Journal of
Biomedical Optics

SPIEDigitalLibrary.org/jbo

Measurement of ocular anterior segment dimension and wavefront aberration simultaneously during accommodation

Guohua Shi
Yuanyuan Wang
Yimin Yuan
Lin Wei
Fan Lv
Yudong Zhang

SPIE

Measurement of ocular anterior segment dimension and wavefront aberration simultaneously during accommodation

Guohua Shi,[a,b*] Yuanyuan Wang,[c*] Yimin Yuan,[c] Lin Wei,[a,b] Fan Lv,[c] and Yudong Zhang[a,b]
[a]The Chinese Academy of Sciences, The Key Laboratory on Adaptive Optics, Chengdu 610209, China
[b]The Chinese Academy of Sciences, The Institute of Optics and Electronics, Chengdu 610209, China
[c]Wenzhou Medical College, School of Ophthalmology & Optometry, Wenzhou 32500, China

Abstract. In order to understand the relationship between accommodation and vision quality, a custom-built ultra-long scan depth spectral domain optical coherence tomography (UL-SDOCT) and a Shack-Hartmann wavefront sensor (HSWFS) were combined. The resolution and scan depth of UL-SDOCT are 6 μm and 15.6 mm, respectively, which allow for high-resolution imaging of the whole anterior segment. The HSWFS consists of a 32×32 microlens array, and is able to measure first 35th-order Zernike aberrations with $(1/20)\lambda$ measurement accuracy. The integrated system succeeded in measuring the ocular anterior segment dimension parameters and the ocular monochromatic high-order aberrations simultaneously under the conditions of nonaccommodative and accommodative stimuli. This may help understand the regulatory mechanism of image quality control in the human eye. [DOI: 10.1117/1.JBO.17.12.120501]

Keywords: optical coherence tomography; wavefront sensor; accommodation; wavefront aberration.

Paper 12629L received Sep. 22, 2012; revised manuscript received Nov. 6, 2012; accepted for publication Nov. 8, 2012; published online Nov. 28, 2012.

The purpose of accommodation is to compensate for retinal defocus. According to the theory of Helmholtz[1] and Fincham[2] the ocular anterior segment changes significantly during accommodation to bring the objects from different distance into focus on the retina. However, the accommodation also induces the change in ocular wavefront aberration[3] which determines the vision quality. Thus, it is necessary to explore factors, which alter ocular aberrations during the accommodation. This may help understand the regulatory mechanism of imaging quality control in the human eye.

Some imaging methods, such as magnetic resonance imaging,[4] Scheimpflug photography,[4] and ultrasound biomicroscopy,[5] have measured the dimension change of ocular anterior segment. Furthermore, Shack-Hartmann wavefront sensor (SHWFS) is the successful wavefront measuring device which is widely used in vision research,[6] but previous studies separated the measurement of ocular anterior segment dimension and wavefront aberrations. Besides, these imaging methods have some drawbacks, for example low resolution, slow scan speed, and contactness. So in order to understand the relationship between accommodation and vision quality, an integrated system which can quantify the changes of ocular anterior segment and wavefront synchronously is required.

Optical coherence tomography (OCT) is a rapid and non-contact imaging method. It is widely used in anterior segment imaging.[7–10] The use of near-infrared light makes it possible to maintain the natural accommodative condition during OCT imaging, so OCT is an ideal tool to study the accommodation *in vivo*. In this study, we have developed an integrated system which consists of a custom-built, ultra-long scan depth spectral domain optical coherence tomography (UL-SDOCT) with a Shack-Hartmann wavefront sensor (SHWFS). The system makes it possible to carry out dimension and wavefront aberration measuring synchronously during accommodation. Thereby, the differences in the dimensional parameters and high order aberrations (HOAs) between the accommodative and non-accommodative states can be compared to investigate the relationships between the biometric dimensions of the ocular anterior segment and the ocular high-order aberrations during accommodation.

Figure 1 is the schematic of whole system combining the UL-SDOCT, SHWFS, and vision target. The UL-SDOCT component is based on a classical fiber-type Michelson interferometer. By using a broadband SLD (Superlum, Russia, SLD_371-HP1) which is centered at 840 nm with the bandwidth of 50 nm, the UL-SDOCT leads to 6.0 μm axial resolution in air. A custom spectrometer which consists of a volume holographic diffraction grating (1,800 lines/mm; Wasatch Photonics, Logan, Uttah) and a line scans CCD (Aviiva-SM2010, 2,048 pixels; Atmel, e2v Inc., Elmsford, New York) was developed. As detailed in our previous work,[11] by using a custom method, the raw image with mirror artifacts was processed and reconstructed to obtain the full-range (equivalent depth was 15.6 mm) anterior segment image.

The SHWFS component has a 32×32 microlens array. An LD (780 nm) functions as a beacon of SHWFS. By using P1, the paraxial illumination is formed to reduce the corneal reflected light. Besides, the CA is conjugated with the retina so as to eliminate the stray light. It is able to measure first 35th order Zernike aberrations with $(1/20)\lambda$ measurement accuracy.

A fixation target component was also built. A white "E" fixation target with a black background was displayed on the liquid-crystal display monitor, with a 20/100 letter according to the Snellen visual acuity chart that can be moved forward and backward to guide the subject to do accommodation.

SHWFS and the sample arm of UL-SDOCT were mounted on a modified slit-lamp platform. The dichroic beam splitter (BS2) was used to combine the two measuring lights. The measurement of dimension and wavefront aberration was done on the right eye while the accommodative stimuli was given on the left eye.

*These authors contributed equally to this work.

Address all correspondence to: Fan Lv or Yudong Zhang, The Chinese Academy of Sciences, The institute of Optics and Electronics, Chengdu Shuangliu 610209, China. Tel: +86-28-8510-0168; E-mail: ioe_eye@126.com

0091-3286/2012/$25.00 © 2012 SPIE

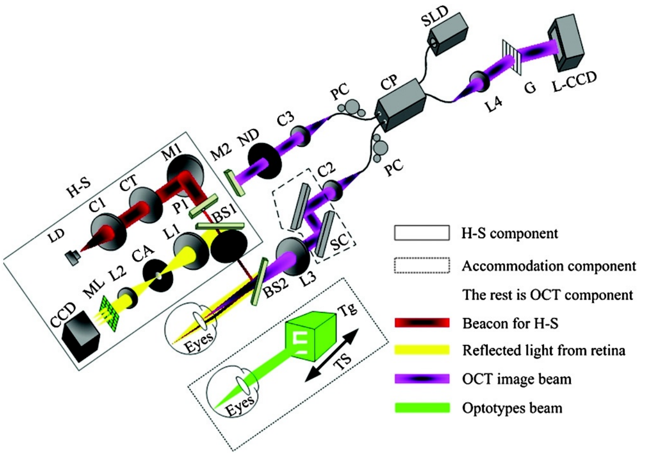

Fig. 1 Schematic of the whole measurement system. LD: laser diode; C1 to C3: fiber collimator; ND: neutral density filter; M1, M2: mirror; P1: pinhole; CA: circular aperture; BS1, BS2: beam splitter; L1 to L4: lens; CT: compensator; ML: microlens array; SC: X-Y scanner; PC: polarization controller; CP: fiber coupler; G: grating; SLD: superluminescent diode; L- CCD: line scan CCD. TS: translation stage; and TG: target.

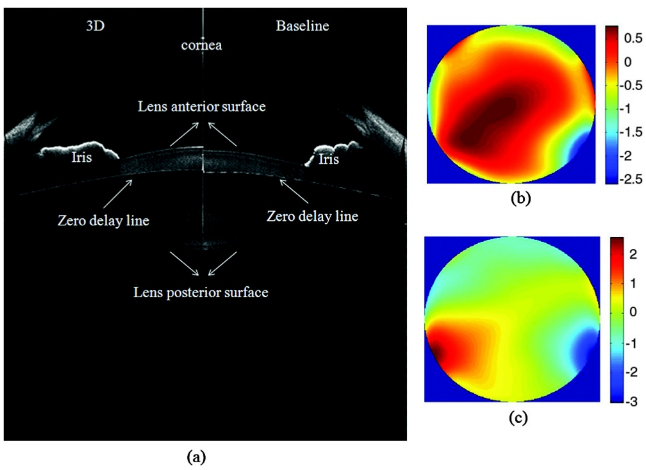

Fig. 2 (a) The OCT image in baseline (right side) and the 3D accommodative states (left side). (b) and (c) The ocular wavefront in baseline and 3D accommodative states.

The study was conducted in accordance to the tenets of the declaration of Helsinki. The Ethics Committee of the School of Ophthalmology & Optometry, Wenzhou Medical College approved the study. Following informed consent, three subjects who signed the informed consent were recruited.

The whole study was carried out in a dark room to eliminate the influence of ambient light. At first, the letter "E" (size: 20/50) is 4.0 m away from the trail lens in front of the left eye which is set as the base line. Via adjusting the slit-lamp platform manually, the right eye was aligned with the OCT system by precisely centering the corneal apex such that the specular reflection of the corneal apex at both vertical and horizontal meridians could be visible. Meanwhile, the ocular high-order aberrations through the whole pupil were recorded by the wavefront sensor. Then, the fixation target was set 1, 0.5, and 0.33 m away from the left eye of the subject, respectively. Accordingly, the subject get 1D, 2D, and 3D accommodative stimuli. The same visual angle was maintained by adjusting the size of the "E" target during different accommodative conditions. The OCT image of the anterior segment and ocular wavefront aberrations were again recorded for the different accommodative conditions.

By using custom-developed algorithms, the OCT image was reconstructed to correct the influence of refraction at the anterior corneal and lens surface. The detailed information of the algorithm is shown in our previous work,[7] As shown in Fig. 2(a), by benefiting from the ultra-long scan depth of our OCT, we can image the whole ocular anterior segment. After image correction, the true surface positions of the lens were obtained, so we can get the dimension values from the OCT image directly such as pupil diameter (PD), anterior chamber depth (ACD), and lens thickness (LT). Besides, we use the least square's method to fit the lens surfaces with a circle equation to get the radius of the lens anterior surface curvature (ASC) and lens posterior surface curvature (PSC).

In order to measure the HOAS correctly, the beacon of SHWFS must focus on the retina. However, the beacon is collimated to a parallel beam. Thereby, except for the accommodative stimuli of base line, the beacon cannot be focused on the retina under the other accommodative stimuli. So as shown in Fig. 1, we use compensators (CT) which are the standard glasses to compensate the refractive change of different accommodative stimuli. Furthermore, we calibrate the SHWFS carefully to minimize the HOAS which is introduced by

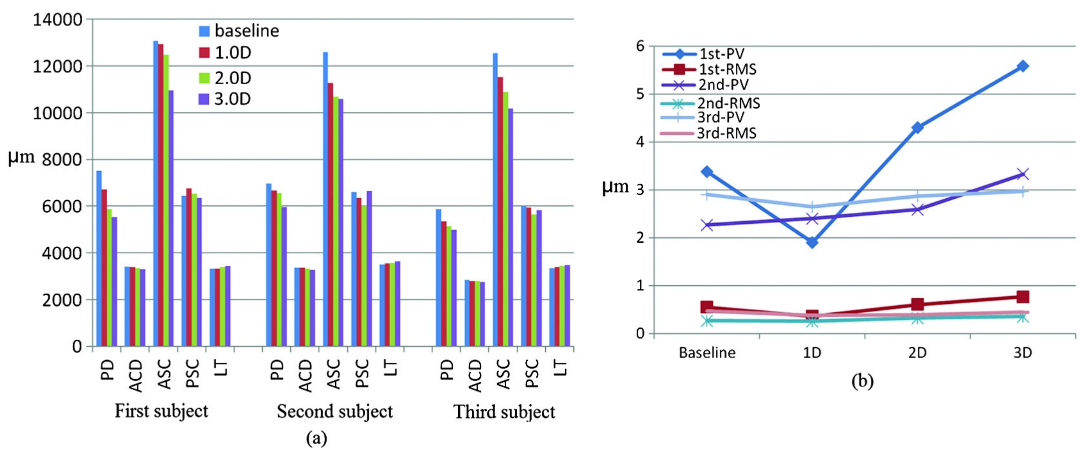

Fig. 3 (a) The change of biometric dimensions. (b) PV and RMS of HOAS changed with accommodative states.

compensators. Our SHWFS is able to capture 20 images per second. So we get the average of these 20 measurements for analysis, and use the 6th to the 35th order Zernike coefficients to calculate the peak and valley values (PV) and root-mean-square (RMS) of the high-order aberrations.

Figure 3(a) shows the change of biometric dimensions with accommodative states. During the experimental procedures, the focus of the eye changes from 4 to $1/3$ m. With the decrease of focus length, the energy of incident light is growing, so the PD changes smaller to protect the retina, and this makes the PV and RMS of HOAS become smaller at first. With the decrease of focus length, ciliary muscle controls the lens to curve its anterior surface sharply to change the focus of the eye. The dramatic bending of the lens anterior surface makes the PV and RMS increase rapidly and finally is larger than base line. At the same time, the ACS becomes significantly smaller too. Besides, this dimension change leads to an increase of LT and decrease the ACD slightly. Otherwise, the amount by which the anterior chamber depth decreased was approximately equal to the increase in the lens thickness, so that there was no movement in the posterior pole of the crystalline lens.

In general, the preliminary experimental results observed in our system meet the previous study, and support the theory of Helmholtz and Fincham. This indicates that the device which we have built is believable. In order to investigate the relationships between the biometric dimensions of the ocular anterior segment and the ocular high-order aberrations during accommodation, we will convene a large number of volunteers to carry out detailed statistical analysis in the future.

In conclusion, we have developed a custom-built device which consists of an ultra-long scan depth OCT and a SHWFS. The 15.6 mm ultra-long scan depth can obtain the OCT image of the whole ocular anterior segment. With the custom-developed algorithms, the biometric dimensions can be found from the OCT image. SHWFS is carefully designed and can measure the HOAS in real time. By using the guild of vision target, the device has successfully recorded the changes of ocular anterior segment and wavefront aberration in the living human eye synchronously during the accommodation. Preliminary experimental results show the changes observed in our system meet the theory of Helmholtz and Fincham. In the future, we will use this device to carry out a large number of experiments to analyze the relationship between the biometric dimension and HOAS; this is useful for understanding the mechanism of accommodation.

Acknowledgments

This work was supported by the National Science Foundation of China (Grant No. 61108082), the Knowledge Innovation Program of the Chinese Academy of Sciences (Grant No. KGCX2-Y11-920), Wenzhou Science and Technology Development Grant (Grant No. Y20100174), Zhejiang Province Science and Technology Development Grant (Grant No. 2010C31060), and Zhejiang Provincial Natural Science Foundation of China (Grant No. Y1110383).

References

1. H. von Helmholtz, "Uber die akkommodation des auges," *Archiv. Ophthalmol.* **1**(1), 1–74 (1855).
2. E. F. Fincham, "The mechanism of accommodation," *Br. J. Ophthalmol.* **8**(Suppl), 2–80 (1937).
3. J. C. He, S. A. Burns, and S. Marcos, "Monochromatic aberrations in the accommodated human eye," *Vision Res.* **40**(1), 41–48 (2000).
4. E. A. Hermans et al., "Constant volume of the human lens and decrease in surface area of the capsular bag during accommodation: an MRI and Scheimpflug study," *Invest. Ophthalmol. Vis. Sci.* **50**(1), 281–289 (2009).
5. J. M. Liebmann and R. Ritch, "Ultrasound biomicroscopy of the anterior segment," *J. Am. Optom. Assoc.* **67**(8), 469–479 (1996).
6. J. Liang et al., "Objective measurement of wave aberrations of the human eye with the use of a Hartmann-Shack wave-front sensor," *J. Opt. Soc. Am. A* **11**(7), 1949–1957 (1994).
7. C. Du et al., "Anterior segment biometry during accommodation imaged with ultralong scan depth optical coherence tomography," *Ophthalmology* (2012) (Epub ahead of print).
8. M. Shen et al., "SD-OCT with prolonged scan depth for imaging the anterior segment of the eye," *Ophthalmic Surg. Laser Imag.* **41**(6), S65–S69 (2010).
9. A. Koivula and M. Kugelberg, "Optical coherence tomography of the anterior segment in eyes with phakic refractive lenses," *Ophthalmology* **114**(11), 2031–2037 (2007).
10. S. Fukuda et al., "Anterior ocular biometry using 3-dimensional optical coherence tomography," *Ophthalmology* **116**(5), 882–889 (2009).
11. Y. Yuan et al., "Repeated measurements of the anterior segment during accommodation using long scan depth optical coherence tomography," *Eye Contact Lens* **38**(2), 102–108 (2012).