NIH Public Access
Author Manuscript
Optom Vis Sci. Author manuscript; available in PMC 2013 May 01.

Published in final edited form as:
Optom Vis Sci. 2012 May ; 89(5): 719–726. doi:10.1097/OPX.0b013e318252cadc.

Measuring Changes in Ciliary Muscle Thickness with Accommodation in Young Adults

Laura Ashley Lossing, OD, MS, **Loraine T. Sinnott, PhD**, **Chiu-Yen Kao, PhD**, **Kathryn Richdale, OD, PhD, FAAO**, and **Melissa D. Bailey, OD, PhD, FAAO**
The Ohio State University College of Optometry, Columbus, Ohio (LAL, LTS, MDB), The Ohio State University, College of Mathematics and Physical Sciences, and Department of Mathematics and Claremont McKenna College, Department of Mathematics and Computer Science, Claremont, California (C-YK), and SUNY College of Optometry, New York, New York (KR)

Abstract

Purpose—To develop a measurement protocol for changes in the shape and size of the ciliary muscle with accommodation using the Zeiss Visante™ Anterior Segment Optical Coherence Tomographer (AS-OCT) and to determine the test-retest repeatability of these measurements.

Methods—Subjects were 25 adults ages 23–28 years. The ciliary muscle was imaged at two visits with the Visante™ while accommodative response was monitored during imaging using the PowerRefractor. Ciliary muscle thickness was measured at 1 mm (CMT1), 2 mm (CMT2), and 3 mm (CMT3) posterior to the scleral spur and at the point of maximal thickness (CMTMAX). Thickness was measured at these locations while subjects viewed a target at distance and at a 4.00-D accommodative stimulus. Outcome measures were the change in thickness between distance and the 4.00-D stimulus and the change in thickness per diopter of accommodative response (PowerRefractor). Finally, the repeatability measurements between visit 1 and visit 2 were determined with a Bland-Altman analysis.

Results—The statistically significant modeled changes in ciliary muscle thickness were as follows: CMTMAX = 69.2 μm (4.00-D stimulus) and 18.1 μm (per diopter of accommodation); CMT1 = 45.2 μm (4.00-D stimulus) and 12.3 μm (per diopter of accommodation); and CMT3 = −45.9 μm (4.00-D stimulus) and −12.0 μm (per diopter of accommodation); $p < 0.0001$ for all.

Conclusions—The combination of the Visante™ and the PowerRefractor is a feasible tool for measuring thickening of ciliary muscle at more anterior locations and thinning at more posterior locations during accommodation. We noted a wide range of accommodative responses during the time of image capture in this study indicating that the most accurate estimates of the change in ciliary muscle dimensions with accommodation may be obtained by using accommodative response rather than stimulus values and by using measurements taken simultaneously with image capture.

Keywords

ciliary muscle; accommodation; adults

Over the past several decades, researchers have produced a body of literature that has given us an in-depth understanding of ciliary muscle anatomy. *In vivo* function remains an elusive aspect to study because of visualization difficulties. Recent advances in imaging technology

Corresponding author: Melissa D. Bailey, The Ohio State University College of Optometry, 338 West 10th, Ave Columbus, OH 43210, mbailey@optometry.osu.edu.

NIH-PA Author Manuscript
NIH-PA Author Manuscript
NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

have enabled us to continue to build on our current understanding of normal ciliary muscle function. These advances will elevate the level of comprehensive eye care we can provide for the entire visual system.

Patients present with symptoms of accommodative dysfunction in optometric practices daily. While reading additions successfully alleviate these symptoms in the young and old alike, continued research is needed to gain a greater understanding of the *in vivo* muscle function in young patients with accommodative dysfunction and also after presbyopia onset. A recent review article has shown that multiple companies are working to develop accommodative intraocular lenses (IOLs) that rely on the action of the ciliary muscle; although, there remains a limited understanding of presbyopic muscle function.[1]

In addition to presbyopia, other types of accommodative dysfunction are also important to consider because our daily activities increasingly place demands on our ability to see clearly at close distances, i.e., computer use, video games, electronic book readers, smart phones, etc. Few studies have explored the prevalence of accommodative dysfunction in the general population, but 60% to 80% of patients diagnosed with binocular vision disorders have been found to suffer from accommodative dysfunction.[2–3] The symptoms that are commonly associated with accommodative anomalies include blurred vision, headache, ocular discomfort, ocular or systemic fatigue, and loss of concentration during a task performance.

Studies have shown vision therapy can improve both accommodative amplitude and facility, as well as increase the magnitude and velocity of accommodative responses.[4–5] Nonetheless, specific muscular and/or neurological changes that might take place during vision therapy remain unmeasured and the exact effects of therapy remain unknown. Similarly, an increased accommodative lag has been observed after the onset of myopia, but we have been unable to identify the source of this anomaly in the accommodative system.[6]

Further studies are needed to provide a complete understanding of the childhood development and then the gradual decline of the human accommodative system and how it may relate to myopia, accommodative dysfunction, and the feasibility of IOLs that restore accommodation. Until recently, however, we have not had the imaging capability to measure *in vivo* changes in the ciliary muscle with accommodation. Recent studies have successfully used magnetic resonance imaging (MRI), ultrasound biomicroscopy (UBM), and anterior segment optical coherence tomography (AS-OCT) to visualize the ciliary muscle and/or to make measurements of the muscular changes that take place with accommodation.[7–10] The present study combined the imaging capabilities of the Visante™ AS-OCT (Carl Zeiss Meditec™, Dublin, CA), which is capable of imaging the ciliary muscle and allows for further extraction of thickness measurements,[11] with simultaneous monitoring of accommodative status (vertical meridian) by the PowerRefractor II (MultiChannelSystems, Reutlingen, Germany). Combining data from these two devices with knowledge of ciliary muscle anatomy allows one to make measurements of changes in ciliary muscle thickness while accounting for the subject's accommodative response. In addition, the Visante™ is a non-contact, non-invasive, imaging system that is also easy to operate. It acquires images in a rapid fashion that makes it possible to image the ciliary muscle in adults and children.[12–13]

METHODS

Subjects

Subjects were recruited within the Ohio State University College of Optometry. Adults, under the age of 30 years were eligible. Twenty-five subjects ages 23 to 28 years (mean ± SD = 24.2 ± 1.1 years) participated in the study. At the time of planning this study, we were uncertain of what amount of change in the ciliary muscle thickness should be expected. A

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

sample of 25 was thought to be sufficient for this exploratory investigation. Seventeen of the subjects (68%) were female. Subjects could have any refractive error, i.e., myopia, hyperopia, or astigmatism, as long as it was correctable to 20/20 with contact lenses. Exclusion criteria were any history of ocular diseases or disorders other than refractive error; a history of strabismus; a history of any previous eye surgery; and the use of any systemic or topical medications that are known to affect the ciliary muscle. After a presentation and discussion of the study procedures, all subjects provided written informed consent. The study was approved by the Institutional Review Board of The Ohio State University.

Testing Procedures

All subjects underwent the same testing protocol, as described below, at two, separate, study visits that were scheduled approximately two weeks apart. All subjects who required refractive error correction wore contact lenses while all measurements were taken. All measurements were made on the right eye while the left eye was occluded.

Ciliary Muscle Measurements

Images of the temporal ciliary muscle of the right eye were taken without the use of any pharmaceutical agents. Images were obtained with the Zeiss Visante™ Anterior Segment OCT while the subjects viewed targets at 1.00 m (1.00-D stimulus) and at 25 cm (4.00-D stimulus). The target placed at 1.00 m will be referred to as “distance” throughout the manuscript because the PowerRefractor monitoring showed that mean ± SD accommodative response to the 1.00-D target was −0.20 ± 0.54 D, the median was −0.08 D, and the range was −1.12 D to +0.99 D, indicating that most subjects’ accommodative systems were at rest when viewing the 1.00-D stimulus. Six ciliary muscle images were obtained from each subject for both targets in the Enhanced High Resolution Corneal Mode (axial resolution = 18 μm and transverse resolution = 60 μm, according to the manufacturer). The scleral spur was selected in each image by one examiner (MDB) who was masked to both the subject identification number as well as the accommodative state for the image. Thickness measurements were obtained from these ciliary muscle images using a semi-automatic algorithm to obtain a maximum thickness measurement (CMTMAX) as well as thickness measurements at 1 mm (CMT1), 2 mm (CMT2) and 3 mm (CMT3) posterior to the scleral spur (Figure 1).[11]

To determine the accommodative state of the eye during ciliary muscle imaging with the Visante™, simultaneous measurements of monocular accommodative response were taken using the PowerRefractor II. The PowerRefractor is an autorefractor that is capable of determining the power of the eye when positioned approximately 1.0 m from the subject’s eye. It samples at a rate of 25 Hz, has a range of −8.75 to +4.00 D,[14] and requires a pupil size larger than 3.7 mm.[15] While subjects were positioned in the Visante™ head and chin rest, they viewed either the distance or the 4.00-D targets. At the same time, the PowerRefractor was positioned to read the power of the eye continuously through a mirror positioned on the side of the Visante while six images of the ciliary muscle were obtained using the Visante™. The PowerRefractor data were filtered to eliminate changes in accommodation greater than 10 D/s because an accommodative change of that magnitude is faster than what is known to be physiologically possible.[16] The analysis used the mean PowerRefractor reading for the horizontal meridian over the entire time subjects were viewing the distance and the 4.00-D targets. Thus, at each visit, each subject had one mean PowerRefractor reading for the distance target and one mean PowerRefractor reading for the 4.00-D target. A diagram of the setup for the ciliary muscle image acquisition with simultaneous accommodative monitoring is shown in Figure 2.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

All 25 subjects completed the required two visits. For six subjects, PowerRefractor data were not available for one or both visits due to an equipment malfunction, so we were unable to include the data from these subjects' visits in analyses that accounted for accommodative response. In addition, one visit's data was removed from all analyses for two subjects because he or she did not exhibit an appropriate accommodative response during testing, i.e., the subject did not have an accommodative response of at least 2.00 D when he or she was presented with the 4.00-D stimulus. This was likely due to a lack of attention or understanding of the task on the part of the two subjects, rather than an inability to accommodate, because the problem only occurred at one of the two study visits.

While the ciliary muscle imaging was completed according to our laboratory's previous publication,[11] some minor adjustments to the protocol were needed for some of the 4.00-D images. In our original publication on measuring the ciliary muscle,[11] all of the images were obtained under cycloplegic conditions. In the present study, some images that were taken while subjects responded to the 4.00-D stimulus were darker than cycloplegic or non-accommodative images in the anterior region of the muscle. Figure 3 is an example of one subject who had darker images under accommodative conditions. For some subjects, an adjustment was made to the contrast settings in our algorithm in order to obtain the outline depicted as a solid white line as opposed to the outline depicted as a white dashed line in Figure 3. This algorithm adjustment allowed the outline of the ciliary muscle to include the entire anterior region of the muscle, such that the CMTMAX measurement was located at the apex of the muscle.

Statistical Analyses

The action of the ciliary muscle during accommodation was described by our data in two ways. First, we determined the mean change in the thickness of the ciliary muscle for all subjects as they changed their focus from a distance target to a 4-D stimulus. This calculation did not account for the actual accommodative response of each subject, and it is referred to as the "change for a 4-D stimulus" in ciliary muscle thickness in this report. Second, we divided the change for a 4-D stimulus by the accommodative response recorded by the PowerRefractor (the difference between the distance and the 4-D measurements taken during Visante™ imaging). This ratio (change for a 4-D stimulus/accommodative response) represented the amount of thickening or thinning that occurred in the ciliary muscle per diopter of accommodative response, or the "change per diopter of accommodation." For each measurement of change in ciliary muscle thickness (CMT1, CMT2, CMT3 and CMTMAX), we fitted the following multilevel model:

$$\text{Change}_{ij}=\mu+\delta_i+\varepsilon_{ij}.$$

In the model μ is the population mean for change in thickness. Estimating μ was the goal of the analysis. The deviation from the mean had two components, a deviation due to biological variability between subjects (δ_i) and within-subject measurement error (ε_{ij}).

Analyses suggested by Bland and Altman (1986) were used to assess the inter-visit repeatability of the change for a 4-D stimulus and change per diopter of accommodation for each ciliary muscle thickness measurement.[17] Plots of the difference versus the mean of the measurements were visually inspected to determine if the difference between measurements was related to the mean. The mean difference between measurements was calculated and compared to zero using a one sample t-test to determine if any bias was present. The mean of the differences and its standard deviation were used to calculate the degree of repeatability also commonly referred to as the limits of agreement. The limits of agreement

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

(mean ± [1.96 x standard deviation]) characterize the expected difference between repeated measures.

RESULTS

Table 1 shows the mean ciliary muscle thickness values for the distance and 4.00-D measurements at both visits. Note that even though this sample was relatively small, i.e., 25 subjects, the mean and median are similar, suggesting that the data were distributed symmetrically around the mean.

Action of the Ciliary Muscle During Accommodation

Descriptions of the observed change for a 4-D stimulus and the change per diopter of accommodation in ciliary muscle thickness with accommodation are shown in Table 2. The results for the modeled change for a 4-D stimulus and the change per diopter of accommodation, which provided 95% confidence intervals, are shown in Table 3. The modeled results showed a statistically significant thickening of the ciliary muscle with accommodation at both CMT1 and CMTMAX. No thickening or thinning was found for CMT2 with the change for a 4-D stimulus or the change per diopter of accommodation. Statistically significant thinning of the ciliary muscle was found with accommodation at CMT3 for both the change for a 4-D stimulus and the change per diopter of accommodation.

Inter-visit Repeatability

The results of the Bland-Altman analysis are shown in Table 4. No statistically significant bias was noted between visits for any ciliary muscle thickness measurement, which was not surprising because no learning effects were anticipated to occur for the accommodative task. The coefficients of repeatability for all ciliary muscle thickness measurements were less than 130 μm for the change for a 4-D stimulus and less than 40 μm for the change per diopter of accommodation.

DISCUSSION

There is a growing body of literature exploring changes in the ciliary muscle structure with accommodation. Recent advances in imaging technology have made it possible to more easily visualize *in vivo* changes in the ciliary muscle with accommodation.[11] The primary objective of this study was to determine if the Visante™ AS-OCT was capable of providing images with enough resolution to observe changes in ciliary muscle shape with accommodation. During the course of our efforts to develop a protocol using the Visante™, we did determine that it is important to monitor accommodation during the imaging as it did differ slightly from measurements obtained prior to imaging on an autorefractor (data not shown).

In a published letter,[18] we have attempted to encourage those who measure the ciliary muscle in accommodative research to discuss and consider how the ciliary muscle should be measured. Two previous studies have demonstrated that the Visante™ is capable of imaging the ciliary muscle *in vivo*,[13, 19] and reported changes in the ciliary muscle morphology that are similar to our results even though their data collection and image analysis techniques were different from the ones used in this report.[18] While Sheppard and Davies (2010) did not use exactly the same locations for thickness measurements as we did, i.e., their thickness measurements were referenced to the overall length of the muscle rather than the scleral spur, their CM25 measurement is probably in the general area of our CMT1, and their CM75 is probably similar to our CMT3. Both studies included an evaluation of ciliary muscle thickness differences, comparing distance and 4.00-D accommodative stimuli. When the

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

measurements from our study and Sheppard and Davies (2010) are compared, we found a 45.2 μm mean thickening at CMT1, and Sheppard and Davies (2010) found a mean increase in thickness from 550 μm to 571 μm (or 21 μm) at CM25. Similarly, we reported a mean thinning of −45.9 μm at CMT3 and Sheppard and Davies (2010) reported a mean thinning from 174 μm to 166 μm (or 8 μm) at CM75. Sheppard and Davies (2010) also reported a measurement at 2 mm posterior to the scleral spur (CM2), and they found a very small, but statistically significant thinning of 21 μm at this location where we observed no significant change (−7.3 μm, p = 0.5). It is possible that we might have observed a statistically significant change if we had included more than 25 subjects in our study.

Our results and previous studies confirm that it is possible to measure the action of the ciliary muscle during accommodation using images from the Visante™, and that there appears to be a thickening of the anterior portion and a thinning of the posterior portion of the ciliary muscle during accommodation. Still, there are improvements that could be made to the protocol for making these measurements. It is possible that the best protocol for obtaining these measurements in future studies would include having a measure of the accommodative response at the exact time of image capture. This suggestion is based on observations from a couple of subjects with a wide range of accommodative responses during Visante™ imaging. For example, one subject had similar mean ± SD PowerRefractor readings while viewing the distance target at the two study visits, but the range of responses was more variable than some other subjects [Visit 1: −0.92 ± 0.17 D (range = −0.28 to −1.44) and Visit 2: −0.98 ± 0.19 D (range = −0.33 to −1.62)]. This subject also had more variable ciliary muscle measurements than other subjects. For example, CMTMAX at visit 1 was 780 μm and was 700 μm at Visit 2. We noted at least two subjects with discrepancies as extreme as these. Of course when we are measuring human subjects and relying on their responses and attention in a study such as this, some variability is inevitable and likely unavoidable. Nonetheless, in future studies, we will use an imaging protocol that includes measurements of accommodative response at the exact time each image is obtained to try to reduce the variability of the measurements and improve estimates of how much change in ciliary muscle thickness is required per diopter of accommodative response.

While accommodative monitoring during image acquisition is certainly one major limitation of the estimates of the change in ciliary muscle thickness during accommodation for the present study, we should also acknowledge one additional limitation. In our original publication of the semi-automatic algorithm we use to analyze the dimensions of the ciliary muscle, we included only cycloplegic images. When we began analyzing images that had been obtained during accommodation, it was clear that the anterior portion of the ciliary muscle was, at times, much darker than the cycloplegic images. It would not be surprising that the spacing of fibers within the muscle might vary between the accommodative and cycloplegic states of the muscle, resulting in different levels of contrast in the two types of images. The process of adjusting the contrast for some of the 4.00-D images, as depicted in Figure 3, did require some subjectivity on our part. For future studies, we are exploring how image capture and/or analysis might be adjusted so that all images could be analyzed with the same contrast settings in the algorithm.

While we are certain that refinements of the methods used to monitor *in vivo* accommodation in humans is important, we would also like to remind the reader that we have already discussed the fact that our results were similar to those of Sheppard and Davies (2010), even though our measurement techniques were not identical.[18] In addition, we have collected data similar to these for additional studies, i.e., a study of children[20] and also in a study of pre-presbyopic and presbyopic adults (unpublished data), where we made protocol adjustments but still obtained remarkably similar results. Based on the fact that we have repeated these results in other samples, we are confident that the results presented in this

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

study are a good estimate of the change in ciliary muscle thickness per diopter of accommodation, despite the limitations of the study that are discussed above.

In summary, the combination of the Visante™ AS-OCT and the PowerRefractor provide a feasible method for future studies to continue to explore the exact nature of ciliary muscle contraction in adult subjects. In future studies, we intend to further refine the estimates of how the shape of the ciliary muscle changes with accommodation, and refine our procedures for determining the subject's accommodative response. The information about ciliary muscle contraction and also the evolution of our methodology and protocols provided here and in our companion paper in this issue of the journal describing these measurements in children,[20] should allow for more definitive and insightful studies of the ciliary muscle during accommodation in the future.

Acknowledgments

This research was supported by Beta Sigma Kappa (Lossing), the National Science Foundation NSF DMS 0811003 and Sloan Fellowship (Kao), and National Institutes of Health, National Eye Institute Grants R24-EY014792 (Sinnott), T32-EY013359 and K23EY019097 (Richdale).

The project described was supported by Award Number KL2 RR025754 (Bailey) from the National Center for Research Resources, funded by the Office of the Director, National Institutes of Health (OD). The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Center for Research Resources or the National Institutes of Health.

The Ohio State University has filed a provisional patent application on the behalf of the authors: U.S. Provisional Patent Application No. 61/594,027, filed February 2, 2012, entitled: "Semiautomatic Extraction of Algorithm for Images of the Ciliary Muscle".

References

1. Glasser A. Restoration of accommodation: surgical options for correction of presbyopia. Clin Exp Optom. 2008; 91:279–95. [PubMed: 18399800]
2. Hokoda SC. General binocular dysfunctions in an urban optometry clinic. J Am Optom Assoc. 1985; 56:560–2. [PubMed: 4020010]
3. Hoffman L, Cohen AH, Feuer G. Effectiveness of non-strabismus optometric vision training in a private practice. Am J Optom Arch Am Acad Optom. 1973; 50:813–6. [PubMed: 4520500]
4. Randle RJ, Murphy MR. The dynamic response of visual accommodation over a seven-day period. Am J Optom Physiol Opt. 1974; 51:530–44. [PubMed: 4416172]
5. Liu JS, Lee M, Jang J, Ciuffreda KJ, Wong JH, Grisham D, Stark L. Objective assessment of accommodation orthoptics. I. Dynamic insufficiency. Am J Optom Physiol Opt. 1979; 56:285–94. [PubMed: 495685]
6. Mutti DO, Mitchell GL, Hayes JR, Jones LA, Moeschberger ML, Cotter SA, Kleinstein RN, Manny RE, Twelker JD, Zadnik K. Accommodative lag before and after the onset of myopia. Invest Ophthalmol Vis Sci. 2006; 47:837–46. [PubMed: 16505015]
7. Oliveira C, Tello C, Liebmann JM, Ritch R. Ciliary body thickness increases with increasing axial myopia. Am J Ophthalmol. 2005; 140:324–5. [PubMed: 16086961]
8. Sheppard AL, Davies LN. In vivo analysis of ciliary muscle morphologic changes with accommodation and axial ametropia. Invest Ophthalmol Vis Sci. 2010; 51:6882–9. [PubMed: 20671285]
9. Stachs O, Martin H, Kirchhoff A, Stave J, Terwee T, Guthoff R. Monitoring accommodative ciliary muscle function using three-dimensional ultrasound. Graefes Arch Clin Exp Ophthalmol. 2002; 240:906–12. [PubMed: 12486512]
10. Strenk SA, Strenk LM, Guo S. Magnetic resonance imaging of aging, accommodating, phakic, and pseudophakic ciliary muscle diameters. J Cataract Refract Surg. 2006; 32:1792–8. [PubMed: 17081859]

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

11. Kao CY, Richdale K, Sinnott LT, Grillott LE, Bailey MD. Semiautomatic extraction algorithm for images of the ciliary muscle. Optom Vis Sci. 2011; 88:275–89. [PubMed: 21169877]
12. Bailey MD, Sinnott LT, Mutti DO. Ciliary body thickness and refractive error in children. Invest Ophthalmol Vis Sci. 2008; 49:4353–60. [PubMed: 18566470]
13. Schultz KE, Sinnott LT, Mutti DO, Bailey MD. Accommodative fluctuations, lens tension, and ciliary body thickness in children. Optom Vis Sci. 2009; 86:677–84. [PubMed: 19417700]
14. Hunt OA, Wolffsohn JS, Gilmartin B. Evaluation of the measurement of refractive error by the PowerRefractor: a remote, continuous and binocular measurement system of oculomotor function. Br J Ophthalmol. 2003; 87:1504–8. [PubMed: 14660462]
15. Wolffsohn JS, Hunt OA, Gilmartin B. Continuous measurement of accommodation in human factor applications. Ophthalmic Physiol Opt. 2002; 22:380–4. [PubMed: 12358306]
16. Harb E, Thorn F, Troilo D. Characteristics of accommodative behavior during sustained reading in emmetropes and myopes. Vision Res. 2006; 46:2581–92. [PubMed: 16545421]
17. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet. 1986; 1:307–10. [PubMed: 2868172]
18. Bailey MD. How should we measure the ciliary muscle? Invest Ophthalmol Vis Sci. 2011; 52:1817–8. [PubMed: 21444926]
19. Sheppard AL, Davies LN. Clinical evaluation of the Grand Seiko Auto Ref/Keratometer WAM-5500. Ophthalmic Physiol Opt. 2010; 30:143–51. [PubMed: 20444118]
20. Lewis HA, Sinnott LT, Kao CY, Bailey MD. Changes in ciliary muscle thickness during accommodation in children. Optom Vis Sci. 2012; 89:XXX–X.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

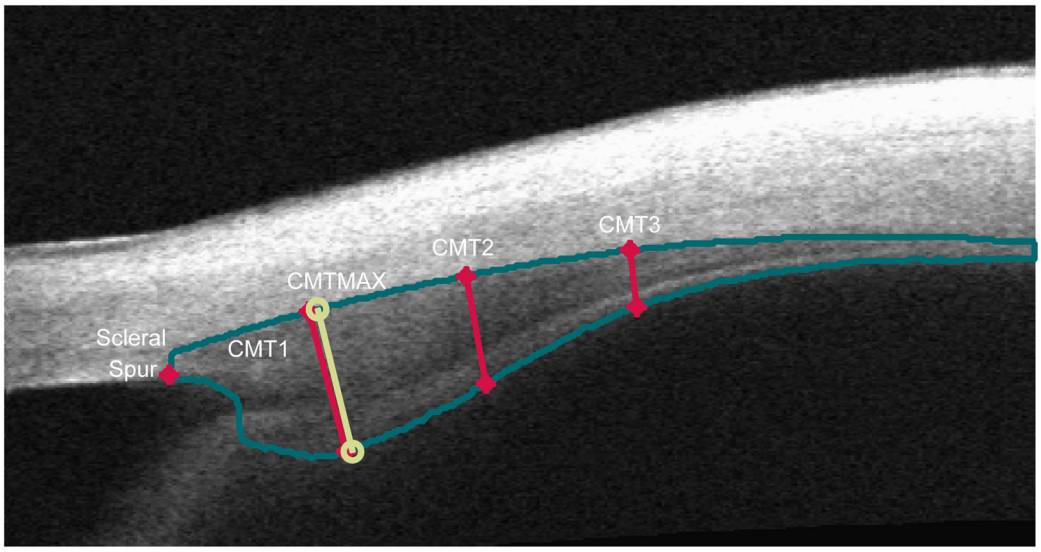

Figure 1.
Representative Visante™ image of the sclera and ciliary muscle while the subject views an external fixation target. The thickness measurements 1 mm (CMT1), 2 mm (CMT2), and 3 mm (CMT3) posterior to the scleral spur are shown (pink). The maximum thickness of the ciliary muscle is also shown (CMTMAX, yellow).

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

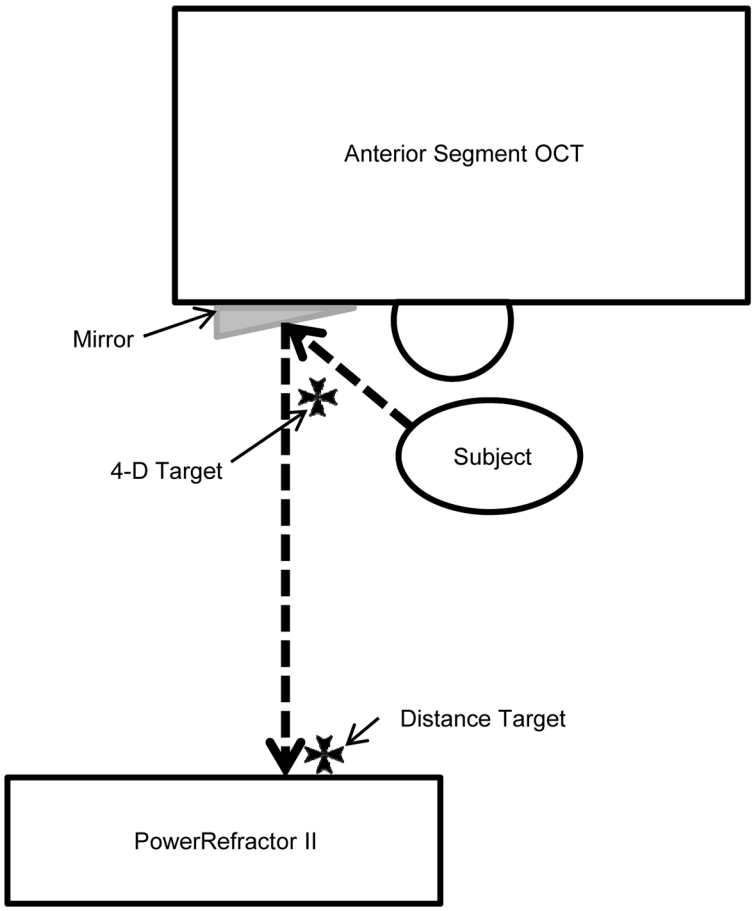

Figure 2.

A diagram of the set up used to simultaneously monitor accommodation during imaging of the ciliary muscle. While the subject was positioned in the head rest for the Visante™ Anterior Segment Optical Coherence Tomographer, he or she viewed targets at either 1.0 m (distance) or 0.25 cm (4-D) through a mirror that was positioned on the left side of the Visante™. The PowerRefractor II was positioned so that it could read the power of the eye through the mirror. The dashed line shows the optical path of the eye viewing the targets as well as the optical path of the PowerRefractor.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

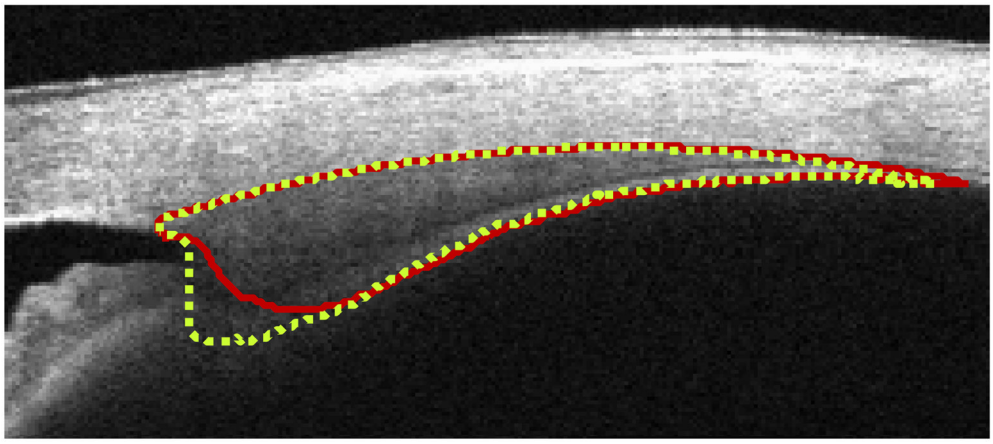

Figure 3.

Outline of the ciliary muscle in an image that was captured while the subject viewed at 4.00-D stimulus. Because the image contrast seems to change for some subjects during accommodation, i.e., the anterior portion of the muscle is slightly darker, the outline obtained with the standard contrast settings[11] (solid line in print, red line on line) did not capture the entire muscle structure. A minor adjustment of the contrast settings was needed in order to fully outline the ciliary muscle (dashed line in print, yellow line on line). A color version of this figure is available online at www.optvissci.com.

NIH-PA Author Manuscript NIH-PA Author Manuscript NIH-PA Author Manuscript

Table 1

General morphological characteristics of the ciliary muscle for all subjects while they viewed the distance and 4.00-D targets.

Ciliary Muscle Measurement Location†	Distance					4.00-D				
	Mean	SD	Median	Min	Max	Mean	SD	Median	Min	Max
				Visit 1						
CMT1	774.8	66.3	780.0	640.0	940.0	813.9	85.8	820.0	640.0	1150.0
CMT2	557.8	80.8	560.0	350.0	720.0	535.5	98.2	540.0	340.0	720.0
CMT3	353.7	67.6	350.0	200.0	480.0	303.8	70.8	310.0	110.0	490.0
CMTMAX	795.2	65.4	800.0	640.0	960.0	868.5	83.3	870.0	650.0	1150.0
				Visit 2						
CMT1	776.2	68.8	790.0	560.0	910.0	819.0	80.1	820.0	620.0	1010.0
CMT2	566.3	75.7	580.0	370.0	690.0	551.0	91.7	555.0	370.0	740.0
CMT3	354.1	65.3	360.0	170.0	470.0	299.3	62.9	310.0	130.0	410.0
CMTMAX	798.2	65.0	810.0	590.0	920.0	874.4	82.0	870.0	680.0	1080.0

† Ciliary muscle thickness (in μm) was measured at the point of maximum thickness (CMTMAX) and at 1 mm (CMT1), 2 mm (CMT2), and 3 mm (CMT3) posterior to the scleral spur.

SD = standard deviation, Min = minimum value observed in the dataset, Max = maximum value observed in the dataset.

NIH-PA Author Manuscript NIH-PA Author Manuscript NIH-PA Author Manuscript

Table 2

Observed changes in ciliary muscle thickness as subjects focused from the distance to the 4.00-D target.

	Visit 1					Visit 2				
	Mean	**SD**	**Median**	**Min**	**Max**	**Mean**	**SD**	**Median**	**Min**	**Max**
					CMTMAX					
Change for a 4-D Stimulus†	71.0	46.9	56.7	17.3	175.0	67.4	53.6	69.3	−3.3	154.0
Change per diopter of Accommodation‡	18.3	12.3	12.7	4.9	45.6	17.6	14.5	14.0	−1.0	45.4
					CMT1					
Change for a 4-D Stimulus†	37.3	51.8	35.3	−65.0	113.3	49.2	44.6	44.8	−38.3	108.3
Change per diopter of Accommodation‡	10.1	14.9	7.8	−14.0	47.0	13.2	12.5	9.6	−11.5	33.5
					CMT2					
Change for a 4-D Stimulus†	−11.0	54.3	−11.6	−138.0	77.0	−4.8	53.7	−20.1	−75.7	133.5
Change per diopter of Accommodation‡	−1.7	16.3	−2.9	−39.0	37.6	−0.7	16.2	−5.4	−22.3	45.9
					CMT3					
Change for a 4-D Stimulus†	−45.2	21.0	−46.2	−81.3	−11.7	−46.5	21.8	−47.5	−83.3	4.5
Change per diopter of Accommodation‡	−11.6	5.2	−12.4	−23.0	−3.2	−12.4	6.3	−13.8	−21.5	1.5

†Change for a 4-D Stimulus (μm) = Ciliary muscle thickness while viewing the 4.00-D target – ciliary muscle thickness while viewing the distance target.

‡Change per diopter of Accommodation (μm /D) = Raw change / accommodative response, or the change in ciliary muscle thickness per 1.00 D of accommodative response. The accommodative response was calculated as the difference in PowerRefractor readings between viewing the distance and the 4.00-D targets.

CMTMAX = maximum ciliary muscle thickness; CMT1, CMT2, and CMT3 = ciliary muscle thickness (μm) at 1 mm, 2 mm, and 3 mm posterior to the scleral spur, respectively.

NIH-PA Author Manuscript NIH-PA Author Manuscript NIH-PA Author Manuscript

Table 3

Modeled change in ciliary muscle thickness for a 4-D stimulus and for the change per diopter of accommodation.

Ciliary Muscle Measurement Location†	Measurement of Change	Modeled Change	95% Confidence Intervals		p-value
			Lower Bound	Upper Bound	
CMTMAX	Change for a 4-D Stimulus ≠	69.2	49.4	89.0	<0.0001
	Change per diopter of Accommodation *	18.1	12.9	23.3	<0.0001
CMT1	Change for a 4-D Stimulus ≠	45.2	27.1	63.2	<0.0001
	Change per diopter of Accommodation *	12.3	7.2	17.4	<0.0001
CMT2	Change for a 4-D Stimulus ≠	−7.3	−28.1	13.5	0.47
	Change per diopter of Accommodation *	−1.0	−7.1	5.0	0.72
CMT3	Change for a 4-D Stimulus ≠	−45.9	−53.6	−38.2	<0.0001
	Change per diopter of Accommodation *	−12.0	−14.2	−9.8	<0.0001

† Ciliary muscle thickness (in μm) was measured at the point of maximum thickness (CMTMAX) and at 1 mm (CMT1), 2 mm (CMT2), and 3 mm (CMT3) posterior to the scleral spur.

≠ Change for a 4-D Stimulus ‡ (μm) = Ciliary muscle thickness while viewing the 4.00-D target – ciliary muscle thickness while viewing the distance target.

* Change per diopter of accommodation (μm /D) = Change for a 4-D Stimulus / accommodative response. The accommodative response was calculated as the difference in PowerRefractor readings between viewing the distance and the 4.00-D targets.

NIH-PA Author Manuscript NIH-PA Author Manuscript NIH-PA Author Manuscript

Table 4

Bland-Altman analysis for the inter-visit repeatability of the change in ciliary muscle thickness for a 4-D stimulus and for the change per diopter of accommodation.

Ciliary Muscle Measurement Location†	Mean of the Differences					Standard Deviation of the Differences	95% Limits of Agreement		Coefficient of Repeatability
	Mean	t Value	p Value	Lower Bound	Upper Bound		Lower Bound	Upper Bound	
Change for a 4-D Stimulus‡									
CMT1	14.6	1.1	0.3	−12.1	41.3	60.2	−103.3	132.5	117.9
CMT2	9.5	0.8	0.4	−15.8	34.9	57.2	−102.5	121.6	112.0
CMT3	−0.1	0.0	1.0	−16.0	15.8	35.9	−70.4	70.3	70.4
CMTMAX	7.4	0.5	0.6	−22.8	37.7	64.6	−119.1	134.0	126.5
Change per diopter of Accommodation*									
CMT1	−0.7	−0.2	0.9	−9.7	8.2	15.5	−31.1	29.6	30.4
CMT2	−1.7	−0.3	0.7	−12.6	9.1	18.8	−38.5	35.1	36.8
CMT3	−0.8	−0.5	0.6	−4.7	3.0	6.6	−13.8	12.2	13.0
CMTMAX	−3.3	−0.8	0.5	−12.6	6.1	15.4	−33.4	26.9	30.2

†Ciliary muscle thickness (in μm) was measured at the point of maximum thickness (CMTMAX) and at 1 mm (CMT1), 2 mm (CMT2), and 3 mm (CMT3) posterior to the scleral spur.

‡Change for a 4-D Stimulus(μm) = Ciliary muscle thickness while viewing the 4.00-D target – ciliary muscle thickness while viewing the distance target.

*Change per diopter of Accommodation (μm /D) = Change for a 4-D Stimulus / accommodative response. The accommodative response was calculated as the difference in PowerRefractor readings between viewing the distance and the 4.00-D targets.