How Should We Measure the Ciliary Muscle?

In an in vivo analysis of ciliary muscle morphologic changes with accommodation and axial ametropia by Sheppard and Davies,1 the authors state that “There is a paucity of literature documenting in vivo changes in human ciliary muscle biome- try with accommodation.” I agree with the authors, and they should be commended for tackling a wanting area of scientific investigation. Subsequently, the authors also published a paper entitled, “The Effect of Ageing on In Vivo Human Ciliary Muscle Morphology and Contractility.”2 Very little is known about the human ciliary muscle, its exact behavior during contraction, its growth and development during overall eye growth, and how it may or may not change throughout all the various decades of life. Is the ciliary muscle really the only smooth muscle in the human body that is not subject to any disease states? Or, have we missed these problems simply because we could not see them? Given that the ciliary muscle may be one of the most understudied structures in the human body, the purpose of this letter is to engage the authors and the larger research community in a much-needed dialog regarding how the ciliary muscle should be measured.

In their article, Sheppard and Davies1 have opened this important debate with their statement that “...thickness measurements taken at a fixed distance from the scleral spur do not take into account the fact that the ciliary muscle overall length varies significantly with refractive error, so a point 2 mm from the scleral spur may represent an anatomically different region of the ciliary body in varying refractive error groups. Proportional thickness measurements such as CM25, CM50, and CM75 may be more valid in analyzing subjects of different refractive error and ensuring that similar regions of the ciliary muscle are compared.” Sheppard and Davies, as well as Muftuoglu et al.,3 have raised this issue in their publications, and the topic is of great interest to me in my research.4,5 My laboratory has also worked to address possible measurement errors and biases by developing methods for ciliary muscle image analysis.6 It is important to note that there is no universally accepted method for measuring ciliary muscle dimensions.

I suggest that there are several issues related to best practices for imaging and measuring the ciliary muscle that require discussion by the larger research community. What metrics should be used (i.e., thickness, length, or cross-sectional area)? What is the best reference point for these metrics (i.e., the scleral spur, the overall length of the muscle, or the point of maximum thickness)? Can one accurately use straight-line calipers on the curved sclera and ciliary muscle? What is the appropriate refractive index or scaling factor to use when analyzing ciliary muscle images, and when should it be applied? When comparing different refractive error groups, is it enough to presume a relaxed muscle state, or is cycloplegia required?

Other investigators have used ciliary muscle measurements that were a specific distance from the scleral spur,4,7 the maximum thickness of the ciliary muscle,3 and in the two papers of Sheppard and Davies, the measurements were made at landmarks referenced to the overall length of the muscle, which they term proportional thickness measurements.1,2 Sheppard and Davies provide an excellent rationale for using the proportional thickness measurement, and they take the time to evaluate the performance of their measurement methods in a way that others have not.4,5,7 Nonetheless, I have obtained many anterior segment optical coherence tomography (OCT) images such as Figure 1, where there was no obvious convergence of the ciliary pigmented epithelium and the scleral wall that was consistent with the known length of the muscle.8 Given that some anterior segment OCT images resemble those in Figure 1, researchers who want to use the length of the ciliary muscle should confirm that two different examiners will consistently choose the same posterior end-point. Also, the posterior zonules, which have been used to identify the posterior end of the ciliary muscle in ultrasound biomicroscopy images,9 are not visible in anterior segment OCT images, because they are obscured by the ciliary pigmented epithelium. Because the posterior zonules cannot be used to assist in identifying the end of the ciliary muscle, it seems appropriate to histologically confirm that the posterior ciliary muscle endpoint found in OCT images is indeed the end of muscle tissue and the beginning of the choroid. While identification of the posterior endpoint may prove to be difficult, there is an additional limitation to the proportional thickness strategy proposed by Sheppard and Davies (i.e., the use of straight-line calipers in ciliary muscle images). We have shown in a recent publication that the curvature of the sclera differs across subjects.9 Thus, to identify a measurement location that is posterior to the scleral spur or to measure the overall length of the ciliary muscle in a manner that is independent of scleral curvature, one should have a measurement tool that is capable of following the scleral curvature.10 Until the issues regarding the validity of identifying a ciliary muscle endpoint and making measurements along the curvature of scleral wall are resolved, it may be best to follow the lead of Muftuoglu et al.5 and also to include a measurement of the maximum thickness of the ciliary muscle,3 and in the two papers of Sheppard and Davies, the measurements were made at landmarks referenced to the overall length of the muscle, which they term proportional thickness measurements.1,2 Sheppard and Davies provide an excellent rationale for using the proportional thickness measurement, and they take the time to evaluate the performance of their measurement methods in a way that others have not.4,5,7 Nonetheless, I have obtained many anterior segment optical coherence tomography (OCT) images such as Figure 1, where there was no obvious convergence of the ciliary pigmented epithelium and the scleral wall that was consistent with the known length of the muscle.8 Given that some anterior segment OCT images resemble those in Figure 1, researchers who want to use the length of the ciliary muscle should confirm that two different examiners will consistently choose the same posterior end-point. Also, the posterior zonules, which have been used to identify the posterior end of the ciliary muscle in ultrasound biomicroscopy images,9 are not visible in anterior segment OCT images, because they are obscured by the ciliary pigmented epithelium. Because the posterior zonules cannot be used to assist in identifying the end of the ciliary muscle, it seems appropriate to histologically confirm that the posterior ciliary muscle endpoint found in OCT images is indeed the end of muscle tissue and the beginning of the choroid.

While identification of the posterior endpoint may prove to be difficult, there is an additional limitation to the proportional thickness strategy proposed by Sheppard and Davies (i.e., the use of straight-line calipers in ciliary muscle images). We have shown in a recent publication that the curvature of the sclera differs across subjects.9 Thus, to identify a measurement location that is posterior to the scleral spur or to measure the overall length of the ciliary muscle in a manner that is independent of scleral curvature, one should have a measurement tool that is capable of following the scleral curvature.10 Until the issues regarding the validity of identifying a ciliary muscle endpoint and making measurements along the curvature of scleral wall are resolved, it may be best to follow the lead of Muftuoglu et al.5 and also to include a measurement of the

**Figure 1.** Anterior segment OCT (Visante; Carl Zeiss Meditec, Dublin, CA) images of the nasal ciliary muscle. *Question marks:* multiple choices for the location of the posterior end of the ciliary muscle. (A) Image from a 5-year-old, emmetropic (+0.25 D) boy with an axial length of 22.3 mm. The *arrow* is located at a position that may be a point of convergence and the end of the ciliary muscle; however, it is located almost 6.0 mm from the scleral spur. This location is clearly too posterior to be the end of the ciliary muscle in a child’s shorter eye (i.e., the histologically estimated nasal ciliary muscle length for children aged 2 to 6 years is 3.75 to 4.95 mm; mean adult nasal ciliary muscle length = 4.6 mm to 4.79 mm). (B) Image from a 9-year-old, emmetropic (+0.25 D) boy with an axial length of 23.6 mm. The *arrow* is located at a position that may be a point of convergence and the end of the ciliary muscle, although an exact convergence point is difficult to identify. It is approximately 5.5 mm from the scleral spur, which, once again, is too posterior, making it unlikely that this is the true posterior end of the ciliary muscle.
maximum thickness of the ciliary muscle. This should be easy to obtain in any measurement platform.

An additional issue to consider is the application of an appropriate refractive index to ciliary muscle images. In the two published papers in which UBM systems were used, it is not clear which refractive index was applied (1.0 or 1.38). Neither of these papers discuss whether the UBM was set to account for the speed of sound through the sclera. In previous publications from my laboratory, a refractive index of 1.0 was applied to the images before making measurements, and we acknowledged that this resulted in a larger-than-physiological estimate of ciliary muscle thickness. While our previous publications and the two previous UBM studies may not have provided physiologically accurate estimates of ciliary muscle thickness, the error was consistent across all subjects and would not have affected within-subject or across-subject comparisons. In the semiautomatic algorithm we developed for analyzing ciliary muscle images, we now adjust the images before analysis so that we can provide measurements in a physiologically accurate range.

Sheppard and Davies used a different approach to adjust thickness measurements for the appropriate ciliary muscle refractive index. They made caliper measurements in images that were scaled for a refractive index of 1.0, and then they divided each thickness measurement by 1.382. The inaccuracy of this approach is that refractive indices in anterior segment OCT images should only be applied parallel to the axial scan depth of the image, or in the y-dimension of the image. They are not applied in the lateral or x-dimension of the image. This point is marked by the black line (1.38 mm) in Figure 2, which is an example of Sheppard and Davies’ measurement of the distance between the inner apex and the scleral spur. In the paper by Sheppard and Davies, a measurement of 1.38 mm/1.382 or 1.0 mm would have been used in the analysis. It is clear, however, that this measurement (Fig. 2, black line) is located at an angle that is oblique to the y-dimension of the image.

To adjust the measurement in the y-dimension only, we imported the anterior segment OCT image in Figure 2 into software with image-analysis capabilities (MatLab; The Math-Works, Natick, MA). Then, the x- and y-coordinates of both the scleral spur and in the inner apex were identified. If these coordinates are then used to adjust the 1.38-mm measurement in the y-dimension only, as described in Figure 2, it yields a measurement of 1.21 mm. In this case, division by the refractive index would have resulted in a measurement of 1.0 mm, which would be affected by the application of straight-line calipers across a curved scleral wall. In addition, if researchers wish to apply a refractive index correction to ciliary muscle measurements, the calculations should be conducted like the example in Figure 2, the anterior segment OCT image should be adjusted before the application of caliper measurements, or the operator of the UBM should adapt the system for a speed of sound that is appropriate to the sclera/ciliary muscle. Finally, when studying the relationship between the ciliary muscle and refractive error, it would also be best practice to obtain the maximum thickness in any measurement platform.

In summary, based on the work presented by Sheppard and Davies and several other research groups, it is clear that the interest in studying ciliary muscle morphology and function in humans is growing. Until the more difficult measurement issues can be resolved and presented to the research community in a user-friendly software format, I suggest the following: Future studies should include a measurement of the maximum thickness. It does not rely on the location of the scleral spur or the accurate identification of the posterior endpoint of the ciliary muscle, nor will it be affected by the application of straight-line calipers across a curved scleral wall. In addition, if researchers wish to apply a measurement in the y-dimension only, as described in Figure 2, it yields a measurement of 1.21 mm. In this case, division by the refractive index would have resulted in a measurement of 1.0 mm, which would be affected by the application of straight-line calipers across a curved scleral wall. In addition, if researchers wish to apply a refractive index correction to ciliary muscle measurements, the calculations should be conducted like the example in Figure 2, the anterior segment OCT image should be adjusted before the application of caliper measurements, or the operator of the UBM should adapt the system for a speed of sound that is appropriate to the sclera/ciliary muscle. Finally, when studying the relationship between the ciliary muscle and refractive error, it would also be best practice to obtain the measurements with subjects under cycloplegia.

Melissa D. Bailey
College of Optometry, The Ohio State University, Columbus, Ohio.
E-mail: mbailey@optometry.osu.edu

References


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