Measurement of wavefront aberrations and lens deformation in the accommodated eye with optical coherence tomography-equipped wavefront system

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Abstract: To quantitatively approach the relationship between optical changes in an accommodated eye and the geometrical deformation of its crystalline lens, a long scan-depth anterior segment OCT equipped wavefront sensor was developed and integrated with a Badal system. With this system, accommodation was stimulated up to 6.0D in the left eye and also measured in the same eye for three subjects. High correlations between the accommodative responses of refractive power and the radius of the anterior lens surface were found for the three subjects ($r>0.98$). The change in spherical aberration was also highly correlated with the change in lens thickness ($r>0.98$). The measurement was very well repeated at a 2nd measurement session on the same day for the three subjects and after two weeks for one subject. The novelty of incorporating the Badal system into the OCT equipped wavefront sensor eliminated axial misalignment of the measurement system with the test eye due to accommodative vergence, as in the contralateral paradigm. The design also allowed the wavefront sensor to capture conjugated sharp Hartmann-Shack images in accommodated eyes to accurately analyze wavefront aberrations. In addition, this design extended the accommodation range up to 10.0D. By using this system, for the first time, we demonstrated linear relationships of the changes between the refractive power and the lens curvature and also between the spherical aberration and the lens thickness during accommodation in vivo. This new system provides an accurate and useful technique to quantitatively study accommodation.

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1. Introduction

The human eye is an optical image-formation system, and its function is to form images of exterior visual objects on the retina. But, in order to obtain sharp images on the retina for objects at different distances, the eye needs to switch its focus point from one object to another one at a different distance. This is achieved through a biological process called accommodation, during which the shape of the crystalline lens is deformed and consequently its refractive power is adjusted to make the objects conjugate with the retina [1–8]. Although the lens deformation is well known to play a critical role in accommodation, the quantitative relationship between the geometrical change of the lens shape and its optical change in an accommodated eye has not yet been well characterized. Establishment of the relationship between the physical and optical factors relies on the accurate measurement of the lens shape and the optical performance of the eye during accommodation in vivo.
Recently, optical properties of the eye have been successfully assessed by using modern wavefront aberrometry [9–11]. When the wavefront technique was applied to measure accommodation, it was found that not only the refractive power, the 2nd order wavefront aberrations, but also the higher order aberrations were changed with accommodation [12–16]. The changes in higher order aberrations could provide useful information for better understanding the accommodative effect of the lens deformation on optical performance of the eye. For example, in an early in vitro study [17], higher order spherical aberration of younger lenses were found to become more negative as starching forces on the lens were released, a situation mimicked in in vivo accommodation. The negative change in spherical aberration for the in vitro lens is in good agreement with the observation from wavefront measurement in vivo, and the results were believed to be important to understand the mechanisms underlying accommodation and presbyopia.

Optical coherence tomography (OCT) is a quick, non-contact and non-invasive imaging modality [18–20] that has been used to image the anterior segment of the eye [21,22]. However, due to a limitation in its scan depth, most commercially available low speed OCT instruments are not capable of simultaneously imaging the whole anterior segment with the cornea and the lens together. Recent improvements have made it possible to image the entire anterior segment in real time, allowing the anterior and posterior lens to be non-invasively measured at high speed and with high resolution [23].

A combination of the OCT and the wavefront sensor therefore provide a proper approach to quantify accommodative changes in the lens shape and the optical performance of the eye. But, there are only two studies reported in the literature to employ such a combination [24,25]. In these studies, accommodative response was measured from the test eye while accommodative stimulation was presented to the contralateral eye. With this contralateral paradigm, it is operationally difficult to align the optical axis of the measurement system with a specific axis of the test eye because of accommodative vergence. The wavefront aberrations and anterior segment parameters measured under this paradigm therefore can suffer from measurement errors due to alignment shifting. In addition, in these two previous studies, the measurement range of the wavefront sensor was limited to only 3.0D. With such a short measurement range, it is impossible to test accommodative response at higher accommodative demands. Moreover, wavefront aberrations and anterior segment images were not simultaneously measured, probably due to noise of the light sources between the two systems. The purpose of this study, therefore, was to develop an OCT equipped wavefront system to be used for measuring geometrical and optical changes in the lens and the eye with a large accommodation range (up to 10.0D), while accommodation was stimulated and measured for the same eye.

2. Methods

2.1 Apparatus

A slit-lamp platform was used to mount the OCT scanning probe equipped wavefront system. Figure 1 illustrates a principal sketch of the OCT equipped wavefront system, where the channel of Hartmann-Shack (HS) wavefront sensor (green channel) is combined with the anterior segment OCT (AS-OCT) by a short-pass dichroic mirror (DM) (DMSP805R, Thorlabs Inc, NJ, USA). The DM reflects more than 90% for wavelengths longer than 820nm and transmits more than 90% for wavelengths shorter than 790nm. The peak wavelength of super-luminescent light emitting diode (SLED) for the HS wavefront sensor is 750nm with a bandwidth of 20nm (EXS7505-B001, Exalus Inc, PA, USA), fitted into a collimation tube (LT240P-B, Thorlabs Inc, NJ, USA), and it is 840nm with a bandwidth of 50nm (IPSDD0808, InPhenix Inc, CA, USA) for the AS-OCT. Usage of this DM reduced the noise light interaction of the light sources between the two systems very well.
In order to stimulate accommodation and simultaneously measure the accommodative response for the same eye, a Badal system was introduced into the wavefront sensor channel. The Badal system consisted of two lenses (L7 and L8), which were so arranged that lights from the accommodative stimulation target (AST), merged into the Badal system by a beam splitter (BS), formed an image by the lenses L8 and L7 at the focal plane of the lens L7. The image of AST was movable with respect to the lens L6. A transparent slide printed with different sizes of letters and numbers served as the AST, and was conjugate to the retina. The wavefront sensor consisted of a CCD camera (UNIQ UP680CL, Audio Video Supply, CA, USA), which was conjugate to the retina, and a 10x10mm lenslet (A64-482, Edmund Optics Inc, NJ, USA) which was conjugate to the entrance pupil of the eye. The focal length of the lenslet was 32.8mm and the diameter of each sub-lens was 0.5mm. In order to make the lenslet always conjugate with the entrance pupil, the wavefront sensor was built with the Badal lenses and the AST together on a small platform which was movable along the optical axis of the wavefront sensor (see the dashed line block). In this study, the setup is capable of inducing up to 10.0 diopters of accommodation; a larger range of accommodation can be easily achieved by simply changing the focal lengths of the Badal lenses.

The setup of the long scan-depth spectral-domain OCT has been previously described in detail [23]. The system features a long scan-depth OCT engine coupled together with the imaging system. The system has 24,000 A-scans per second and a 12.00mm scan depth. The axial resolution is ~10 µm. To compensate for the drop of the signal to noise ratio with image depth, two reference arms were used alternatively to shorten the image depth in each arm. Two images were acquired separately with these two arms. An alternative placement of the zero-delay line on the top and bottom of the image was specially designed to acquire multiple images. Image enhancement was realized by overlapping the 2 acquired images [23]. This approach was first introduced by Wang et al. who used an optical switch to realize the extension of the imaging depth [26]. The alternation of the reference arms was done using a galvanometer (Cambridge Technology, Boston, MA) which was controlled by the PC and synchronized with the X-Y scanner in the sample arm. The depth difference of the two OCT images was accurately controlled by the path length difference of the reference arms. The two OCT images can be merged accurately into one cross-sectional image of the whole anterior segment of the eye. This arrangement ensures a high signal-to-noise ratio within the whole depth of the merged cross-sectional image using two focal planes through these two imaging channels. The two images were interlinked by precise calibration. An ocular imaging eye model (OEMI-7, Ocular® Instruments Inc., Bellevue, WA, USA) was used to validate the
OCT system [23]. The differences in radius of the lens surfaces of the model eye between our OCT measurements and those determined by a Zygo interferometric system were within 0.5%.

### 2.2 Subjects

Three female subjects participated in this study; S1 (age 25), S2 (age 24), and S3 (age 27). The refractive errors of the subjects ranged from emmetropic to −1.5D. Other than exhibiting refractive errors, all subjects were ocularly normal. The research followed the tenets of the Declaration of Helsinki, and was approved by the New England College of Optometry institutional review board. Informed consent was obtained from the subjects after oral and written explanations of the nature and possible consequences of the study.

### 2.3 Procedure

Accommodation measurement was conducted with room lights off, and the subject was asked to sit in front of the system with her chin and forehead against the rests of the slit-lamp platform. At the start of each experimental session we aligned the subject to the apparatus and adjusted the Badal system for the subject’s far point. The subject’s task was to fixate the AST with her left eye while the right eye was patched. Natural pupils were used. As the subject was aligned with the apparatus, both the Hartmann-Shack image of the test eye and the OCT image of its anterior segment would appear on the computer screens of the wavefront sensor and AC-OCT system respectively. By carefully adjusting the slit-lamp position, the system could be perfectly aligned to corneal vertex of the subject’s eye, and a sharp reflection of the OCT light would appear. Once the sharp corneal reflection appeared, image acquisition for the OCT and wavefront sensor could be performed. Three image acquisitions were repeated for the far-point visual condition. After that, the Badal system was moved toward the subject to induce 2D, 4D and 6D accommodation, and the image acquisitions were repeated three times for each of the stimulation conditions. A typical session of the accommodation measurement usually lasted about 20 minutes. After about a 5 minute break, another session was repeated. In this way, the experiment could be completed within one hour for each visit. For subject S1, accommodation was retested after two weeks.

### 2.4 Data analysis

The Hartmann-Shack image provides measures of the slope of the wave-front at each point of the sub-aperture of the lenslet within the pupil area. A least-squares procedure [27] was used to fit the slope measurements to a set of Zernike polynomials [28,29] to approximate the wave-front height. Up to the seventh order of the Zernike expansion (35 terms) were derived, and their coefficients were used to estimate the wavefront aberrations of the eye.

OCT images of the anterior segment and the lens were processed using custom software, by which the boundaries of the cornea and lens were semi-segmented to obtain the morphometric dimensions of the anterior chamber depth, pupil diameter, lens thickness, and the radius of curvatures of both lens surfaces. Based upon Snell’s law, an algorithm was developed to optically correct image distortion and yield the true values of the ocular morphometric dimensions in three steps [30]: 1) the positions of all interfaces in the original OCT image were semi-segmented; 2) the surface extraction algorithm was used to produce a set of positions for well-defined interfaces, and 3) the refraction correction algorithm was applied by ray tracing.

The average of three measurements in each session was used to estimate the mean wavefront aberrations and anterior segment parameters. Statistical analysis was performed to test the repeatability of the measurements.
3. Results

3.1 Measurement of wavefront aberrations and anterior segment during accommodation for an individual eye

Wavefront and OCT measurements for subject S1 at two accommodative levels are illustrated in Fig. 2, where Figs. 2(a)–2(c) show the Hartmann-Shack image, a higher order wavefront aberration map at a 4.0mm diameter pupil area and the anterior segment image at 0D baseline accommodation respectively. The corresponding images and map at 6D are presented in Figs. 2(d)–2(f).

![Fig. 2](image)

Fig. 2. Hartmann-Shack image (a, d), higher order wavefront aberration map at a 4.0mm diameter pupil area (b, e) and uncorrected original anterior segment image (c, f) for a subject at 0.0D (a-c) and 6.0D (d-f) accommodative levels. The x-y axes of wavefront aberration maps represent pupil axes in mm, and the z axis indicates the wavefront aberrations in μm.

From the Figs. 2(c) and 2(f), it is apparent that the pupil size was reduced and the lens surfaces were more curved as the eye accommodated from 0D to 6D. The higher order wavefront aberrations were also clearly changed with accommodation (Figs. 2(b) and 2(e)).

Figure 3 plots the accommodative responses of refractive power (a) and spherical aberration (b) against the changes in radius of anterior lens surface and lens thickness respectively for three subjects when accommodative demand was changed from 0D to 6D. From Fig. 3, it appears that the increase in accommodative response of refractive power was closely correlated to the decrease in radius of the anterior lens surface (slope = -1.06, r = -0.99 for S1; slope = -1.00, r = -0.98 for S2 and slope = -0.73, r = -0.99 for S3), while the negative shift of spherical aberration was closely correlated to an increase of lens thickness (slope = -2.31, r = -0.99 for S1; slope = -2.18, r = -0.98 for S2 and slope = -2.06, r = -0.97 for S3). The slope of the regression line varied slightly from subject to subject.
Fig. 3. The changes in accommodative response of refractive power (a) and spherical aberration (b) with the changes in radius of anterior lens surface and lens thickness respectively for three subjects when accommodation was changed from 0D to 6D.

Figure 4 shows accommodative changes in the Zernike aberrations from the 2nd order up to the 5th order and the anterior segment measurements for two subjects (S1 and S2). More Zernike higher order aberrations were not presented due to their small amounts. The Zernike aberrations and anterior segment measurements are illustrated in Figs. 4(a) and 4(b) for the subject S1 and Figs. 3(c) and 3(d) for subject S2. Each symbol represents the mean of three measurements at each accommodation level, with the error bar depicting the standard error of the mean. The Zernike defocus term (Z4) is not included in Fig. 4 because the measurement was transferred to the accommodative response of refractive power and presented in Fig. 3. The radius of the anterior lens surface and the lens thickness are also excluded from Fig. 4 since they are shown in Fig. 3 as well. It can be seen from Fig. 4 that when accommodation stimulation was changed from 0D to 6D, the oblique astigmatism term (Z3) was changed and the main axis astigmatism (Z5) was changed at the 6D for both subjects. Standard deviation of each Zernike term indicates how repeatable was the three measurements of the Zernike term at an accommodation level. When the standard deviations were averaged across the four accommodation levels, the mean standard deviations of the main astigmatism (Z5) across the four accommodation levels for both subjects S1 and S2 were 0.032μm and 0.074μm respectively, corresponding to 0.039D and 0.091D astigmatism respectively.

Fig. 4. Accommodative changes in the Zernike aberrations from the 2nd order up to the 5th order (a, c) and the anterior segment parameters (b, d) for two subjects S1 (a-b) and S2 (c-d) at four accommodation levels from 0.0D to 6.0D. Each symbol indicates mean of three measurements with the error bar representing standard error of the mean.
For higher order aberrations, no systematic change in either the vertical coma (Z7) or the horizontal coma (Z8) was observed for subject S1. But, a systematic increase in vertical coma (Z7) with accommodation was found for subject S2, while no such a change was found in horizontal coma (Z8). The mean standard deviations across the four accommodation levels were 0.030μm and 0.034μm for subject S1 and 0.054μm and 0.042μm for subject S2.

For anterior segment measurements, the pupil diameter (PD), the anterior chamber depth (ACD), the radius of posterior lens surface (PLSR) systematically changed with accommodation for both subjects. For subject S1, the mean standard deviations across the four accommodation levels in PD, ACD, and PLSR were 0.14, 0.06, 0.29mm respectively, and the corresponding mean standard deviations for subject S2 were 0.13, 0.03, and 0.18mm respectively.

3.2 Repeatability of measurement

Repeatability of this system was tested by examining correlation of the measurements from two sessions on the same day or two sessions from different days. Figure 5 shows the accommodative responses of refractive power (a and c) and spherical aberration (b and d) against the changes in the radius of anterior lens surface and lens thickness respectively for subjects S2 (a and b) and S3 (c and d) when accommodation was changed from 0D to 6D. The solid circle and line represent the measurement and regression lines for the 1st measurement session and the empty circle and dash line show those for the 2nd measurement session. Both regression slope and correlation coefficient were very well repeated in the 2nd measurement session for both subjects in either the correlation between accommodative response of refractive power and radius of anterior lens surface (slope = −1.07, r = −0.98, for S2; slope = −0.70, r = −0.99, for S3) or the correlation between spherical aberration and lens thickness (slope = −2.51, r = −0.99, for S2; slope = −2.95, r = −0.97, for S3).

Figure 6 shows the correlations of the accommodative responses of refractive power (a) and spherical aberration (b) with the changes in radius of anterior lens surface and lens
thickness respectively for subject S3 collected after a two week interval. Relative to the 1st day measurement (solid circle and line), both accommodative response of refractive power and radius of anterior lens surface were systematically reduced in the 2nd session after two weeks, thus resulting in a left shift of the regression line, but with similar slope and correlation coefficient (slope = −0.71, r = −0.98). A systematic decrease in spherical aberration and increase in lens thickness were also found in the 2nd session, but with very similar correlations as in the 1st session (slope = −2.00, r = −0.93).

Fig. 6. The changes in accommodative response of refractive power (a) and spherical aberration (b) with the changes in radius of anterior lens surface and lens thickness respectively for subjects S3 when accommodation was changed from 0D to 6D.

4. Discussion

Zernike aberrations in the accommodated eye were successfully measured over a large accommodation range for a group of young adults with a psychophysical wavefront sensor in 2000 [12]. In addition to the 2nd order defocus and astigmatism, higher order Zernike aberrations were also found to change with accommodation, especially the spherical aberration. The spherical aberrations become more negative as the accommodative stimulation was increased to higher demands. The observation was confirmed by several following studies [13–16], and it is in good agreement with the negative change in spherical aberration for the in vitro lens [17]. The studies indicate that in the future accommodation studies it is necessary to measure wavefront aberrations, not just the 2nd order defocus and astigmatism, because the information from wavefront aberrations could help us more deeply understand accommodation mechanisms in vivo.

However, during the measurement of wavefront aberrations for an accommodated eye, alignment of the optical axis of measurement system with a specific axis of the eye is critical to experimental control since wavefront aberration patterns change with the alignment axis. Meanwhile, the alignment control is important for the measurement of anterior segment parameters also because the parameters could change with alignment shifting as well. In order to correctly attribute the accommodative changes in wavefront aberrations to lens deformation, the influence of the axis alignment on both measurements should be well controlled. In the current study, due to the introduction of a Badal system, the optical axis of the measurement system was carefully aligned to the corneal vertex of the test eye while the subject was always fixed at the visual target inside the Badal system with the same eye. This measurement condition held for all four accommodation levels, and thus, the possible influences of axial alignment shifting between the measurement system and the eye, due to accommodative vergence, on measurements of the wavefront aberrations and anterior segment parameters were eliminated.

In this study, the incorporation of the Badal system into the OCT equipped wavefront sensor made the wavefront sensor always had the Hartmann-Shack image sharply formed on
the CCD of the wavefront sensor. This condition holds for all accommodation levels. The method avoids the need for additional focus compensation and for subsequent additional calibration procedures for the wavefront sensor. This makes the wavefront sensor accurately measure wavefront aberrations at all accommodation conditions. In addition, the combined system is capable of inducing accommodation up to 10.0 diopters, due to the usage of Badal system.

Both the Hartmann-Shack wavefront sensor and the anterior segment OCT have been widely used to study the accommodated eye separately, and the high reliability of each system has been previously reported. In this study, a dichroic mirror was carefully selected to co-axially combine the two systems in order to reduce the noise light interaction between both systems. It is therefore not surprising that very good repeatability of the combined system was observed for our subjects. The reliability of defocus and astigmatism measurements in this study (Fig. 4) was compatible with the results from a widely used commercial unit [31] as well as for the higher order spherical aberration and comas. The reliability of the anterior segment measurement repeats a previous study very well [23].

By using this new system, accommodation was successfully stimulated and measured for the same eye up to 6.0D with good repeatability for our subjects. High correlations between the accommodative changes in the refractive power and the lens surface curvature were observed for each subject. The changes in spherical aberration were also found to be closely correlated to the changes in lens thickness for each subject. This is the first time to demonstrate the association of the accommodative changes between the Zernike aberrations of the eye and the geometrical parameters of the lens in vivo. The results therefore indicate that the system is ready to accurately study accommodation.

Overall, a Badal system was integrated into an OCT equipped wavefront system, with which accommodation can be stimulated and measured for the same eye. The system with good control of axial alignment has a large measurement range (10.0D) and high repeatability, and it would be useful for quantitatively investigating the relationship between the changes in optical performance of the eye and its lens deformation during accommodation.

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