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Correction of aberrations in the human eye using computational methods

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Abstract

Phase-sensitive imaging and computational correction of patient-specific optical aberrations enable high-resolution imaging of the human retina to aid diagnosis and treatment of eye diseases.

Optical imaging is widely used to examine the human eye, both in clinical and research settings. To image the retina, light must first pass through the cornea and lens. Unfortunately, the optics in the eye are imperfect and introduce significant aberrations, which vary from person to person. To obtain high-resolution images of the human retina, it is necessary to correct for these patient-specific aberrations.

It is possible achieve aberration correction through use of a hardware adaptive optics (HAO) system,[1] which exploits a wavefront sensor to measure the optical aberrations, and a deformable mirror to correct them. HAO systems are costly and complex, however, and have not seen widespread use. Ideally, we would obtain high-resolution images without requiring these hardware additions. Using a popular phase-sensitive imaging technique called optical coherence tomography (OCT), it is possible to correct aberrations computationally. We call this approach computational adaptive optics (CAO), and it was first demonstrated by Adie and co-workers,[2,3] who showed correction of aberrations in ex vivo samples. Liu and co-workers[4] later extended the technique to in vivo samples.

OCT is a phase-sensitive imaging technique. Thus, it provides access to the complex values of the optical wavefront returning from the sample being imaged. We can manipulate this wavefront computationally to remove aberrations. Additionally, OCT provides depth-resolved imaging, which we can use to isolate and correct specific depth layers of interest, termed ‘en face’ planes (see Figure 1).

In recent work, we extended CAO to retinal imaging.[5,6] The living human eye constantly moves, even involuntarily, and this movement disrupts the phase information needed for CAO. To overcome this issue, we constructed a high-speed en face OCT system that acquires data from a single retinal layer at 4000 en face lines per second. This was fast enough to overcome the transverse motion of the eye. However, even at this speed, it was necessary to apply a phase-based algorithm to correct residual axial motion. After correcting for motion, we removed the aberrations by applying a phase-only filter in the spatial frequency domain of the image. There are several methods by which we can determine the appropriate correction. These approaches include optimization of image sharpness metrics, guide-star optimization (using a point-scattering wavefront reference from within the sample itself), and computational wavefront sensing comparable to the popular Shack-Hartmann sensor. We used each of these approaches successfully in the human eye.

Our approach resulted in a high-resolution image of retinal layers achieved without the use of additional HAO components (see Figure 2). The images show cone photoreceptors (neurons in the retina) and retinal fibers, both of which are involved in the process of diseases such as macular degeneration, glaucoma, and multiple sclerosis. Improved visualization of the retina using aberration correction could lead to better diagnosis and treatment of disease.

In summary, computational aberration correction provides a promising alternative to traditional hardware methods to achieve high-resolution retinal imaging. We have shown computational aberration correction for imaging of multiple retinal layers. Our future work will focus on making the imaging system and software methods robust for widespread use.

Biographies

Fredrick South received his BS and MS in electrical and computer engineering from the University of Illinois in 2010 and 2013, respectively. He is currently a PhD candidate in the Biophotonics Imaging Laboratory at the Beckman Institute for Advanced Science and Technology. His research focus is on development of computational optics for biomedical imaging.

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Stephen Boppart is an Abel Bliss Professor of Engineering, and has appointments in the Departments of Electrical and Computer Engineering, Bioengineering, and Medicine. He is head of the Biophotonics Imaging Laboratory at the Beckman Institute for Advanced Science and Technology.

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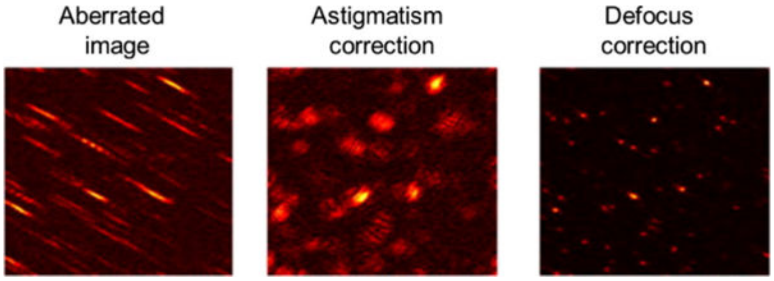

Figure 1.

Aberrated and computationally corrected optical coherence tomography (OCT) images of a scattering phantom consisting of titanium dioxide particles suspended in silicone gel. The en face planes are taken from a 3D data set 300μm below the focal plane. The dimensions of each image are 256 × 256 μm.

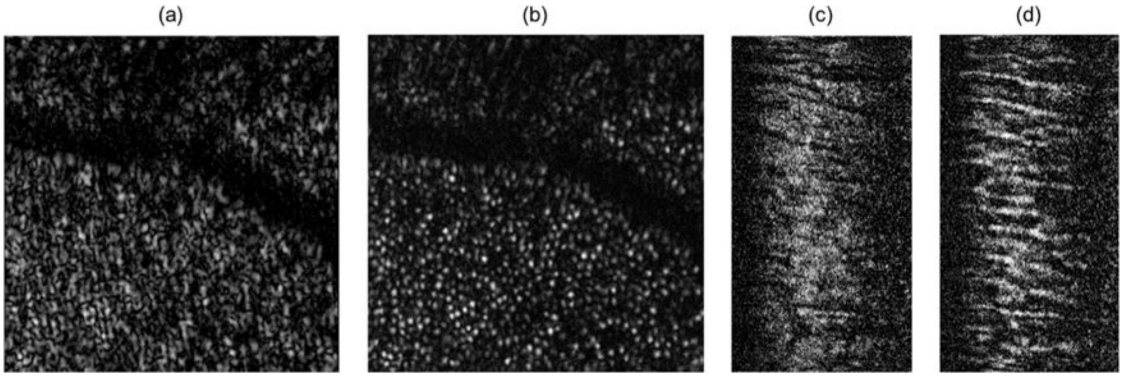

Figure 2.

Aberrated and computationally corrected OCT images of the human retina. (a) Aberrated cone photoreceptors. (b) Computational adaptive optics (CAO)-corrected cone photoreceptors. (c) Aberrated retinal fiber structures. (d) CAO-corrected retinal fiber structures.