Adaptive Optics for Vision Science

Principles, Practices, Design, and Applications

Edited by

JASON PORTER, HOPE M. QUEENER, JULIANNA E. LIN,
KAREN THORN, AND ABDUL AWWAL

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Front cover art: In an adaptive optics system, a lenslet array (left circle) is used to measure an aberrated wavefront (top circle) that is then corrected by a deformable mirror (right circle) to produce a flattened wavefront (bottom circle). Lenslet array and deformable mirror images are courtesy of Adaptive Optics Associates, Inc. and Boston Micromachines Corporation, respectively.

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Foreword

The rationale for this handbook is to make adaptive optics technology for vision science and ophthalmology as broadly accessible as possible. While the scientific literature chronicles the dramatic recent achievements enabled by adaptive optics in vision correction and retinal imaging, it does less well at conveying the practical information required to apply wavefront technology to the eye. This handbook is intended to equip engineers, scientists, and clinicians with the basic concepts, engineering tools, and tricks of the trade required to master adaptive optics-related applications in vision science and ophthalmology.

During the past decade, there has been a remarkable expansion of the application of wavefront-related technologies to the human eye, as illustrated by the rapidly growing number of publications in this area (shown in Fig. F.1).

The catalysts for this expansion have been the development of new wavefront sensors that can rapidly provide accurate and complete descriptions of the eye's aberrations, and the demonstration that adaptive optics can provide better correction of the eye's aberrations than has previously been possible. These new tools have generated an intensive effort to revise methods to correct vision, with the wavefront sensor providing a much needed yardstick for measuring the optical performance of spectacles, contact lenses, intraocular lenses, and refractive surgical procedures. Wavefront sensors offer the promise of a new generation of vision correction methods that can correct higher order aberrations beyond defocus and astigmatism in cases where these aberrations significantly blur the retinal image.

The ability of adaptive optics to correct the monochromatic aberrations of the eye has also created exciting new opportunities to image the normal and diseased retina at unprecedented spatial resolution. Adaptive optics has strong roots in astronomy, where it is used to overcome the blurring effects of atmospheric turbulence, the fundamental limitation on the resolution of

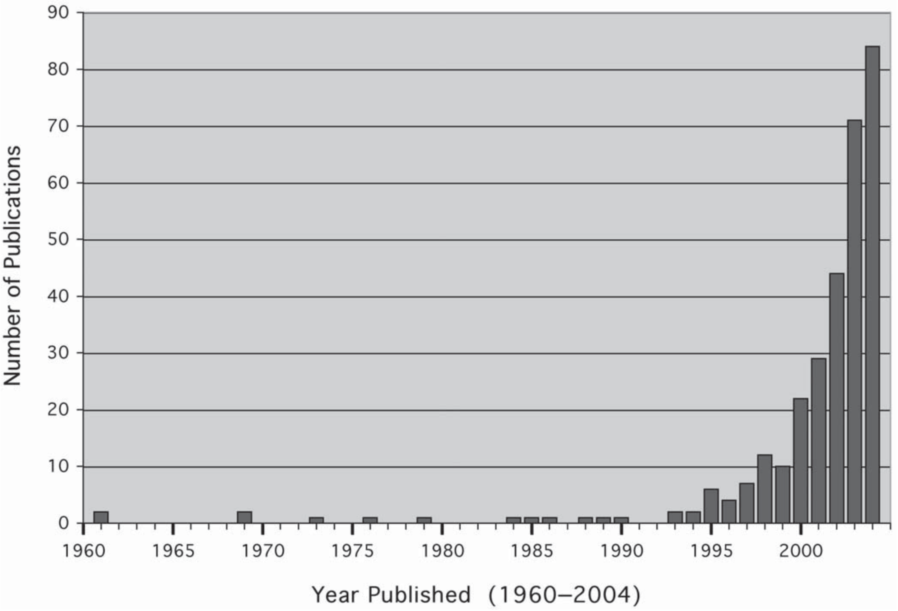

FIGURE F.1 Number of publications listed in PubMed (National Library of Medicine) that describe work where wavefront sensors were used to measure the full wave aberration of the human eye. Types of wavefront sensors included in this graph: Shack–Hartmann, spatially resolved refractometer, crossed-cylinder aberroscope, laser ray tracing, scanning slit refractometer, video keratography, corneal topography, phase retrieval, curvature sensing, and grating-based techniques.

ground-based telescopes. More recently, adaptive optics has found application in other areas, most notably vision science, where it is used to correct the eye's wave aberration. Despite the obvious difference in the scientific objectives of the astronomy and vision science communities, we share a technology that is remarkably similar across the two applications.

Recognizing this, together with Jerry Nelson and other colleagues, we created a center focused on developing adaptive optics technology for both astronomy and vision science. The Center for Adaptive Optics, with headquarters at the University of California, Santa Cruz, was founded in 1999 as a National Science Foundation Science and Technology Center. Initially under the leadership of Jerry Nelson and more recently of Claire Max, the Center for Adaptive Optics is a consortium involving more than 30 affiliated universities, government laboratories, and corporations. The Center has fostered extensive new collaborations between vision scientists and astronomers (who very soon discovered they were interested in each others' science as well as their technology!). This handbook is a direct result of the Center's collaborative energy, with chapters contributed by astronomers and vision scientists alike.

We wish to thank all of the contributors for generously sharing their expertise, and even their secrets, within the pages of this book. Especially, we congratulate Jason Porter, lead editor, and Hope Queener, Julianna Lin, Karen Thorn, and Abdul Awwal, coeditors, for their tireless dedication to this significant project.

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JASON PORTER

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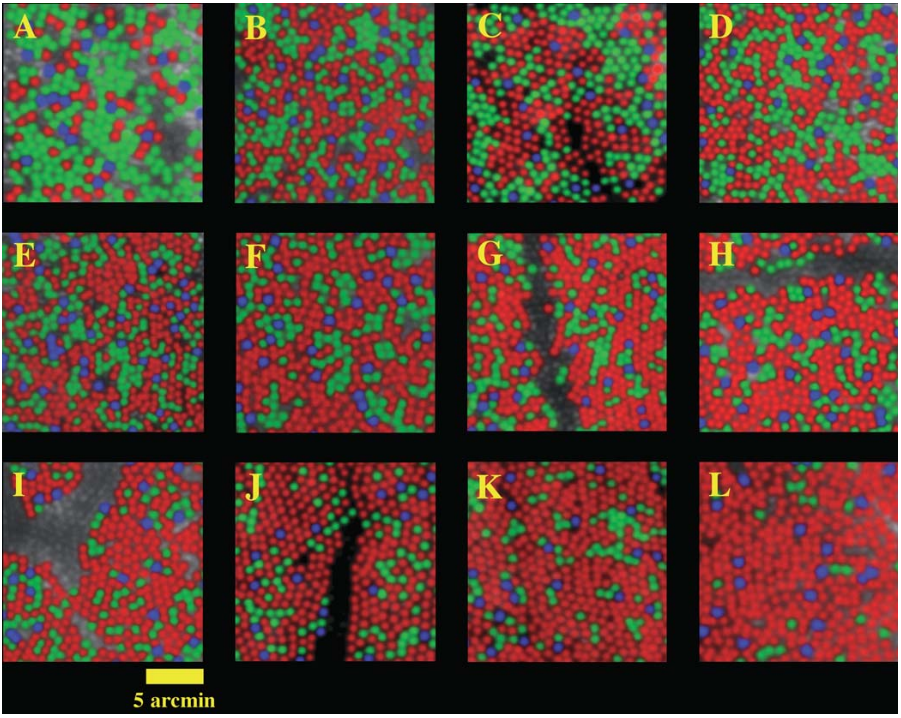
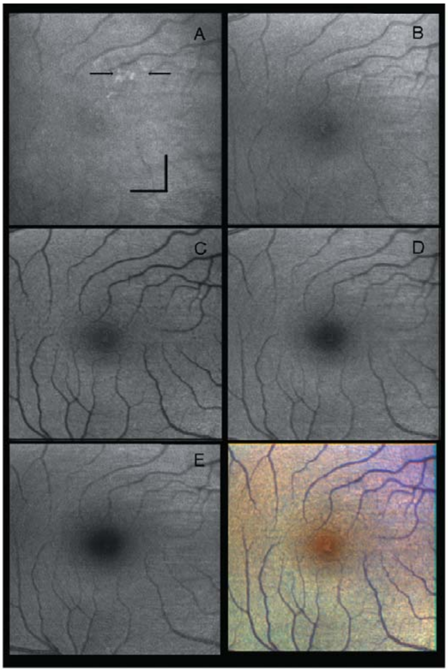


FIGURE 1.7 Images of the cone mosaics of 10 subjects with normal color vision, obtained with the combined methods of adaptive optics imaging and retinal densitometry. The images are false colored so that blue, green, and red are used to represent the S, M, and L cones, respectively. (The true colors of these cones are yellow, purple, and bluish-purple). The mosaics illustrate the enormous variability in L/M cone ratio. The L/M cone ratios are (A) 0.37, (B) 1.11, (C) 1.14, (D) 1.24, (E) 1.77, (F) 1.88, (G) 2.32, (H) 2.36, (I) 2.46, (J) 3.67, (K) 3.90, and (L) 16.54. The proportion of S cones is relatively constant across eyes, ranging from 3.9 to 6.6% of the total population. Images were taken either 1° or 1.25° from the foveal center. For two of the 10 subjects, two different retinal locations are shown. Panels (D) and (E) show images from nasal and temporal retinas, respectively, for one subject; (J) and (K) show images from nasal and temporal retinas for another subject. Images (C), (J), and (K) are from Roorda and Williams [52]. All other images were made by Heidi Hofer. (See page 16 for text discussion.) (From Williams and Hofer [57]. Reprinted with permission from The MIT Press.)



830 nm

Drusen

633 nm

Some Nerve
Fiber Layer

543 nm

Retinal Vessels

514 nm

Some
Macular
Pigment

488 nm

Macular Pigment,
Nerve Fiber Layer

633, 543, and
488 nm

Images
Combined

FIGURE 9.9 Images centered on the human macula, acquired with laser illumination over a range of wavelengths. The bottom right panel is the combination of three colors: red (633 nm), green (543 nm), and blue (488 nm). (See page 219 for text discussion.)

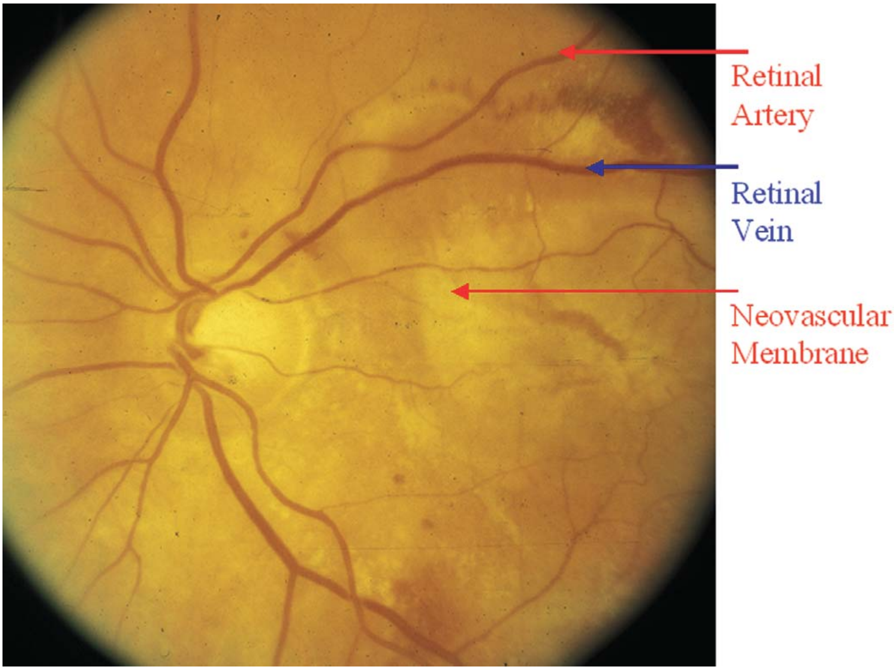


FIGURE 9.10 A color fundus photograph of the patient in Figures 9.4 and 9.5, showing that the larger retinal vessels are seen, but that the choroidal ones (other than the largest ones that feed and drain the neovascular membrane) are obscured. (See page 219 for text discussion.)