our lives and in our professional capabilities. I am also a big enthusiast of aviation and its related documentaries. One of the stories that has captivated my imagination has been the 'Miracle on the Hudson'—the Airbus A320 that 'landed' on the Hudson River after losing power to both engines from bird strikes just after taking off from New York's LaGuardia Airport on a cold January morning. Was that truly a miracle? Was the plane saved because of its advanced technology?

In my opinion, the miraculous outcome was neither a miracle nor driven by technology (which helped, no doubt!). It was pure professionalism. Capt. Chesley Sullenberger (or the newly naturalized Greek citizen, Mr. Thomas Jeffrey—Tom—Hanks, whomever you prefer) is quoted as saying '*I know exactly* *what the Airbus A320 can and cannot do*.' The last part is the most important: every technological 'tool,' however advanced, has and will always have certain limitations. It is up to the properly trained professionals to know the limits of what technology can deliver. Capt. Chesley Sullenberger had precise knowledge about his 'toy' and its limits.

No laser can be safely used without a comprehensive understanding of its interaction with tissue and a thorough training of the surgeon. No clinical diagnostic device will ever tell you a number that will substitute for a methodical, detailed, elaborate, and in-person ophthalmic chair diagnosis. Technology is here to aid, facilitate, speed, document, and correct, but not as a substitute for the eye care professional. All of the technologies presented in this book carry notable weight in the proper management and planning of laser refractive procedures, as presented in the final chapter.

With that said, this book is about some, but not all, ocular imaging technologies that pertain to (mostly) the anterior segment of the eye, with the aim to cover those devices most often used. Several current diagnostic modalities are left out. There are many reasons for their omission, the primary one being the impossibility of including them all and presenting them in adequate depth. The choice of what to include in this book has been, undeniably, influenced by my personal experience in my roles as a researcher and instructor at various research, ambulatory, and educational institutions. There is no limit to how thankful I am for the influence I have received from the institutions I have had the honor to serve: Tufts University, Harvard Medical School, Wellman Labs of Photomedicine, George Mason University, Aristotle University of Greece, Democritus University of Greece, LaserVision.gr Research Center, University of Pikeville / Kentucky College of Optometry, and my current institution, the New England College of Optometry as well as the *Journal of Refractive Surgery*, for which I have the honor to serve as Associate Editor.

I hope that this final book of the *Lectures in Optics* series will be the culmination of an interesting journey for the reader and will provide significant incentive to never stop learning, never stop reading, and never stop searching for the scientific truth.

George Asimellis, PhD, MBA
Boston, Massachusetts
October, 2023

Acknowledgments

I am particularly thankful for the advice and guidance that I received from the following colleagues:

Antonio J. Del Águila-Carrasco, PhD
Lecturer in Optometry, Faculty of Health, University of Plymouth, Plymouth, United Kingdom

Thomas TJ van den Berg, PhD
Netherlands Institute for Neuroscience, Royal Netherlands Academy for Arts and Sciences, Amsterdam, The Netherlands

Bartłomiej Kałużny, MD, PhD
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Konstantinos F Katsoulos, DOptom, MSc, FBCLA, FEAOO, FAAO
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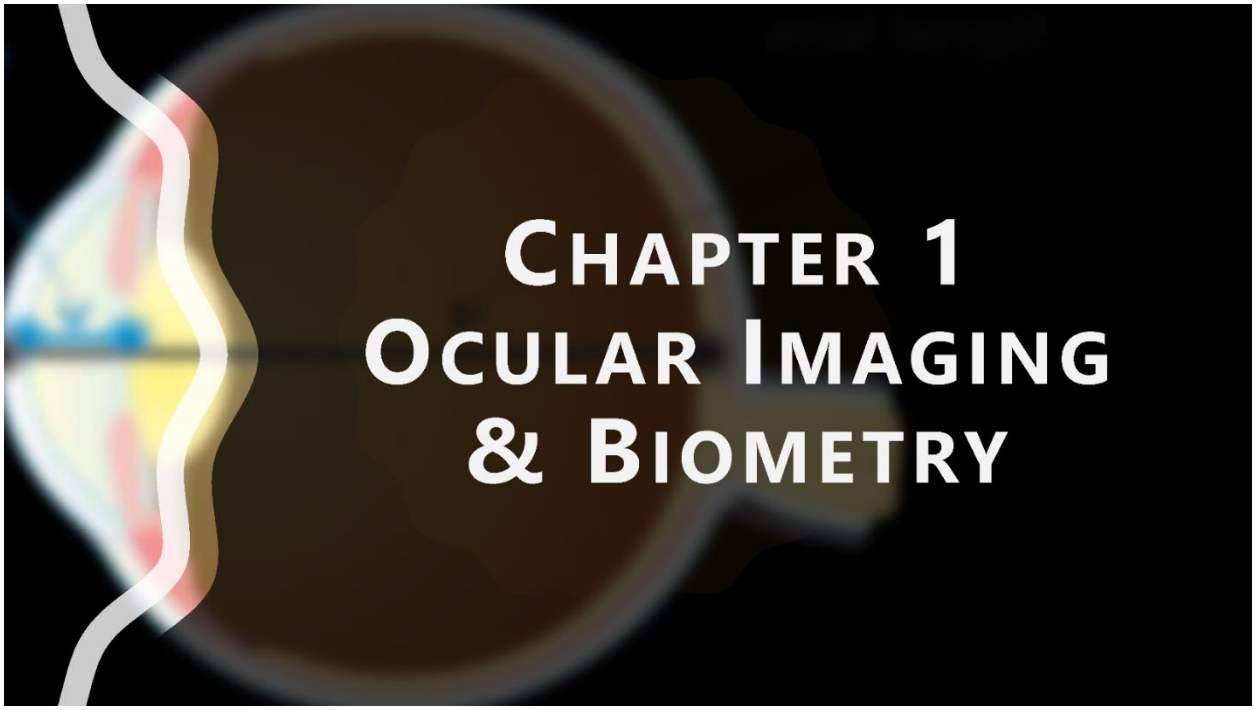
Image Credits

Most of the artwork in this book was created by the author. Any figure that was not created by the author is attributed to the source provided in the caption.

The aberrometry image data presented in Chapters 5 and 6 were initially published in an earlier version of this book, entitled *Optics and Superacuity*, ISBN 96093251-3 (2008), with the help of Drs. Lefteris Karageorgiadis, BDO, DOptom, CEO of EYEART optical centers and EYEART Laboratories (Thessaloniki, Greece) and Konstantinos Katsoulos, DOptom, MSc, FBCLA, FEAOO, FAAO, Director of Optometry at Athens Eye Hospital (Athens, Greece).



CHAPTER 1
OCULAR IMAGING & BIOMETRY

1.1 BIOMETRY

Biometry (*βιο-* for living & *-μετράν* for measuring) is a collective name describing techniques that aim to measure various dimensions in a living (*in vivo*) eye. Although the name suggests the collection and analysis of biological data, ocular biometry is far more than that, as it is considered an integral part of a complete ocular examination. The reason is that ocular biometry enables comprehensive and advanced clinical investigation through objective and detailed measurements and assessments of the structures of the living eye, which are otherwise unavailable to traditional clinical examination.

Ocular biometry measures essential anatomical dimensions of the eye; these data aid in the evaluation of certain pathologies and the assessment of the eye's visual (refractive) function. Therefore, biometry can aid in certain diagnoses[1] and together with a professional clinical evaluation can be used to suggest therapy. The measurement of the anterior chamber angle, for example, can be extremely valuable in the diagnosis of glaucoma.[2] Biometry data are essential for precise planning in refractive surgery, e.g., for laser-vision correction or calculation of the intraocular lens power to be implanted in cataract-removal surgery.[3]

---

[1] Sparrow JM, Bron AJ, Brown NA, Neil HA. Biometry of the crystalline lens in early-onset diabetes. Br J Ophthalmol. 1990; 74(11):654-60.

[2] Ursea R, Silverman R. Anterior segment imaging for the assessment of glaucoma. Expert Rev Ophthalmol. 2010; 5(1):59-74.

[3] Lee AC, Qazi MA, Pepose JS. Biometry and intraocular lens power calculation. Curr Opin Ophthalmol. 2008; 19(1):13-7.

1.3 ULTRASOUND BIOMETRY

Ultrasound biometry or echobiometry is considered one of the earliest applications of biometry, dating back to the mid-1950s.[14] This technique relies on the principle of **ultrasonography**, in which the depth of tissue structure is determined by directly measuring the time delay (time-of-flight) in the returning, acoustical backscatter (echo) signal. It employs ultrasounds in a fashion similar to procedures involving cardiac or fetal imaging (echography).

Tissue axial measurements, such as the separation of the two surfaces that confine a tissue, as well as their orientation, can be determined by the directional orientation of the acoustic pulse, the time interval between transmission and echo reception (time-of-flight), and the speed of sound in the medium.[15]

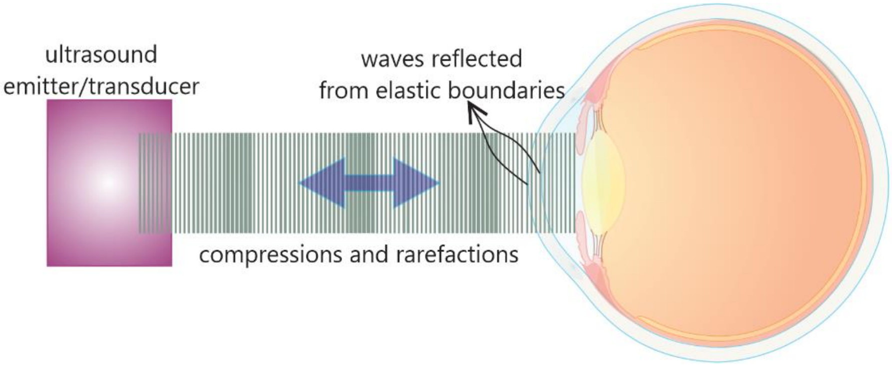


Figure 1-7: Principle of operation of ultrasound imaging.

The ultrasound wave is emitted by a piezoelectric element, called a **transducer**, which is a quartz or ceramic crystal that vibrates when a time-modulated electrical signal is applied. The sound wave can propagate and be spatially modulated (focused) by an acoustic lens or by the curved surface of the piezoelectric element. After emitting a salvo of short pulses, a brief interval allows the reflected echo to be detected by the transducer (thus, this transducer acts as both an emitter and a receiver). The detected signal is then amplified and processed by digital means to finally produce an A-scan.

The ultrasound probe, often in the form of a stylus, is manually moved over the surface of the eye while the signal strength is recorded. Strong signals are reflected from the anterior corneal surface, which is in contact with the probe or immersed in a balanced sterile saline serum. Strong signals are also received from (1) the posterior corneal surface, which separates the cornea from the aqueous, (2) the anterior and the posterior surface of the crystalline lens, and (3) the anterior retina surface. Diminishing echoes are received from choroidal tissue and orbital fat.

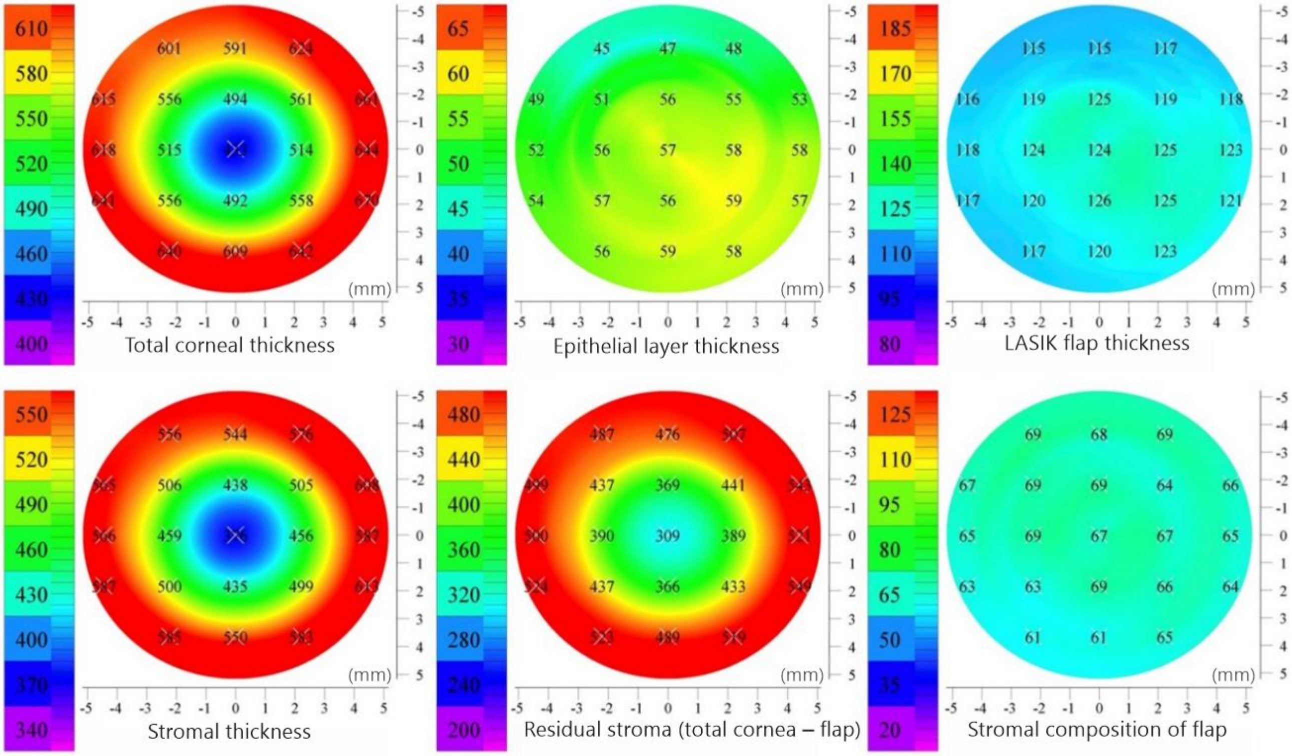


Figure 1-18: Examples of layered corneal pachymetric maps following LASIK, provided by the Artemis system. Left to right, and top to bottom: total corneal thickness, epithelial thickness, flap thickness (depth), stromal thickness, residual stroma, and stromal composition of the flap.[33]

Pros	Cons
High resolution, white-to-white visualization,	Patient discomfort during the imaging process,
Epithelial and stromal thickness maps,	Difficult to maintain centration, long acuisition time,
Corneal sublayer pachymetry, lamellar graft, and flap imaging.	Significant capital acquisition cost.

Figure 1-19: Pros and cons of ultrasound imaging.

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[33] Kanellopoulos AJ, Asimellis G. Three-dimensional LASIK flap thickness variability: topographic central, paracentral and peripheral assessment, in flaps created by a mechanical microkeratome (M2) and two different femtosecond lasers. Clin Ophthalmol. 2013; 7:675-83.

1.5 OCULAR IMAGING & BIOMETRY QUIZ

1) The differences between biometry and ocular imaging are that (two correct)
   a) biometry can only be performed on cadaver eyes
   b) ocular imaging produces (mainly) 2-D data
   c) biometry provides (mainly) numerical data
   d) ocular imaging can be performed by either acoustic or optical modalities, while biometry can only be performed using acoustic modalities

2) Which of the following can be considered as the three main advantages of the optical (in comparison to acoustic) modalities (select three)?
   a) increased resolution
   b) fast image acquisition
   c) naturally aided alignment
   d) increased penetration depth
   e) device acquisition cost
   f) non-contact mode of operation

3) An A-scan provides …
   a) axial dimensions in the eye
   b) 2-D images of the eye
   c) corneal curvature measurements
   d) estimate of the refractive status of the eye

4) In an A-scan, the data are usually presented in the form of…
   a) 1-D plot
   b) 2-D image
   c) speed of sound graph
   d) numerical sequence

5) In an A-scan, signal peaks are recorded when the wave is …
   a) refracted forward
   b) absorbed strongly
   c) reflected strongly
   d) scattered laterally

6) The resolution in an A-scan is primarily dependent on …
   a) tissue density
   b) refractive index of tissue
   c) radiated signal intensity
   d) probe wavelength

7) Which A-scan is expected to have a better axial resolution (better = shorter minimum discernible distance)?
   a) short wavelength, long pulse width
   b) long wavelength, long pulse width
   c) short wavelength, short pulse width
   d) long wavelength, short pulse width

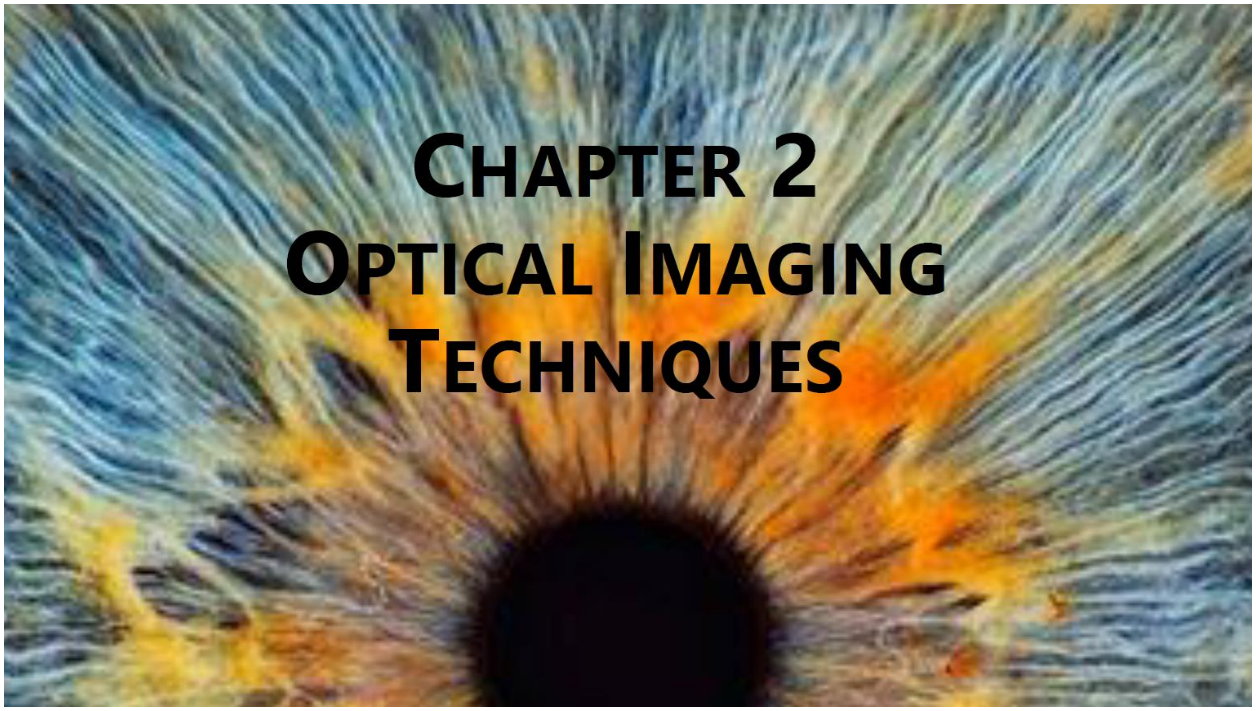
8) The signal recorded in an A-scan consists of primary returns from …
   a) tissue discontinuities
   b) dense tissue
   c) watery media
   d) neural fibers

9) The axial separation between two successive peaks in a A-scan can be an indication of … (select two)
   a) tissue thickness
   b) time of flight difference between the two points
   c) difference in refractive index
   d) surface curvature

10) The axial resolution limit (minimum discernible distance) in a good ocular acoustic imaging A-scan is about …
    a) 1 μm
    b) 10 μm
    c) 100 μm
    d) 1 mm (=1000 μm)

11) The signal intensity recorded in an A-scan is stronger when …
    a) the difference in refractive index / elastic modulus is minimized
    b) the speed of light / sound in that medium is greater
    c) the absorbance of the medium is strong at that point
    d) the tissue depth in which the probe wave propagates is long
    e) there is significant change in the speed of the probe wave across the interface

12) A B-scan relates to the A-scan by …
    a) alphabetical order
    b) an axial combination of several A-scans



CHAPTER 2
OPTICAL IMAGING TECHNIQUES

2.1 AXIAL LENGTH MEASUREMENT

The distance between the anterior and posterior poles of the eye is called the **axial length**. The axial length of the eye plays a fundamental role in visual optics because it relates to the focal length and, subsequently, the optical power associated with emmetropia.[47] While the axial length averages between 22 and 24 mm, a longer axial length—typically longer than 24 mm—is associated with axial myopia, whereas a shorter axial length —typically shorter than 22 mm—is associated with axial hyperopia.[48]

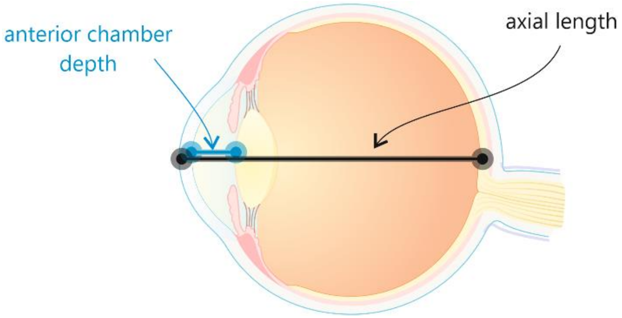


Figure 2-1: Anterior chamber depth and axial length.

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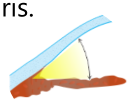
[47] *Visual Optics* § 6.2.1 Axial Length and Focal Length.

[48] Meng W, Butterworth J, Malecaze F, Calvas P. Axial length of myopia: a review of current research. Ophthalmologica. 2011; 225(3):127-34.



- The anterior chamber angle is the angle formed by the posterior cornea at the root of the iris.
- Its normal range in an adult eye is 30°.
- This angle if narrow if less than 30° and wide if more than 30°.
- Pathologies such as cataracts and glaucoma are associated with a small anterior chamber angle.

Anterior Chamber Angle

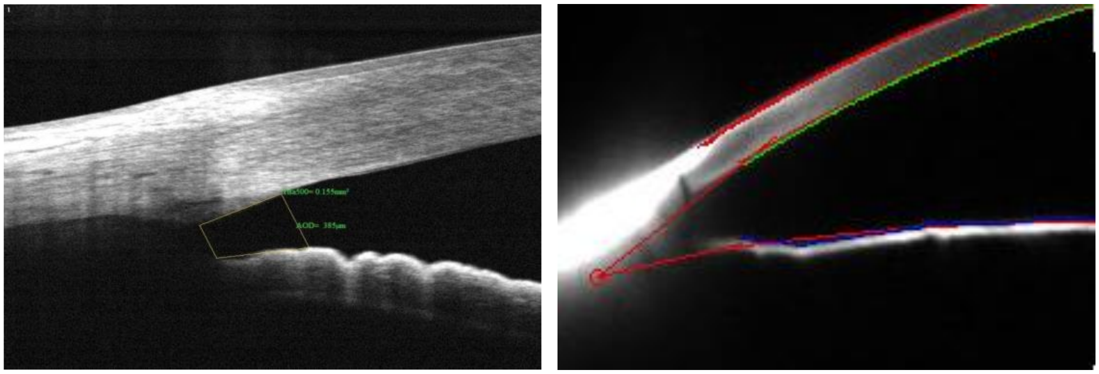


Figure 2-12: Anterior chamber angle determination with (left) OCT and (right) Scheimpflug imaging.

2.4 PUPILLOMETRY

Pupillometry (pupillometry) is the measurement of **pupil diameter**. The objective measurement of pupil diameter is among the most challenging of ocular measurements. The reason is that there are constant reflex pupil and size adjustments with varying ambient illumination, which makes a precise and accurate pupil size measurement quite complicated.

Manual measurement of pupil size can be achieved by simple visual observation alone using a millimeter ruler or pupillary scale while the examinee fixates on a distant, non-accommodative target. To avoid stimulating the accommodative response and resulting constriction, the ruler should be at a distance from the eye. Darkly shaded irises present an even larger challenge to this measurement.

Most pupillometry systems use near-infrared light to digitally capture the pupil image.[82, 83] Because the retina is not sensitive to the infrared, this radiation does not elicit a response that

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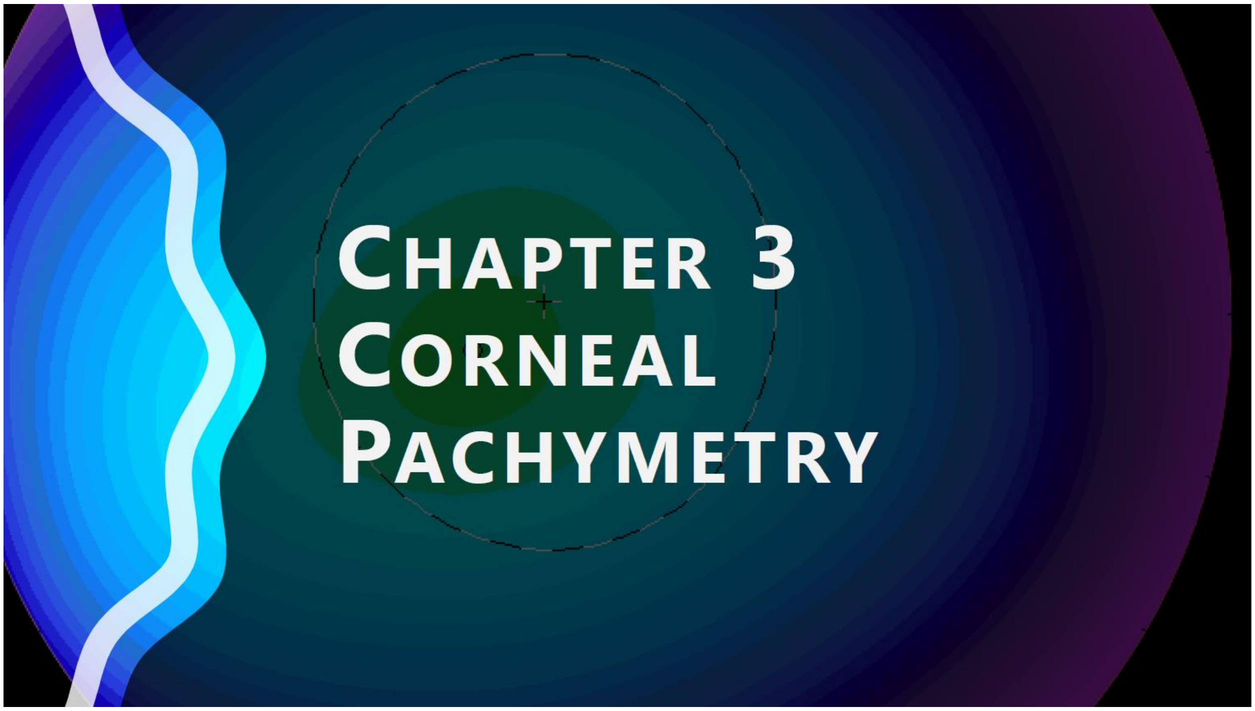
[82] Lee JC, Kim JE, Park KM, Khang G. Evaluation of the methods for pupil size estimation: on the perspective of autonomic activity. Conf Proc IEEE Eng Med Biol Soc. 2004; 2:1501-4.

[83] Roberts DK, Yang Y, Lukic AS, Wilensky JT, Wernick MN. Quantification of pupil parameters in diseased and normal eyes with near infrared iris transillumination imaging. Ophthalmic Surg Lasers Imaging. 2012; 43(3):196-204.



CHAPTER 3
CORNEAL PACHYMETRY

Corneal pachymetry encompasses techniques that measure the thickness of a live (*in vivo*) cornea, by providing either a simple numerical result or a 2-D thickness distribution map. The **corneal thickness** is defined as the separation between the anterior and posterior surface (anteroposterior distance). Corneal pachymetry is perhaps among the most developed and diverse areas of ocular biometry, and it is an indispensable part of any ocular examination.

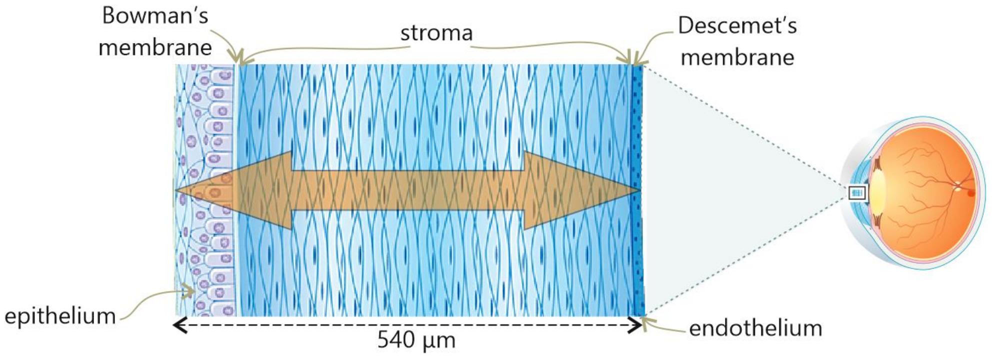
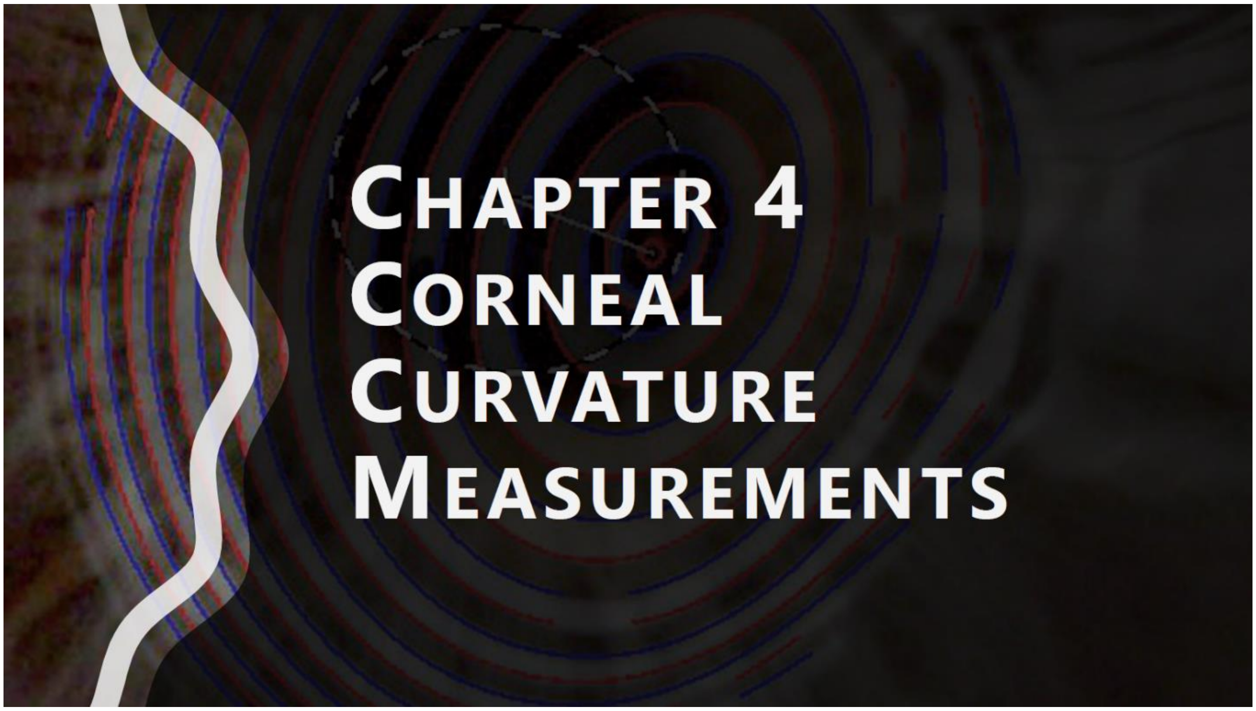


Figure 3-1: Corneal pachymetry measures the distance separating the anterior epithelium from the endothelium.

When stating corneal thickness, three parameters must be considered: the first and perhaps most important is the type of device used for this measurement. The measurement of corneal thickness requires precision on the order of a few micrometers, given the range of very short distances that are being measured. For such a short length, and considering that

Traditional Ultrasound	• 8–20 MHz sound waves • Contact • No sublayer pachymetry • Low resolution, No 2-D imaging • Not reliable peripherally • Most common method used clinically • Fast, simple technique • Not accurate for edematous corneas, difficult to reposition
Ultrasound Biomicroscopy and Scanning VHF-US	• 50 MHz up to 70 MHz • Immersion (saline bath) • Sublayer pachymetry • High resolution 2-D mapping • Easy to obtain peripheral, difficult to standardize • Post-op lamellar thickness visualization • Sublayer detail • Requires saline bath, complicated technique, difficult to standardize
Optical Slit-Lamp Pachymetry	• Image doubling, manual • Non-contact • No sublayer pachymetry • No 2-D possible • Not reliable for periphery • Slit-lamp mounted • Simple to use • Manual, observer-dependent precision
Confocal Microscopy-based	• Measures focal length through anterior–inferior • Both contact and non-contact • No sublayer pachymetry • No 2-D mapping • Not reliable for periphery • Provides cell counts • Provides cell layer visualization • Risk of corneal abrasion (for contact)
Scanning-Slit-based (Orbscan)	• Based on anterior–inferior surface reflections • Non-contact • No sublayer pachymetry • 2-D data display • Peripheral pachymetry • Applicable for post-refractive pachymetry • Concurrent topography; elevation data • Passes through center only twice



CHAPTER 4
CORNEAL CURVATURE MEASUREMENTS

The cornea is perhaps the most important optical element of the eye, since it accounts for about ⅔ of the total ocular power.[322] Knowledge of the corneal shape is essential for contact lens fitting, laser refractive surgery planning, and assessing the refractive status of the eye, among other things. Naturally, the most important aspect of the cornea is its (nearly but not perfectly so) spherical curvature of its surfaces; the corneal power depends mainly on the radius of curvature of the anterior surface[322] and, to a lesser extent, on the posterior surface.

In addition to being a strong plus-powered refracting element contributing to the formation of the retinal image, the cornea is also a convex reflecting element. The reflection seen on the eye is a minified virtual image of a window light, a bright source, or the sky, for example. The properties of these reflected images are determined by the curvature of the anterior corneal surface. Geometrical optics provides a mathematical relationship between the size of the reflected image and the radius of reflecting surface.

Studies of corneal reflections are traced to the famed Jesuit physicist Christoph Scheiner. Scheiner is credited with the first accurate description of ocular anatomy and the first form of aberrometry (§ 6.1.1). In 1619, Scheiner measured corneal curvature by comparing images formed on the cornea to those formed on glass balls of known curvature.[406] Several others also attempted to develop techniques to measure corneal curvature, including Thomas Young (1800),[407] David Brewster (1808), George Airy (1825), and Ferdinand Cuignet (1825).[408]

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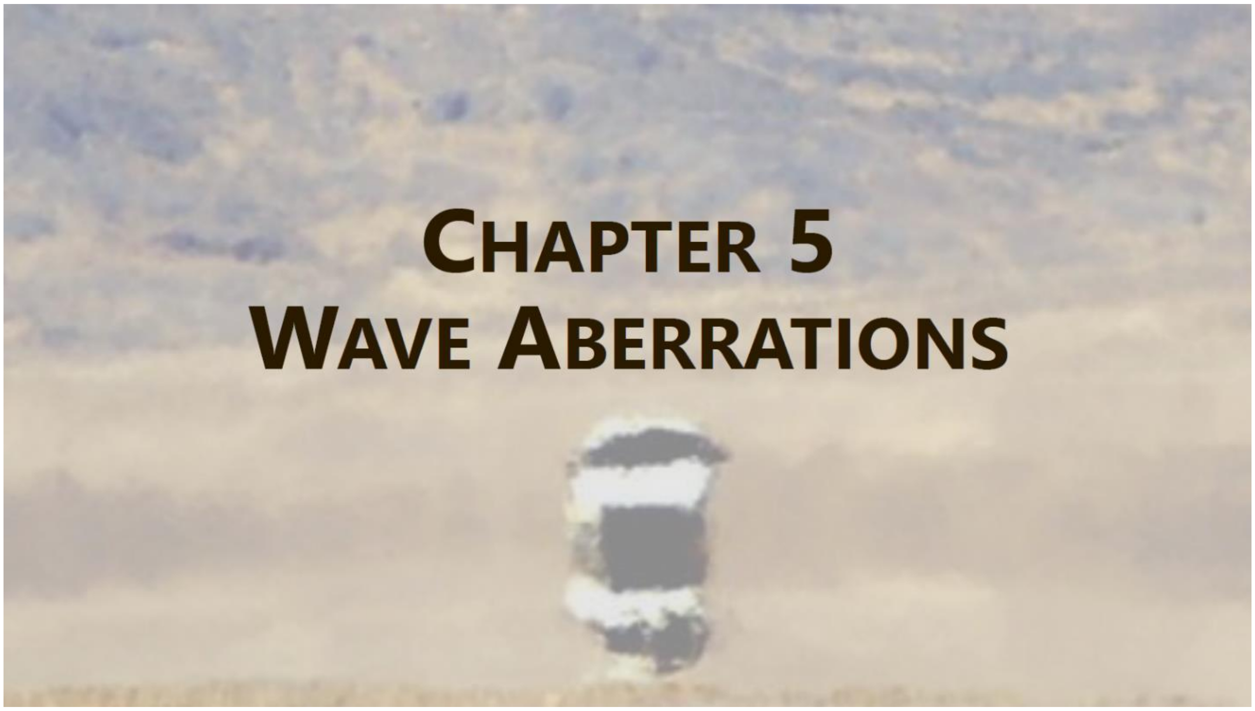
[406] Daxecker F. Christoph Scheiner's eye studies. Documenta Ophthalmol. 1992; 81(1):27-35.

[407] Young T. On the mechanism of the eye. Philos Trans R Soc Lond. 1801; 91:23-88.

[408] Brody J, Waller S, Wagoner M. Corneal topography: history, technique, and clinical uses. Int Ophthalmol Clin. 1994; 34(3):197-207.



CHAPTER 5
WAVE ABERRATIONS

5.1 THE CONCEPT OF WAVE ABERRATIONS

The word aberration hails from the Latin *ab-erratio*, which means going off track or deviating. So, what is 'off track' in optics? Simply, these are imperfections from the ideal focusing.

An ideal optical system free of aberrations has a lot in common with the legendary unicorn; it does not exist. To a certain degree, all systems result in a nonperfect image. The study and management of these 'errors' may take a geometrical optics approach, such as using the concept of ray deviations from the paraxial approximation.[614]

Another way to manage these errors is to use an alternative aspect of light as a wave. Nothing strange here, light is a wave. What is different is the way we study light propagation: not with rays, as in geometrical optics, but with wavefronts. A **wavefront** is a locus or a surface of a wave perturbation that connects points with constant phase; successive wavefronts are spaced one wavelength apart.

A wavefront can be represented in two or three dimensions in space using equispaced surfaces, separated by the length of a wavelength. A plane wavefront consists of plane surfaces. If we use rays to visualize it, it looks like a bundle of rays that travels parallel to itself (collimated) [Figure 5-1 (left)]. A spherical wavefront consists of spherical surfaces, either originating from

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[614] *Geometrical Optics* Chapter 8. Optical Aberrations.

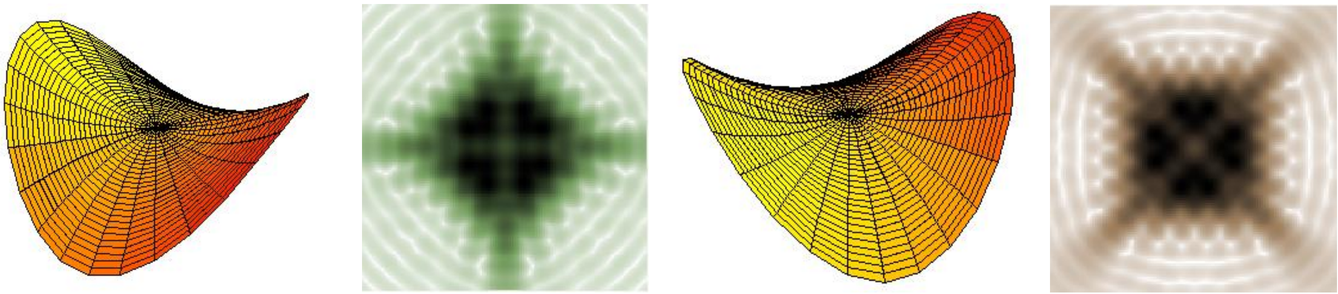


Figure 5-23: Three-dimensional representations and PSF renditions of the Z_2^{-2} and Z_2^{+2} functions.

5.3.4 High-Order Aberrations

High-order aberrations (HOA) are located in and below the fourth row of the Zernike pyramid.

Order $n = 3$

The permitted values for m are +3, +1, –1, –3. There is no $m = 0$, which means that no aberration in this order has rotational symmetry. For $m = \pm 1$, the polynomials are **vertical coma** Z_3^{-1}, and **horizontal coma** Z_3^{+1}. Their expressions are

Vertical Coma:

$$Z_3^{-1} = \sqrt{8}\,(-2\rho + 3\rho^3)\cdot\sin(\vartheta) \tag{5.7}$$

Horizontal Coma:

$$Z_3^{+1} = \sqrt{8}\,(-2\rho + 3\rho^3)\cdot\cos(\vartheta) \tag{5.8}$$

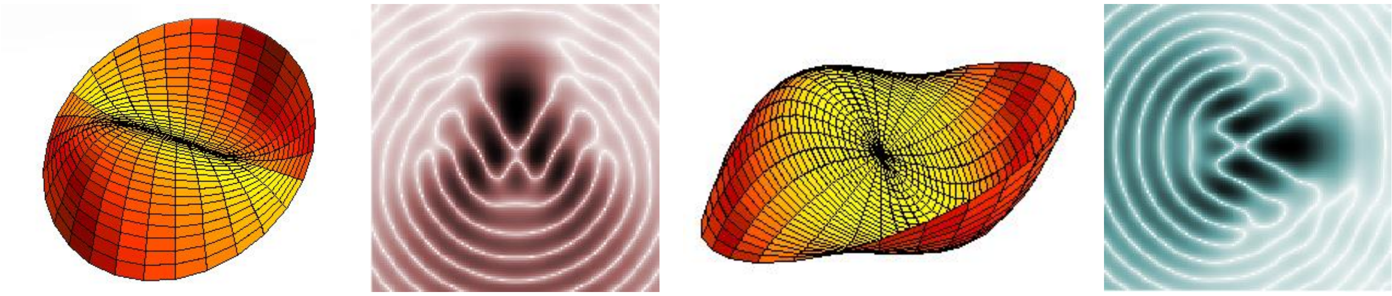


Figure 5-24: Three-dimensional representations and PSF renditions of the Z_3^{-1} and Z_3^{+1} functions.

For $m = \pm 3$, the polynomials are **vertical trefoil** Z_3^{-3} and **oblique trefoil** Z_3^{+3}:

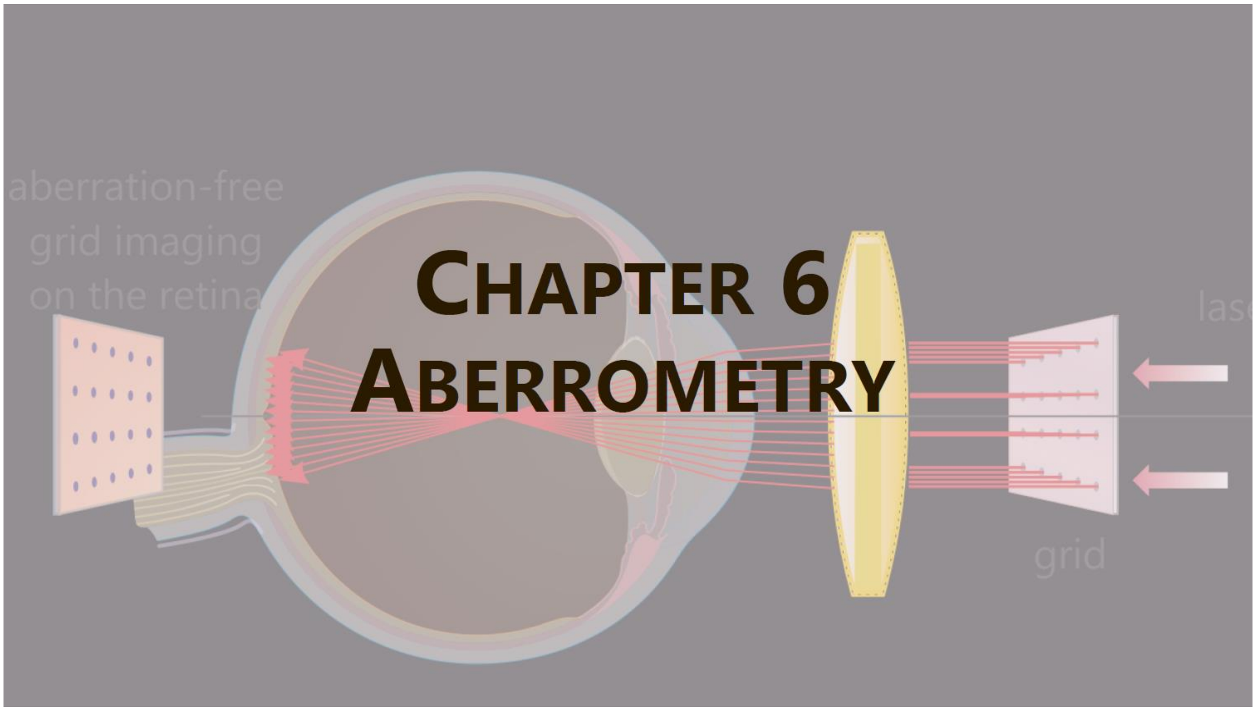
Vertical Trefoil:

$$Z_3^{-3} = \sqrt{8}\,(\rho^3)\cdot\sin(3\vartheta) \tag{5.9}$$

Oblique Trefoil:

$$Z_3^{+3} = \sqrt{8}\,(\rho^3)\cdot\cos(3\vartheta) \tag{5.10}$$

CHAPTER 6
ABERROMETRY

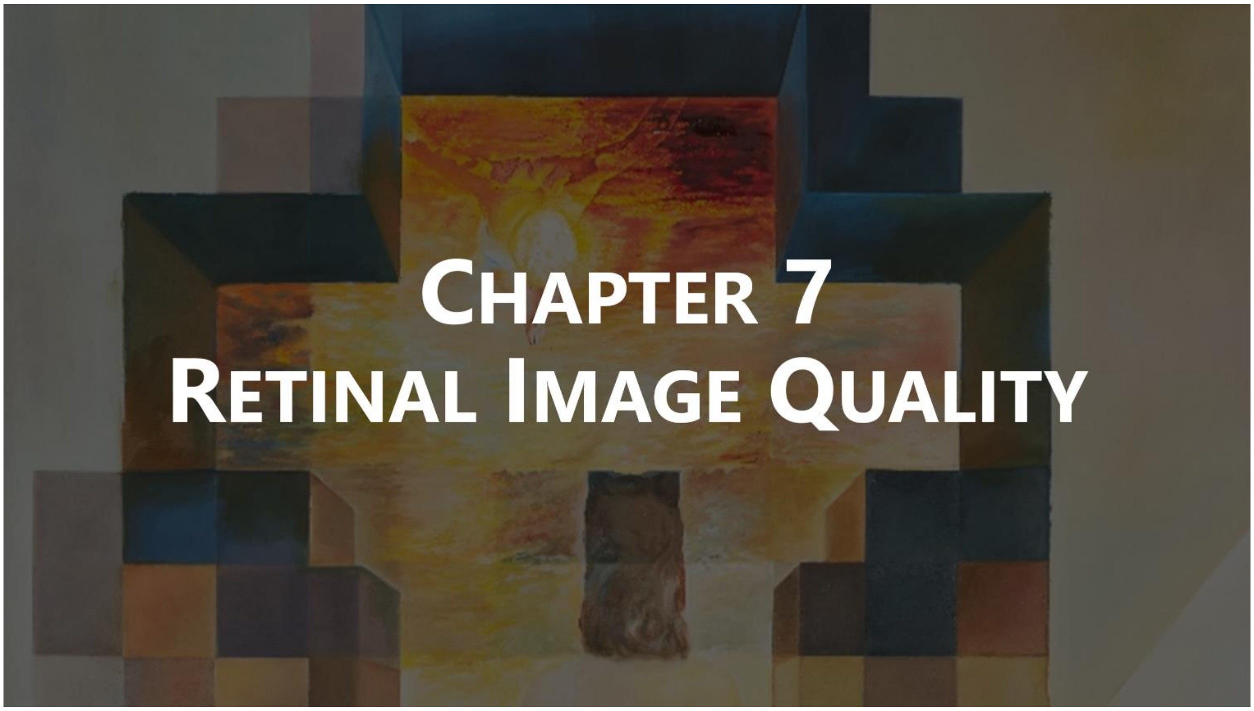


6.1 HISTORICAL DEVELOPMENT OF ABERROMETRY

The low-order or spherocylindrical aberrations, such as spherical defocus and astigmatism (§ 5.4.1) are the dominant ocular aberrations, managed with standard optical lens approaches such as spectacle and contact lenses. Therefore, the management of refractive ametropia is commonly achieved by the spherocylindrical prescription, expressed in sphere and cylinder.

Determination of the high-order aberrations such as spherical aberration and coma (§ 5.4.2) is often not part of a routine clinical ocular examination. This is because these aberrations cannot be measured with classical examination methods and their management cannot be applied with simple spherocylindrical lenses. It is true, however, that the appreciation of these high-order aberrations has gained relevance as we increasingly improve our understanding of visual function and gain refinements in refractive vision correction, such as the highly technical customized laser refractive treatments, which will be discussed in § 8.2.

The measurement of the high-order aberrations is the realm of aberrometry, which maps the transverse variability of ocular refraction across the pupil. Another term used to describe this task is wavefront sensing, whose origins trace back to astronomy. This transverse variability of ocular refraction includes all ocular aberrations, both low- and high-order. The devices, called aberrometers



CHAPTER 7
RETINAL IMAGE QUALITY

'High-order aberrations are ripples in an ocean of waves. But once the waves disappear, ripples matter.'

Larry N. Thibos

7.1 FACTORS AFFECTING RETINAL IMAGE QUALITY

Visual performance is dependent on the optical quality of the retinal image; this constitutes the optical part of vision, which pertains to the formation of the retinal image, and is dependent on the biometrical, refractive, and physical properties of the eye. This image is detected (perceived) and subject to further receptoral and neural processing. This chapter is devoted to describing how we quantify the quality of the retinal image; in other words, how we attach a 'number value' to how well we see.

The biometrical eye properties affecting image quality are the axial length—with respect to the retina and—to a lesser degree, lens location and shape (accommodative status).[733, 734, 735] The refractive aspect determines the sharpness of the retinal image, which is dependent on both the low- and high-order aberrations and also on diffraction effects, which in turn, depend on the

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[733] López-Gil N, Iglesias I, Artal P. Retinal image quality in the human eye as a function of the accommodation. Vision Res. 1998; 38(19):2897-907.

[734] He JC, Gwiazda J, Thorn F, Held R, Huang W. Change in corneal shape and corneal wave-front aberrations with accommodation. J Vis. 2003; 3(7):456-63.

[735] Maiello G, Kerber KL, Thorn F, Bex PJ, Vera-Diaz FA. Vergence driven accommodation with simulated disparity in myopia and emmetropia. Exp Eye Res. 2018; 166:96-105.

7.5 WAVE FUNCTIONS AND THEIR EFFECT ON VISION

Retinal image quality is affected by a multitude of factors. Even in an emmetropic eye, there are factors such as diffraction, high-order aberrations, absorption, and scattering along the propagation of light in the eye that affect the retinal image.

The generalized pupil function (GPF) can describe the distribution of light at the pupil (§ 7.2). We also note that GPF is dynamic, as the state of accommodation affects the expressions of GPF and the extent of aberrations.[821] The GPF is then subject to a Fourier transform to yield the PSF at the focal plane. The wavefront that corresponds to a specific ocular system describes the aberrations of that system, adjusted for the GPF distribution. These aberrations affect the shape of the formed PSF. Therefore, it is the rule rather than the exception that the PSF is not the diffraction-limited Airy disk, but a rather deformed distribution. The two main features of a deformed PSF are a reduced central intensity and an extended span on the x-y plane.

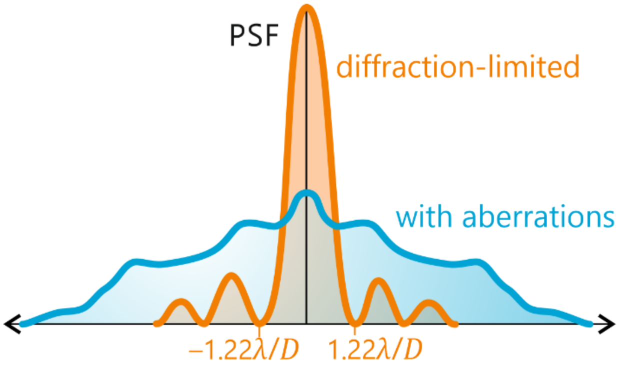

Figure 7-45: Comparison of a diffraction-limited PSF to a PSF in a system with aberrations.

Figure 7-46: PSF at the location of the circle of least confusion for (left to right) spherical aberration, astigmatism, keratoconus, and pellucid marginal degeneration.

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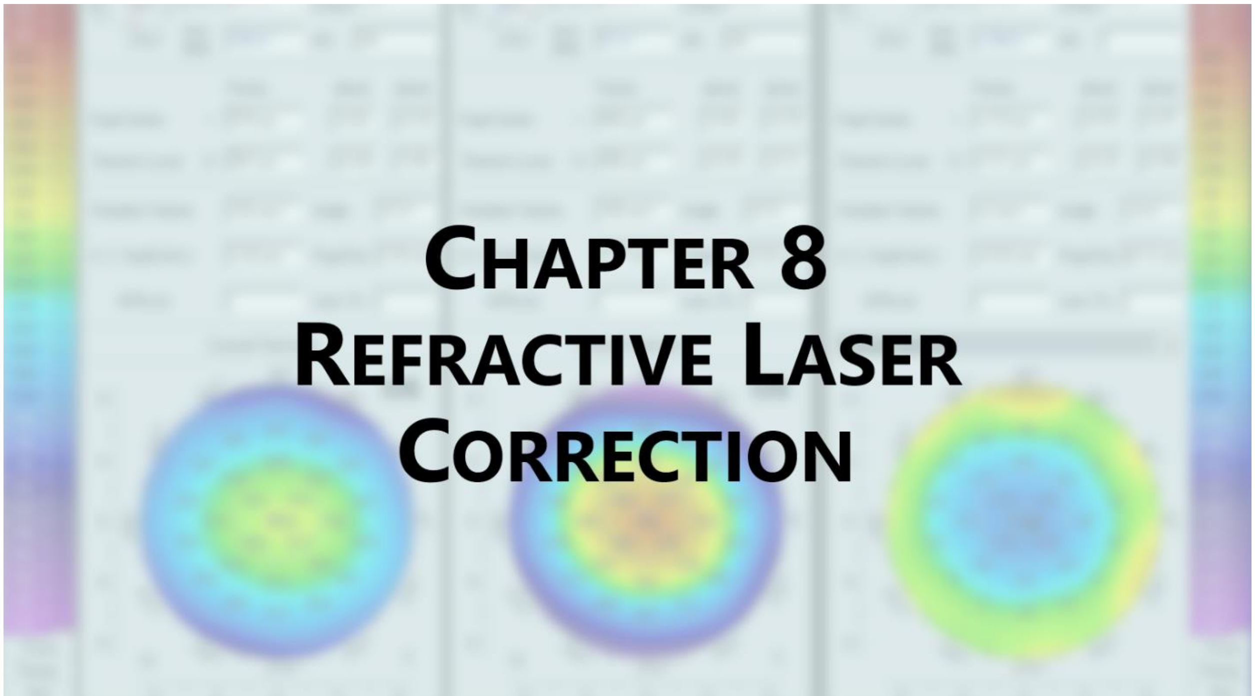
[821] Iskander DR, Collins MJ, Morelande MR, Zhu M. Analyzing the dynamic wavefront aberrations in the human eye. IEEE Trans Biomed Eng. 2004; 51(11):1969-80.



CHAPTER 8

REFRACTIVE LASER CORRECTION

8.1 LASER APPLICATIONS IN REFRACTIVE SURGERY

The concept of **refractive surgery** includes operations that intend to improve the refractive function of the eye. Often, the goal is to achieve a predictable emmetropia within ±0.25 D in a predictable and stable correction without any loss of corrected visual acuity. Less often, the goal may be to simply reduce the refractive error of the eye to the extent possible.

Depending on the application, various forms of refractive surgery affect one of the two refractive elements of the eye, the cornea and the crystalline lens. Thus, there are two major classifications within the concept of refractive surgery, corneal refractive surgery and cataract refractive surgery.

The first class, which is the most important both historically as well as by sheer popularity, involves operations that affect the corneal shape. Corneal refractive surgery has evolved as the major application of laser vision correction due to the decisive impact of the laser as the main surgical tool being used, as will be discussed in § 8.1.2 and § 8.2.

There are two reasons that the cornea is so important in refractive surgery. First, the cornea is the optical element of the eye that is responsible for ⅔ of the total ocular power. Modification of the optical power of this element alone can significantly affect the optical power of the eye. Second, the cornea is the most accessible of all optical elements of the eye.

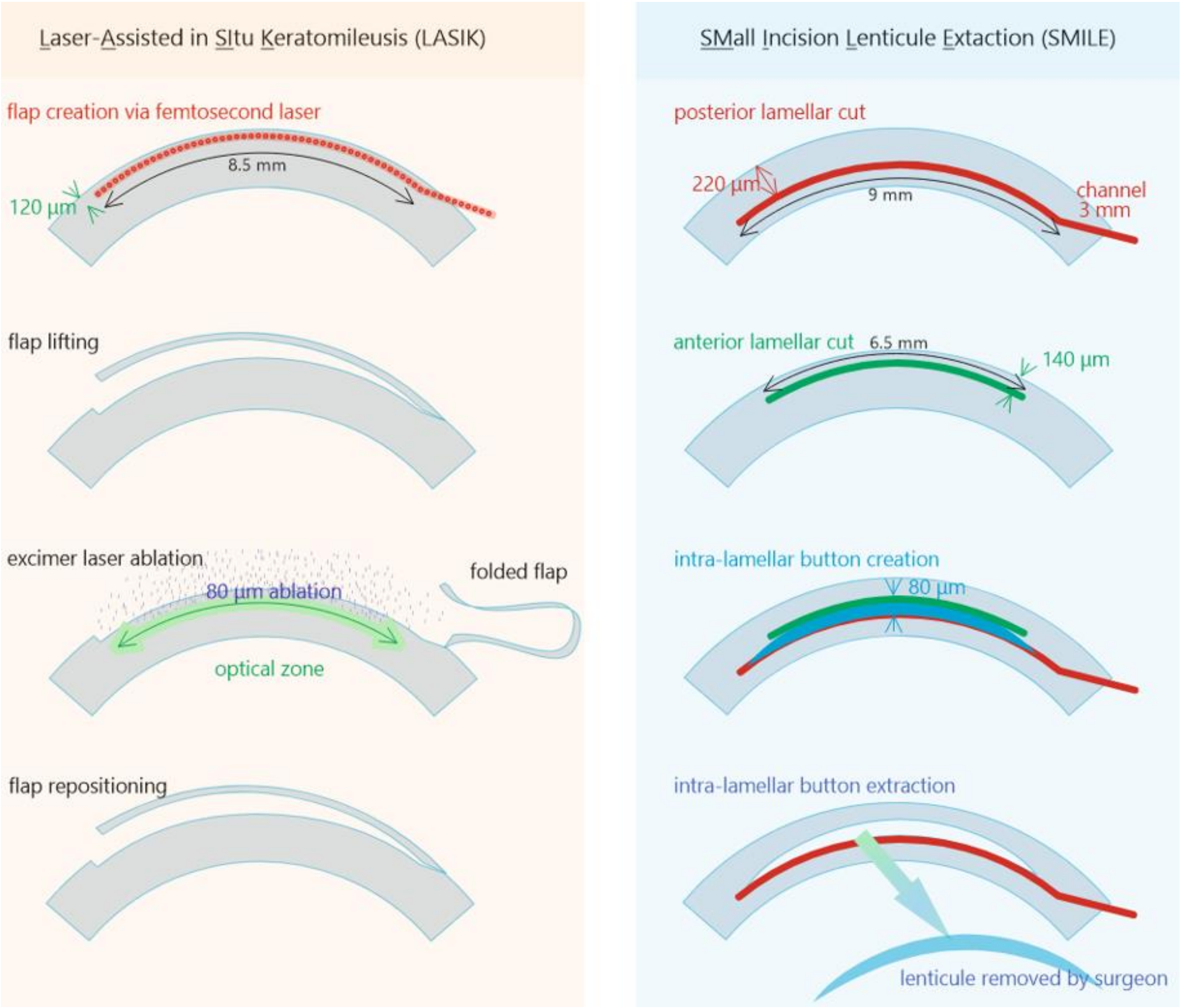


Figure 8-17: Steps involved in laser refractive procedures for correction of myopia: the LASIK and SMILE options (same amount of intended correction as in Figure 8-16).

8.3 OPTICAL PRINCIPLES OF LASER-VISION CORRECTION

8.3.1.1 Myopia Treatment

The correction of **myopia** with laser surgery aims to sculpt and change the cornea shape to a flatter contour (keratomileusis). The use of the laser achieves this by removing part of the anterior stromal tissue. The centrally thinned cornea has an anterior surface with a flatter curvature, or equivalently, an increased radius of curvature. This results in a reduced optical power such that the optical system of the eye becomes emmetropic.

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In the past, he served as Associate Professor of Optics and Research Director at the Kentucky College of Optometry (KYCO) (Pikeville, Kentucky), which he joined as Founding Faculty. Other previous positions include: Research Director at the LaserVision.gr Institute (Athens, Greece) and faculty of the Physics Department, Aristotle University (Thessaloniki, Greece); Medical School, Democritus University (Thrace, Greece); and Electrical Engineering Department, George Mason University (Fairfax, Virginia).

His doctorate research involved advanced optical signal processing and pattern recognition techniques (PhD, Tufts University, Massachusetts) and optical coherence tomography (Fellowship, Harvard University, Massachusetts). He then worked on the research and development of optoelectronic devices in a number of research centers in the USA. He has authored more than 75 peer-reviewed research publications, 8 scholarly books on optics and optical imaging, and a large number of presentations at international conferences and meetings.

He is on the Editorial Board of eight peer-reviewed journals, including the *Journal of Refractive Surgery*, for which he serves as Associate Editor. He received the 2017 Emerging Vision Scientist Award from the National Alliance for Eye and Vision Research (NAEVR).

His research interests include optoelectronic devices, anterior-segment (corneal and epithelial) imaging, keratoconus screening, ocular optics, and ophthalmological lasers. His recent contributions involve publications in clinical *in vivo* epithelial imaging and corneal cross-linking interventions.