Translational Science Review

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# Retinal Imaging in the Twenty-First Century

## *State of the Art and Future Directions*

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Assessment of chorioretinal disease is dependent on the ability to visualize pathologic changes occurring in the posterior segment of the eye using optical instruments, termed *ophthalmoscopy*. Ophthalmoscopy, in turn, has been enhanced greatly by the development of techniques that allow recording of these changes, termed *retinal imaging*. As well as documenting pathologic features, retinal and fundal imaging facilitates the identification of morphologic features not visible to the clinician on biomicroscopy. As such, advances in retinal imaging have proven fundamental to many paradigm shifts in our understanding and treatment of ocular disease. In the 1950s, with the advent of electronic flashes and 35-mm cameras, the field of modern fundus photography was born. Similarly, in the 1960s and 1970s, the introduction of fluorescein and indocyanine green angiography revolutionized our ability to assess the integrity of the chorioretinal vasculature. More recently, in the 1990s, the introduction of a wholly new form of noninvasive cross-sectional imaging, optical coherence tomography, has greatly facilitated use of emerging pharmacotherapies in diagnosing and monitoring chorioretinal disease. In this translational science review, we provide an overview of current, state-of-the-art retinal imaging technologies, as well as highlight many emerging imaging technologies that we believe are likely to transform the provision of eye care in the 21st century. *Ophthalmology 2014;■:1–12 © 2014 by the American Academy of Ophthalmology.*

Among all the medical specialties, ophthalmology is perhaps the most technology driven. Innumerable medical lasers have been developed for ophthalmic use, with applications as diverse as correction of refractive error, removal of cataracts, or treatment of retinal disease. Similarly, advances in clinical optics and medical imaging have proven fundamental to many paradigm shifts in our understanding and treatment of ocular disease. In fact, many advances first pioneered in ophthalmology have been extended to use in other medical specialties and even to nonmedical fields. A case in point is the invention of optical coherence tomography (OCT) in the 1990s,[1] the potential of which is increasingly being recognized in other medical fields such as cardiology, gastroenterology, and dermatology and in areas of nonmedical research as diverse as archeology, art conservation, and biometrics.[2]

Outside medicine, technology continues to move quickly, with the recent introduction of mobile and so-called wearable technologies, such as smartphones, smart wristwatches, and optical head-mounted displays such as Google Glass (Google Inc, Mountain View, CA). Our day-to-day lives—from ordering a taxi to working out in a gym—also have been transformed by the widespread use of mobile software applications (known as "apps"). These advances have contributed in large part to the emerging world of so-called Big Data, the collection of massive data sets with the potential to transform fields such as meteorology, Internet searching, finance and business informatics, environmental research, or, indeed, medicine.

In the second decade of the 21st century, therefore, it is incumbent on ophthalmologists to embrace—and contribute to—these technologic advances. The rapidly evolving field of ophthalmic imaging may offer some of the best opportunities to achieve this aim. Although ongoing advances in ophthalmic imaging certainly will offer incremental increases in specifications such as speed and resolution, deeper changes are also afoot, with the potential for fundamental shifts in the way that imaging technology is used in eye examination. These shifts will include new indications for imaging across the spectrum of ophthalmic disease, as well as increased ease of use, portability, durability, and automation of devices. They will also encompass an increased use of multimethod imaging, as well as advances in image analysis to facilitate an


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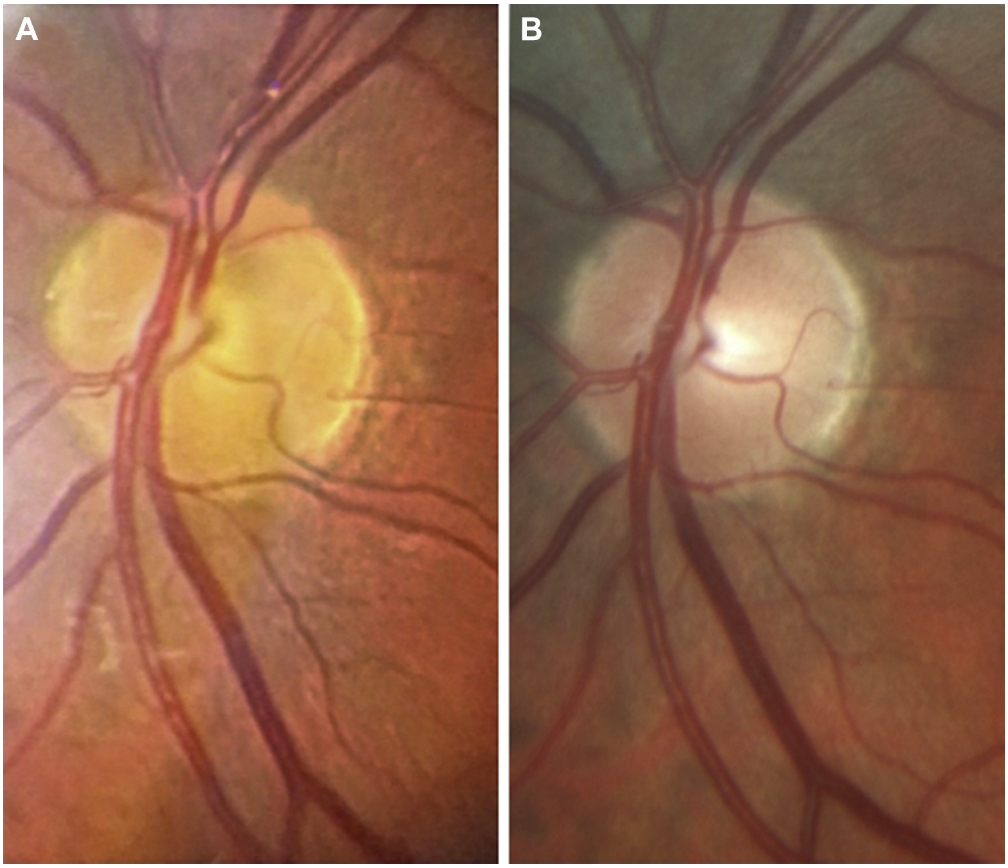


**Figure 1.** Images comparing smartphone ophthalmoscopy with conventional funduscopy. **A**, Color fundus photograph obtained using PEEK, a smartphone-based system for comprehensive eye examination (www.peekvision.org). **B**, Color fundus photograph obtained using a conventional, desktop fundus camera. (Images courtesy of Andrew Bastawrous, London School of Hygiene and Tropical Medicine, London, UK.)

increasingly quantitative approach to the study of eye disease.

In this report, we provide an overview of current, state-of-the-art retinal imaging technologies, as well as highlight many emerging imaging technologies that we believe are likely to transform the provision of eye care in the 21st century.

## Topographic Imaging of the Fundus

### Color Fundus Photography

The history of ophthalmic imaging dates back to the late 1800s, when Jackman and Webster developed a technique for photographing the retina in a living human subject. In the 1950s, with the advent of electronic flashes and 35-mm cameras, fundus photography became practical in routine clinical settings. Since then, color fundus photography has been an essential component of ophthalmic examination, with numerous enhancements, including optimization for nonmydriatic and stereoscopic image acquisition and transition from analog to digital image capture.

In recent years, driven in large part by the widespread adoption of smartphone photography, efforts have been underway to make fundus cameras cheaper, more robust, and easier to use. For example, adaptors are now available to allow smartphone image capture when performing direct ophthalmoscopy. Perhaps more exciting, PEEK, a smartphone-based system for comprehensive eye examinations (www.peekvision.org), currently is being evaluated as part of the Nakuru Eye Disease Project in Kenya and as part of the Coldest Journey winter expedition in Antarctica (Fig 1). These developments are likely to have profound benefits for general ophthalmic examination in the developing world, as well as greatly improving eye examination in pediatric settings and by nonophthalmic-trained physicians in the developed world.

### Scanning Laser Ophthalmoscopy

In fundus cameras, a bright ring of white light is used to illuminate the ocular fundus, the light reflected from the fundus then is captured using film or digitally using a charge-coupled device. In the 1980s, the introduction of scanning laser ophthalmoscopy (SLO) provided an alternative method for the acquisition of fundus images. Scanning laser ophthalmoscopy devices use a single point of laser light at a specific wavelength, which is scanned across the retina in a series of parallel horizontal lines. In this sense, SLO imaging may be thought of as analogous to image