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Accommodation: Mechanism and Measurement

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Accommodation is defined as a dioptric change in the power of the eye [1]. The young phakic eye undergoes an increase in optical power with accommodation for seeing at near. This change is brought about by an increase in the optical power of the crystalline lens owing to a decrease in lens diameter, an increase in lens axial thickness, and an increase in curvature of the lens anterior and posterior surfaces. The physical change in the shape of the lens and the increase in optical power constitute accommodation to allow the eye to focus on near objects.

An effort to focus at near results in accommodation, convergence, and pupil constriction [2–4]. These three events are called the accommodative triad. A convergence response in the absence of blur cues causes a contraction of the iris and the ciliary muscles [5]. The three physiologic functions of accommodation, convergence, and pupil constriction are neurophysiologically coupled in the brain. The Edinger-Westphal (EW) nucleus provides preganglionic parasympathetic input to the iris and the ciliary muscles via the ciliary ganglion [6]. The EW nucleus is located immediately dorsal to the oculomotor nucleus where the neurons innervating the extraocular muscles reside [6]. The neuroanatomic proximity of these preganglionic neurons that provide the parasympathetic input to the iris, ciliary muscles, and medial rectus muscles underlies the close physiologic association among pupil constriction, accommodation, and convergence.

Accommodation versus pseudoaccommodation

There is an important fundamental distinction between accommodation (ie, the optical change in power of the eye) and the ability of a distance-corrected eye to see at near. Functional near vision in a presbyopic eye can be achieved through a variety of nonaccommodative means, such as a multifocal contact lens, a multifocal intraocular lens, or corneal multifocality. All of these approaches afford functional near vision through various static optical means; however, they are clearly not accommodation. The apparent ability of some distance-corrected pseudophakic patients with fixed focal length, monofocal intraocular lenses to see at near has been called apparent accommodation or pseudoaccommodation [7]. Pseudoaccommodation facilitates functional near vision, not through a change in optical power, but through an increased depth of field of the eye. The depth of field is the range of object distances over which no change in retinal image focus can be detected, whereas the depth of focus is the range of image distances on the retina over which no change in retinal image focus can be detected. An increased depth of field of the eye can be due to ocular aberrations such as astigmatism, spherical aberration, or higher order aberrations. The decrease in pupil diameter that accompanies accommodation also acts to increase the depth of field of the eye [8,9]. This increased depth of field occurs because the pupil constriction causes a decrease in the diameter of the cone of light that passes from the lens to focus on the retina. Decreasing the pupil size decreases the size

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of the blur circle on the retina and increases the distance over which no change in image focus can be detected. Although an increased depth of focus provides a range of object distances over which no change in retinal image focus can be detected, this is clearly not accommodation.

Subjective versus objective measurement of accommodation

The distinction between accommodation and the depth of field is most apparent when comparing objectively and subjectively measured accommodative amplitude [10,11]. Objective measurement of accommodation requires the use of an objective instrument such as a refractometer or an autorefractor that measures the optical power or refractive state of the eye [11–14]. As a near target is brought progressively closer to the eyes and the subject accommodates, a more myopic refraction or an increase in the optical power of the eyes will be measured objectively by the instrument. When such objective measurements are made in absolute presbyopes, no refractive change or change in power of the eye (ie, accommodation) is recorded [10,11].

Subjective measurement of accommodative amplitude requires a distance-corrected subject to report when text, moved progressively closer to the eyes, can no longer be held in clear focus. With the "push-up test," perhaps the most widely used subjective clinical test of accommodative amplitude, the distance-corrected subject is required to use their subjective interpretation of blur perception to determine the point at which sustained blur (ie, the near point) is first perceived as a letter chart is moved toward the eyes. The reciprocal of this distance is considered the accommodative amplitude. When this test is performed in a young adult, the eyes will accommodate and converge and the pupils will constrict to increase the depth of field as the near target is brought progressively closer. The near point attained is due to a combination of accommodation and depth of field (or pseudoaccommodation) because of the subjective nature of the test. When this test is performed in an absolute presbyope, the eyes will converge and the pupils will constrict to increase depth of field, but without an accommodative optical change in the lens and eye. There will be some range of target distances over which the presbyope will be unable to perceive a change in focus owing to the depth of field of the eye. One may be led to conclude incorrectly that some accommodation is present. Indeed, the classical curve showing the progression of presbyopia from Duane's subjective measurements of accommodation suggests that about 1.5 D of accommodation remains in the oldest subjects (Fig. 1A) [15]. However, this phenomenon is almost certainly due to depth of field effects inherent in the subjective push-up test due to the pupil constriction that occurs with accommodation [10,14,16]. With the subjective test, it is impossible to distinguish apparent accommodation from the true accommodative optical change in power of the eye; therefore, subjective tests do not unequivocally demonstrate the presence of accommodation. Subjective measurements systematically overestimate the objectively measured accommodative amplitude at all ages (Fig. 1B) [10–14].

When an objective technique is used to measure accommodation, it is evident that the accommodative response generally lags behind the stimulus amplitude. This lag of accommodation increases with increasing stimulus amplitude. The lag of accommodation is due in part to the depth of field of the eye and to the physiologic limitation in the ability of the eye to focus clearly on the target. The intraocular muscles may not contract sufficiently to focus the eye clearly on the stimulus, or the lens may be unable to undergo the changes in shape and optical power required to focus the image clearly on the retina. The lag of accommodation varies in extent for different individuals and depending on the kind of visual stimulus used [17,18].

Stimulating accommodation

To measure an accommodative response, an objective technique must be used. Human subjects must be presented with a compelling accommodative stimulus and must elicit an accommodative response. A real target viewed binocularly at near provides blur, convergence, and proximal cues. These visual cues are important to stimulate the accommodative response. Blur alone can be produced by having the subject view a distant letter chart and then introducing minus trial lenses in front of the eye. The induced negative defocus can then be reduced or overcome with an accommodative increase in power of the eye. Blur, proximal, and convergence cues can be produced with a near reading target such as fine reading text viewed binocularly. The combination of all three of these cues presents a more compelling accommodative stimulus than blur alone, and the resulting accommodative response may then be stronger than to blur cues alone [17,19].

Accommodation can also be stimulated with topical application of pilocarpine. Pilocarpine dif-

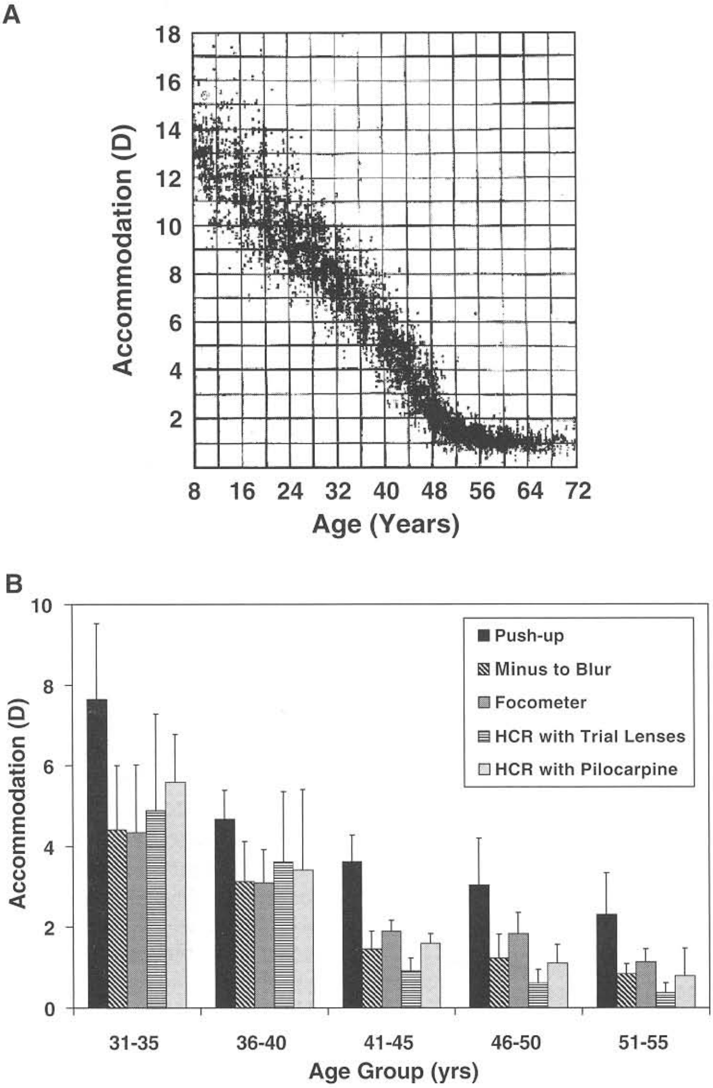


Fig. 1. (*A*) Duane's curve showing the "values of monocular accommodation" [15]. The near point was measured with the subjective push-up test in over 4200 eyes. The graph suggests that approximately 1.5 D of accommodation remains in subjects aged 52 to 72 years; however, this is almost certainly due to the depth of field inherent in the subjective measurement of accommodation that is due in part to small pupil diameters in older subjects. (*B*) Accommodative amplitude was measured monocularly in 31 subjects aged 31 to 55 years using five different methods: (1) the subjective push-up method, (2) subjective minus to blur, (3) defocus with the Focometer, (4) Hartinger coincidence refractometer (HCR) with trial lenses, and (5) HCR with pilocarpine. In the subjective minus to blur, minus trial lenses are held in front of the eye as the subject views a distant letter target. The subject reports when the distance target can no longer be held in clear focus, and the trial lens power represents the accommodative response amplitude. Defocus is introduced with the Focometer, a Badel optical telescope, while the subject views a distant letter target. The subject reports when the first sustained blur occurs, and the power is read off a scale on the Focometer. The HCR is used to measure objectively the accommodative response of the right eye as the left eye views a distant letter target that is defocused with minus trial lenses. The HCR can also be used to measure the accommodative response following topical administration of one drop of 6% pilocarpine. The first three approaches are subjective methods, whereas the latter two are objective methods. In each age group, the subjective push-up test overestimates the objectively measured accommodative amplitudes [14]. (*From* Ostrin LA, Glasser A. Accommodation measurements in a prepresbyopic and presbyopic population. J Cataract Refract Surg 2004;30(7):1435–44; with permission.)

fuses into the eye to stimulate directly the iris and ciliary muscles to contract [20]. Topical application of 2% and 6% pilocarpine has been used to stimulate accommodation [12–14,21–29]. The pupil constricts dramatically soon after pilocarpine is administered, making prolonged objective accommodation measurements difficult. Phenylephrine can be used to predilate the iris without appreciably affecting accommodation, which may increase the duration over which accommodation can subsequently be measured [12–14,30,31]. Refraction measurement with an instrument such as a Hartinger coincidence refractometer, which allows measurement through 1 to 2 mm diameter pupils [32], enables refraction measurements to be performed over longer post-pilocarpine intervals [12–14]. The pilocarpine-induced accommodative response is affected by iris color owing to absorption of the drug by the iris pigment epithelium, resulting in lower accommodative amplitudes in subjects with darker irides [12,14]. Drug-stimulated accommodation produces a net forward shift of the lens in humans [28] and monkeys [33] that does not occur with voluntary accommodation. Nevertheless, in the monkey, a normal accommodative response initially occurs before the forward shift of the lens (Fig. 2) [33].

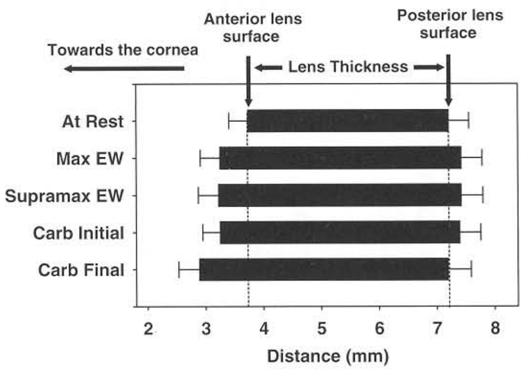


Fig. 2. A-scan ultrasound biometry measured lens thickness in four adolescent monkey eyes at rest (At Rest) during maximally EW-stimulated accommodation (Max EW), during EW stimulation with a current amplitude higher than that required to produce maximum accommodation (Supramax EW), at approximately 5 minutes after topical iontophoretic delivery of 40% carbachol in agar gel (Carb Initial), and at 30 minutes after carbachol iontophoresis after maximum accommodation is achieved (Carb Final). The anterior lens surface moves forward and the posterior lens surface backward during accommodation. There is a forward translational shift of the lens at the final time point of the carbachol-induced accommodative response that does not occur with EW-stimulated accommodation [33]. (*From* Ostrin LA, Glasser A. Comparisons between pharmacologically and Edinger-Westphal stimulated accommodation in rhesus monkeys. Invest Ophthalmol Vis Sci 2005;46(2):609–17; with permission.)

Monkeys versus humans

Young rhesus monkeys have high accommodative amplitudes, and the anatomy of the accommodative structures of the rhesus monkey eye is similar to that of humans [34–39]. Rhesus monkeys develop presbyopia with the same relative age course as humans and are the only known animal model for human presbyopia [34,40]. Although quantitative differences exist between humans and monkeys in regards to accommodation, such as eye size and accommodative amplitude, qualitatively, accommodation in the two species is remarkably similar. Rhesus monkeys are widely regarded as an excellent animal model for studies of human accommodation and presbyopia [34,39–43]. Considerable information about the primate accommodative mechanism and anatomy is available from studies on rhesus monkeys.

Anatomy of the accommodative structures

To understand the mechanism of accommodation, one must understand the gross anatomy of the accommodative structures and their interrelationships. The primary accommodative structures of the eye consist of the ciliary body, the ciliary muscle, the posterior and anterior zonular fibers, the lens capsule, and the lens substance.

The ciliary muscle

The ciliary muscle consists of three subgroups of muscle fiber cells differentiated by their positions and orientations within the ciliary body [44]. The muscle fiber groups are the longitudinal or meridional fibers, the radial or reticular fibers, and the equatorial or circular fibers. The longitudinal fibers are located beneath the sclera at the ciliary region. Beneath the longitudinal fibers and closer to the vitreous are the radial fibers. Beneath these are the circular fibers located most anteriorly in the ciliary body, closest to the apex of the ciliary muscle toward the lens equator. The ciliary muscle is located within the ciliary body bounded externally by the sclera, the collagen fibers, fibroblasts, and melanocytes of the outer surface of the ciliary body [44]. The inner surface of the ciliary muscle is bounded anteriorly by the pars plicata and posteriorly by the pars plana of the ciliary body. Anteriorly, the ciliary muscle inserts into the scleral spur and the trabecular meshwork, which serve as a relatively fixed anterior anchor point against which the ciliary muscle contracts [44]. Posteriorly, the ciliary muscle attaches via elastic tendons to the stroma of the choroid [45].

The zonular fibers

The zonular fibers are fine elastic suspensory fibers and can broadly be broken down into two subgroups based on their location, origins, and insertions: the posterior zonular fibers, or the pars plana zonule, and the anterior zonular fibers. The pars plana zonule extends from near the posterior attachment of the ciliary muscle at the ora serrata of the retina to the ciliary processes [46]. From their posterior origin, the posterior zonular fibers extend longitudinally toward the pars plicata of the ciliary body as a meshwork of interlacing fibers following a straight path toward the tips of the ciliary processes [47]. Most of the posterior zonular fibers course forward to the pars plicata region of the ciliary body and enter the valleys between the ciliary processes, inserting into the walls of the valleys of the ciliary processes [48]. The pars plicate region of the ciliary body separates the posterior zonule from the anterior zonule [48]. The anterior zonular fibers span the circumlental space between the ciliary processes and the equatorial region of the lens (Fig. 3A). Some zonular fibers pass from the pars plana through the valleys between the ciliary processes and on toward the lens [46,48]. A spanning or tension fiber system of many finer strands forms the zonular plexus, which attaches the zonule to the ciliary epithelium in the valleys of the ciliary processes [46]. This plexus serves to anchor the anterior and pars plana zonule to the ciliary epithelium of the ciliary body. As the anterior zonular fibers approach the lens, they fan out to insert into the lens capsule around the equatorial region of the lens (Fig. 3A). The individual zonular fibers terminate within zonular lamella of the lens capsule [46]. The zonular fibers inserting around the lens equatorial region do not form discreet zonular fiber bundles that selectively insert to the lens anterior, equatorial, and posterior surfaces, as has been suggested [49]; rather, in unfixed tissues, they are seen to form a relatively uniform distribution or meshwork of fibers inserting all around the lens equatorial region [50,51].

The lens and capsule

The lens capsule is a thin acellular elastic membrane surrounding the lens. The anterior capsule is thickest near the midperipheral region and thinnest at the pole [52]. On the lens posterior surface, the capsule is thinnest at the posterior pole and thicker toward the periphery [53].

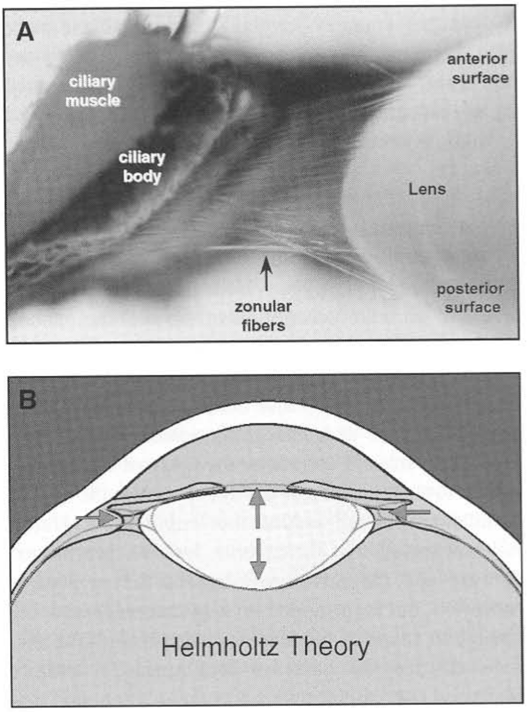


Fig. 3. (*A*) Photograph of a partially dissected, unfixed, 54-year-old human eye showing the relationship of the accommodative structures to each other. The cornea, sclera, and iris have been removed. The ciliary body, but not the lens, has been cut through to allow a sagittal view of the ciliary muscle and an associated ciliary process and the anterior zonular fibers beneath it. The anterior zonular fibers extending from the ciliary body to the lens equator originate along the base of the ciliary process. Note the considerable complexity of the zonular fibers, with crossing of the fibers and a continuous insertion of the zonular fibers around the lens equator [51]. (*From* Glasser A, Campbell MCW. Presbyopia and the optical changes in the human crystalline lens with age. Vision Research 1998;38: 209–29; with permission.) (*B*) Diagram of the accommodative mechanism as described by Helmholtz [55,89]. The dashed red lines show the ciliary body, zonular fibers, and lens in the accommodated state. Helmholtz believed that the posterior lens surface was stationary during accommodation. (*From* Glasser A. Physiology of accommodation and presbyopia. In: Sher NA, editor. Surgery for hyperopia. Thorofare: Slack Incorporated; 2004. p. 11–21; with permission.)

The lens consists of a monolayer of epithelial cells on the anterior surface beneath the capsule, with elongated lens epithelial cells at various stages of maturation. The lens fiber cells are arranged in layers to form the younger peripheral cortex and the more mature central lens nucleus. The lens fiber cells are composed of a complex arrangement of elongated cells that interdigitate to form a tightly coupled hexagonal lamellar arrangement [54].

The accommodative mechanism

Helmholtz [55,56] provided the first comprehensive and accurate description of the accommodative mechanism. In the unaccommodated state, resting tension on the elastic zonular fibers at the lens equator pulls outward and holds the lens in a relatively flattened and unaccommodated state. When the ciliary muscle contracts, the apex of the muscle moves toward the axis of the eye to release the resting zonular tension all around the lens equator. Helmholtz observed that the anterior lens surface moved forward and the curvature increased during accommodation, but he provided no explanation of how the change in shape of the lens occurred. Helmholtz also believed that the posterior lens surface curvature increased only slightly with accommodation, and that there was no appreciable movement of the posterior lens surface. Helmholtz concluded that the lens axial thickness increased by about 0.5 mm with accommodation and that, because the lens volume was constant, the lens equatorial diameter must decrease during accommodation (Fig. 3B).

Fincham [52] identified that the lens thickness increased to a greater degree than the anterior chamber decreased with accommodation, suggesting that the lens posterior surface must move backward with accommodation. From measurements of accommodation in an eye with traumatic aniridia, Fincham directly observed centripetal movement of the ciliary processes and a decrease in lens diameter. Together with Graves, Fincham observed in a patient who had sustained traumatic aphakia that the anterior and posterior capsular surfaces of the empty capsular bag were flattened and parallel to each other in the unaccommodated state but became flaccid, widely separated, and wrinkled during an accommodative effort [52,57,58]. Fincham concluded that the capsule was held under tension in the unaccommodated state and that the tension was released with accommodation. Fincham also measured greater changes in anterior chamber depth with accommodation when a subject was looking down than when looking forward, consistent with the release of zonular tension during accommodation. He observed that, when the zonule is cut and the lens freed from the zonular traction in a young enucleated eye, the lens takes on a more accommodated form with increased anterior surface curvature. When the capsule is removed, the lens substance tends to take on an unaccommodated form. These observations led Fincham to conclude that accommodation of the lens is caused by the elastic capsule molding the lens substance into an accommodated form.

Fincham studied capsules of various animal species and found them to be of relatively uniform thickness in nonaccommodating mammals. In humans and other primates known to accommodate, the capsule was thinnest at the posterior pole and of maximum thickness at the midperipheral anterior and posterior surfaces. Fincham described how this variation in capsular thickness allowed the lens polar surfaces to undergo steeper changes in curvature with accommodation than the peripheral lens surfaces, allowing the accommodated lens to take on a conoidal form. Fincham refined the Helmholtz accommodative mechanism with the recognition that resting zonular tension all around the lens equator pulls the lens into a flattened and unaccommodated form. When zonular tension is released, the capsular forces mold the lens into an accommodated form.

The accommodative mechanism as generally accepted today requires no significant modification of the descriptions provided by Helmholtz and Fincham. When the ciliary muscle contracts with an accommodative effort, the anterior-inner apex of the ciliary body moves toward the lens equator to release the resting zonular tension. When the zonular tension is released, the elastic lens capsule molds the soft lens into an accommodated form. There is a decrease in the lens equatorial diameter and an increase in lens axial thickness, and the lens anterior and posterior central surfaces undergo an increase in curvature. When the accommodative effort ceases, the ciliary muscle relaxes, and the ciliary body is pulled back into the unaccommodated form through the elasticity of the posterior attachments of the ciliary muscle and the posterior zonular fibers. Relaxation of the ciliary muscle reintroduces tension on the anterior zonular fibers around the lens equator, and the lens is pulled into the relatively flattened and unaccommodated state by the zonular forces on the capsule.

Two alternative theories of accommodation have been proposed by Schachar [59–62] and Coleman [63–65]; however, little independent evidence exists in support of these theories. The Coleman theory requires a vitreous force or a pressure differential between the anterior and vitreous chambers, but the lens is able to accommodate following vitrectomy [66] and in the absence of vitreous or intraocular pressure [51,67]. Furthermore, there is substantial evidence opposing the Schachar theory, especially regarding the requirement of this theory that the lens diameter increases during accommodation.

During accommodation in a 26-year-old human subject with congenital aniridia, Grossmann [68,69] measured an 8.8% accommodative decrease in lens diameter. Fincham [52] observed an accommodative decrease in lens diameter in a 22-year-old human subject who had sustained traumatic aniridia. Wilson [70] measured a 7.44% decrease in lens diameter during accommodation with retroillumination infrared video photography in a 27-year-old human subject with ocular albinism. MRI showed a 6.57% decrease in lens diameter during accommodation in the eight youngest subjects studied [71].

Further experimental support for the Helmholtz accommodative mechanism comes from studies in rhesus monkeys. The ciliary body moves toward the axis of the eye and the lens equator moves away from the sclera during accommodation [37,39,72]. Experiments imaging the entire lens diameter show that the lens diameter decreases during both EW-stimulated and pharmacologically stimulated accommodation [39,73]. The lens sags downward under the influence of gravity during accommodation, consistent with a release of zonular tension [39]. This observation is also consistent with in vitro studies in isolated human crystalline lenses in which an outward directed increase in zonular tension applied to young human lenses caused an increase in lens diameter and a decrease in optical power owing to flattening of the lens surface curvatures [51]. These changes are consistent with release of zonular tension during accommodation and the capsule molding the lens into a more accommodated form.

Accommodative axial biometric changes

The accommodative optical change in the lens is brought about by a physical change in the shape of the lens. It is generally accepted that, during accommodation, the lens thickness increases, the equatorial diameter decreases, and the lens surface curvatures become steeper. The extent to which these physical changes occur per diopter of optical change during accommodation is difficult to determine in humans because of the difficulties in measuring the accommodative optical and the corresponding physical changes to correlate them.

In both humans and monkeys, lens axial thickness increases during accommodation. This increase has been measured during EW- and pharmacologic-stimulated accommodation in monkeys with A-scan ultrasonography [33,41,74] and during voluntary accommodation in humans with A-scan ultrasound [75–78], partial coherence interferometry (PCI) [29,79], and Scheimpflug photography [42,78,80–83], and during pharmacologically stimulated accommodation in humans with PCI [29].

Although noncontact optical techniques such as PCI, Scheimpflug photography, and optical coherence interferometry are available that could potentially allow simultaneous measurement of accommodative changes in refraction and lens thickness, to date, this has not been done. Instead, studies in humans have presented the subject with a fixed amplitude stimulus and first measured the accommodative optical response and subsequently the ocular biometric response, or have measured the accommodative changes in lens thickness as a function of the accommodative stimulus demand. The former approach assumes that the accommodative response is identical when the refraction is measured and then again subsequently on the next response when the biometry is measured. The latter approach in which the stimulus amplitude is considered would tend to overestimate the actual accommodative refractive response owing to the lag of accommodation. In human studies, there is variability and uncertainty regarding how much change in lens thickness and anterior chamber depth occurs during accommodation.

EW-stimulated accommodation in anesthetized rhesus monkeys allows rigorous and reliable control of the amplitude and duration of the accommodative response [31,84]. A controlled stimulus current can be delivered repeatedly to the EW nucleus to elicit reliably and repeatedly accommodative responses of the same amplitude and duration. With this approach, first refraction and subsequently biometry can be recorded for stimuli of the same amplitude and duration. Continuous dynamic measurement of the accommodative refractive changes and subsequently the axial biometric changes allows a comparison between the two continuously throughout accommodative responses of exactly the same amplitude and duration. This method has enabled an accurate comparison between the accommodative refractive and axial biometric changes in monkey eyes [74].

Data obtained from six eyes from three adolescent rhesus monkeys accommodating about 13 D show that, on average, lens thickness increases by about 800μm, anterior chamber depth decreases by about 600 μm, and the posterior lens surface moves posteriorly by about 200 μm (Fig. 4). These biometric changes are relatively linearly correlated with the refractive changes throughout the accommodative responses. The relationship between refraction and

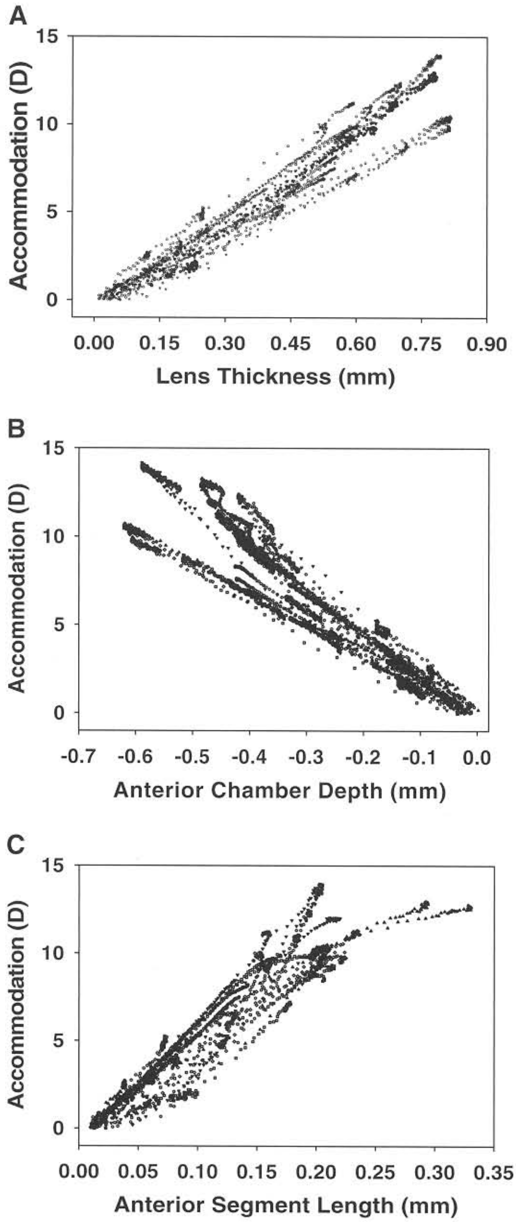
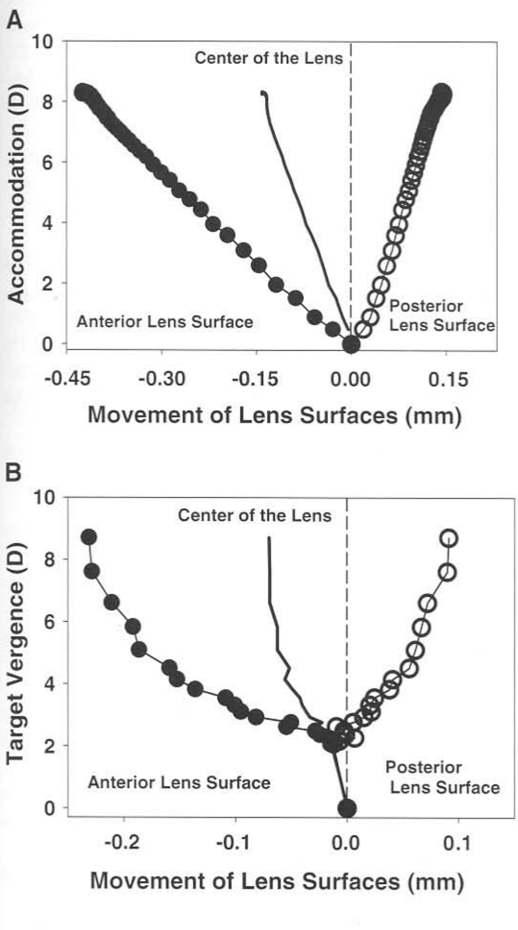


Fig. 4. In six eyes from three adolescent rhesus monkeys, (*A*) lens thickness increases, (*B*) anterior chamber depth decreases, and (*C*) anterior segment length (anterior chamber depth plus lens thickness) increases, that is, the posterior lens surface moves posteriorly during accommodation. In general, the accommodative biometric changes are well correlated with the accommodative optical change in the eyes [74]. (*From* Vilupuru AS, Glasser A. The relationship between refractive and biometric changes during Edinger-Westphal stimulated accommodation in rhesus monkeys. Exp Eye Res 2005;80(3):349–60; with permission.)

biometry differs slightly, although nonsystematically, between monkeys and between eyes. Despite the methodologic differences between human and monkey studies, the challenges of performing these studies in humans, and the differences in eye size and accommodative amplitude between humans and monkeys, there is generally good agreement between the overall results in humans and monkeys. On average, approximately 75% of the increase in lens thickness is due to a forward movement of the anterior lens surface and about 25% to a posterior movement of the posterior lens surface (Fig. 5) [74,79,85]. Nevertheless, a recent study in humans from the same laboratory and using the same methodology did not record a posterior movement of the posterior lens surface [29]. Although there is a small (50–150 μm) net anterior movement of the midpoint of the lens, this movement is most likely a consequence of the greater forward movement of the anterior lens surface and not an integral aspect of the accommodative mechanism. Such a small forward shift of the lens is unlikely to constitute any significant optical accommodative change in power of the eye.

Implications for accommodation restoration in presbyopes

A clear understanding of what accommodation is, of the anatomy of the accommodative structures, of the mechanism of accommodation, and of the causes of presbyopia is necessary to understand whether accommodation may be restored in the presbyopic eye. Not withstanding the significant challenges that are faced owing to age changes in the eye, intraocular lens design, surgical technique, secondary capsular opacification, and fibrosis and shrinkage of the capsular bag secondary to cataract surgery, theoretically, it may be possible to restore accommodation to a presbyopic eye with an artificial accommodative intraocular lens. An increase in lens surface curvature, as occurs in the natural lens, is an efficient way of producing an accommodative change in power of the eye. An accommodative optical change in a pseudophakic eye could also be achieved with the forward movement of a fixed focal length optic or with increased separation between two optics of a dual optic accommodative intraocular lens [86–88]. If the movements or forces generated from the natural accommodative mechanism and structures could be harnessed to induce a change in curvature or movement of optics in the eye, it might be possible to restore accommodation in presbyopes. Although the midpoint of the natural lens in the young primate does move forward with accommodation, this forward movement is probably secondary to the accommodative increase in lens thickness. Nevertheless, with the lens substance removed from the capsular bag, there is potentially 3 to 4 mm of space available for movement within the empty capsular bag if the accommodative forces could be harnessed to move an optic or two optics within this space. Forward movement of a single optic is an inefficient way of producing accommodation because the accomodative optical change is directly proportional to the amount of forward movement that occurs. Increased separation of dual optics is a more efficient approach owing to the combined optical effects of forward movement of one optic and the increased separation of the two optics. If the elasticity of the capsule could be harnessed to produce a change in curvature of a soft polymer lens, an accommodative response closer to that of the natural young lens may be achievable.



Understanding appropriate methods for stimulating and measuring accommodation is essential. Subjective measurement of accommodation is inappropriate to evaluate accommodation restoration concepts because of the inability to distinguish true accommodation from pseudoaccommodation [13,14]. Improving near visual abilities in presbyopes through only pseudoaccommodative means would certainly be beneficial for overcoming the effects of presbyopia; however, to evaluate whether accommodation restoration concepts are achieving their goals, namely, the restoration of active and dynamic accommodation, objective measurement of accommodation is essential. Iterative improvement in lens design and clinical performance will be achieved by understanding how much benefit comes from true accommodation versus pseudoaccommodation. Similarly, understanding how to stimulate accommodation to produce an accommodative response is important. Although topical application of pilocarpine may be useful for producing an involuntary accommodative response, caution should be employed in the interpretation of results from pharmacologic stimulation because of the likelihood that pilocarpine stimulation may not produce an accommodative response that is identical to that in voluntary accommodation.

Fig. 5. (*A*) Biometric and refractive data from a single accommodative response from a monkey eye [74]. EW-stimulated accommodation in the monkey eye allows dynamic objective measurement of refraction and biometry, sequentially. There is a linear anterior movement of the anterior lens surface (*solid symbols*) and posterior movement of the posterior lens surface (*open symbols*) with refraction. The solid line represents the difference between the lens anterior and posterior surfaces, indicating a small net forward movement of the midline of the lens. (*B*) Accommodative biometric measurements from a human eye. Each data point represents the biometry measurements for a particular accommodative stimulus amplitude [79]. Owing to the complexity of simultaneously or even sequentially measuring biometry and refraction in humans, the measured biometry was compared with the stimulus amplitude rather than the accommodative response amplitude. The resulting nonlinearities for the human eye are unlikely to represent the true relationship between the lens physical and optical changes owing to the actual accommodative response lagging behind the stimulus amplitude. Nevertheless, as is true in monkeys, the anterior lens surface moves anteriorly, the posterior lens surface moves posteriorly, and the lens midline moves forward slightly during accommodation. (*From* Vilupuru AS, Glasser A. The relationship between refractive and biometric changes during Edinger-Westphal stimulated accommodation in rhesus monkeys. Exp Eye Res 2005;80(3):349–60; with permission.)

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