CHAPTER 1

Introduction

After decades with relatively few new discoveries, the field of visual optics has been energized by two recent developments: refractive surgery and adaptive optics. Refractive surgery created a clinical need to better understand the optics of the eye, and adaptive optics, borrowed from astronomy, provided new tools that would allow significantly improved measurement of the eye's optical aberrations. We are now prepared to investigate, beyond what was ever possible before, key issues in visual optics such as the role of the cornea in the aberrations of the eye. The specific question that I studied in this dissertation was, What is the corneal contribution to the monochromatic aberrations of the normal human eye? This basic issue has clinical applications to the correction of vision and medical imaging of the internal eye.

1.1 APPROACHES TO VISUAL OPTICS

A fundamental problem in visual optics is, How to best measure optical quality of the human eye? To an optometrist or ophthalmologist, who routinely measures the eye's refractive error, this may appear to be a simple question. Clinically, optical quality of the eye is described by the spherocylindrical spectacle prescription, which specifies two basic optical defects: defocus and astigmatism. The refractive error is specified in terms of the lens required to correct it. Optical aberrations beyond astigmatism and defocus also exist, but in current practice these are ignored for several reasons. First, in normal eyes, these residual aberrations degrade vision very little compared to defocus or astigmatism. Next, there is no clinical test available for measuring the higher order aberrations. Finally, even if the aberrations could be measured, conventional spectacle lenses cannot correct them. For the vast majority of patients, higher order optical aberrations are clinically insignificant. Until recently, and except for cases such as keratoconus, most doctors rarely saw patients with optical defects that could not be largely corrected with either spectacles or contact lenses.

Circumstances are quickly changing, and for many patients, higher order optical aberrations are becoming an important consideration. Three recent developments in eye care and vision science account for this. First, the yet-to-be-perfected refractive surgeries are producing a population of patients with abnormally large optical aberrations (Maguire, 1994). Next, new methods have been developed to measure those aberrations (Salmon & Thibos, 1998). Finally, new devices are being developed that can correct the higher order aberrations of the eye. Deformable mirrors have recently been used in the laboratory to correct the eye's aberrations (Liang, Williams, & Miller, 1997), and liquid-crystal micro lens arrays, which may one day work like electronic spectacles, are under investigation (Thibos & Bradley, 1997; Vargas-Martin, Prieto, & Artal, 1998). Measurement of the eye's optical aberrations is therefore becoming both clinically relevant and technologically feasible. Correction for aberrations will certainly become an integral part of refractive surgery and contact lens fitting of the future.

1.2
OPTICAL QUALITY VERSUS IMAGING PERFORMANCE

One direct approach for evaluating an optical system, such as the eye, is to measure the properties of light passing through the system. Optical performance can also be evaluated indirectly by measuring image quality. For the human eye, a familiar test of image quality is the Snellen visual acuity test. If a patient has 20/15 vision, the doctor usually assumes that they have no significant refractive error (i.e., good optics). On the other hand, if the patient's visual acuity is 20/200 (i.e., poor image quality), the doctor can suspect a refractive error, though without actually measuring the refraction, he will not be able to correct it. Since the eye's aberrations are difficult to measure directly, visual optics research over the last half century has relied on tests of retinal image quality (indirect approach) to evaluate optical performance of the human eye. One technique, the double-pass method, has been used to estimate the eye's modulation transfer function (MTF). Newer tests, which directly measure aberrations in the light itself, can be used to compute, not only the MTF, but other measures of imaging performance such as the phase transfer function, and point spread function. The converse, however, is not true. Neither the optical defects nor the required optical correction can be determined from image quality alone. Shortly before I began this research, a Shack-Hartmann wavefront sensor was, for the first time, used to directly measure the aberrations of the human eye (Liang, 1991; Liang, Grimm, Goelz, & Bille, 1994), and I incorporated this new technology as a major component of my research.

Optical reflection, scatter, and absorption can all theoretically degrade image quality, but for most normal eyes these factors are relatively small and were not investigated in this study. Diffraction is another optical phenomenon that always affects image quality to some degree, and it was taken into account with the wavefront aberration functions when I evaluated imaging performance. In most natural conditions the human eye uses polychromatic light, and chromatic aberration is an important factor that limits retinal image quality. Chromatic aberration varies little between individuals (van Meeteren, 1974). Because of its predictability, chromatic aberration can be calculated by integrating the spectral sensitivity weighted, wavelength dependent defocus across the visible spectrum (Bour, 1980; van Meeteren & Dunnewold, 1983; Thibos, 1987). Monochromatic aberrations, however, show large individual variations (Atchison, Collins, Wildsoet, Christensen, & Waterworth, 1995; Campbell, Bobier, & Roorda, 1995; Collins, Wildsoet, & Atchison, 1995), so they must be measured rather than calculated. This research was concerned with measuring the monochromatic aberrations of the corneal surface and whole eye for three normal eyes.

1.3 Applications

A full knowledge of the eye's optical defects is the key to its complete optical correction. Better optical correction has applications in two broad areas of clinical eye care; namely, visual correction and diagnostic retinal imaging (Fig. 1). Obviously, excellent optical quality is necessary for excellent vision, since light travels inward, through the eye's optics, to form the retinal image. This is the starting point for the visual process. A better understanding of corneal optics and it's role in the optics of the whole eye can help us evaluate and improve vision.

In the case of diagnostic retinal imaging, light is reflected out of the eye and passes outward through the eye's optics. The optical elements of the eye serve as the objective lens of an imaging system designed to view the internal eye. Correction of the eye's optical defects, including the higher order aberrations, has enabled scientists to visualize microscopic structures never before seen in the living eye (Liang, Williams & Miller, 1997), and this is creating new opportunities for basic research and early diagnosis of retinal diseases.

At this point, our understanding of the eye's optics is incomplete. This research is designed to address one of the key unresolved issues—the corneal contribution to the monochromatic aberrations of normal eyes. A knowledge of the aberration structure of normal eyes is a precursor to the correction of aberrations in both normal and anomalous eyes.

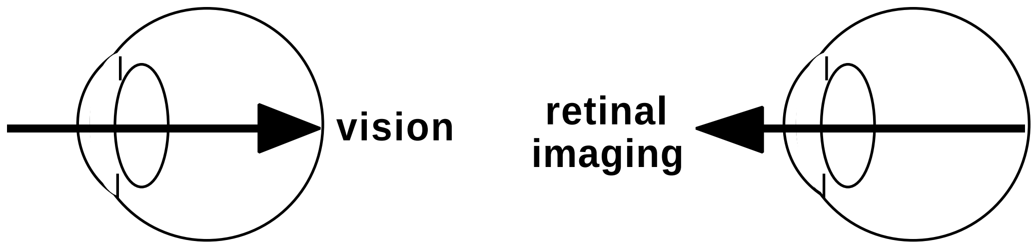

Figure 1
Light must pass through the same optical system, though in opposite directions, for both vision (left) and diagnostic retinal imaging (right). Better optical correction will benefit both.