4

PHYSIOLOGY AND BEHAVIOR OF THE ACCOMMODATION SYSTEM

W. Neil Charman, PhD, DSc and Sotiris Plainis, MSc, PhD

Some 150 years ago, von Helmholtz[1] remarked: "There is no other subject in physiological optics about which so many antagonistic opinions have been entertained as concerning the accommodation system of the eye." Since that time, much progress has been made and there is now broad agreement on the general details of the mechanism of accommodation. Nevertheless, marked differences of opinion about some aspects of the process, and their changes with age, still persist.

BASIC MECHANISM

If we consider the available optical components of the eye, it is clear that, in principle, various mechanisms could actively change ocular focus to produce sharp retinal images of objects at differing distances. These include a change in corneal curvature, axial movement of the crystalline lens, a change in the power of the lens, or a change in axial length (Figure 4-1). All of these suggestions had their early advocates. In addition, other authors noted that pupillary miosis occurs in near vision and suggested that the associated increase in depth of focus (DOF) was great enough to render an active focus change unnecessary or that the same effect was achieved by multifocality in the lens. However, the elegant experiments of Young[2] in 1801 successfully eliminated most of these possibilities and confirmed that a change in lenticular power was the crucial factor, as suspected by Descartes[3] and others long before. Subsequent experimentation has fully supported Young's basic conclusion, although there is still some disagreement as to whether very minor changes in corneal curvature, axial length, and lens position occur during accommodation.

How is the required change in the shape and power of the crystalline lens achieved? The classical view, as indicated by von Helmholtz[1] and elaborated by Gullstrand, Fincham, Weale, Fisher, and others, is that both the lens and its capsule are elastic, and the shape of the isolated lens is dictated by the balance between these elastic forces. This balance results in the isolated lens and capsule taking up their most accommodated form, with steeply curved surfaces. However, within the eye, the lens is supported by the meridionally oriented zonular fibers that are attached in the region of the lens equator (Figure 4-2). Depending on their tension, these fibers apply additional forces to the capsule, which are then distributed by the capsule across the lens to potentially change its shape. Rohen[4] suggested that the anterior zonular fibers are attached near the lens equator in 3 distinct sets. Two of these sets are attached approximately 1.5 mm anterior and posterior to the lens equator, and the third, finer set is attached along the equator itself. In contrast, Glasser and Campbell[5] stated that the attachment of these anterior fibers is essentially continuous across the equatorial region of the lens, with many fibers crossing other fibers. Additional long posterior (or

Pallikaris IG, Plainis S, Charman WN.
Presbyopia: Origins, Effects, and Treatment (pp. 31-40).

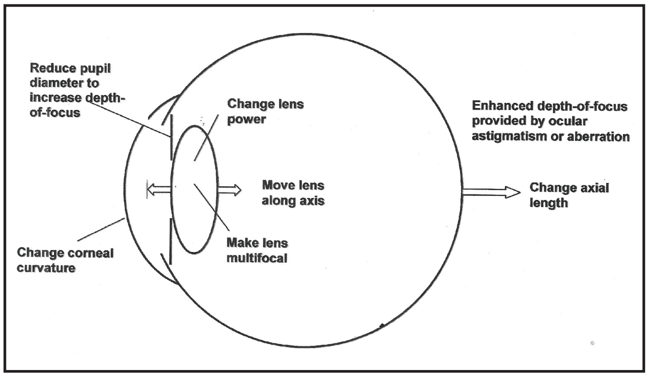

Figure 4-1. Possible mechanisms for focusing the eye.

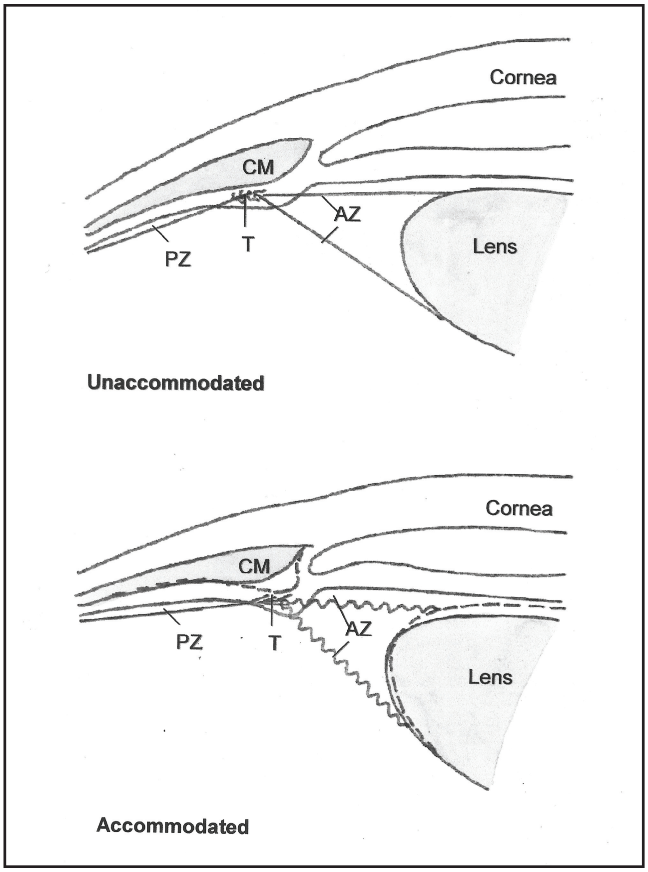

Figure 4-2. Schematic view of the mechanism of accommodation as visualized by Rohen.[4] In the unaccommodated eye (top), the ciliary muscle (CM) is relaxed and the anterior zonular fibers (AZ) are stretched by traction from the posterior pars plana zonular fibers (PZ). The resultant tension in the anterior fibers flattens the lens for distance vision. In the accommodated case (bottom), the forward and inward movement of the ciliary muscle (dashed curve) allows the tension fiber system (T) to take up the tractional force from the posterior zonular fibers and releases the tension in the anterior zonule. The lens and its capsule can then take up their natural, more powerful, accommodated form.

peripheral) holding fibers extend forward from the pars plana to pass through the valleys between the ciliary processes. Shorter tension fibers insert into the ciliary epithelium.

The ciliary muscle acts as a unit, although it contains a mixture of meridional, radial, and circular muscle fibers. The circular fibers run around the free edge of the ciliary body, just behind the root of the iris.

When accommodation is “relaxed” for distance vision, the apex of the ciliary muscle is of a relatively large diameter, and the anterior zonular fibers are stretched by tension from the posterior pars plana fibers. The resultant tension in the anterior zonule exerts strong radial forces on the capsule, tending to stretch it. As a result, the balance of forces on the lens substance causes the lens to flatten and its power to decrease to the value appropriate for distance vision. Accompanying these changes, the lens diameter increases and its thickness reduces.

The accommodation required for near vision results from contraction of the ciliary muscle. This causes the bulk of the muscle mass to move forward and toward the axis, thus reducing the diameter of the ciliary ring. This in turn reduces the tension in the anterior zonular fibers and the force they exert on the lens capsule. Thus, the combined lens-capsule system can change toward the more powerful form that it assumes when isolated in vitro. The surface curvature and lens thickness increase, and the lens diameter reduces, with a consequent increase in lens power (see “Changes in Lens Parameters” section on page 33).

Other factors, particularly the elastic forces provided by the choroid, also play a role. When accommodating, the stresses associated with ciliary muscle contraction cause tension in the elastic choroid and may even cause anterior elongation of the retina. During disaccommodation, these tensional forces aid relaxation of the ciliary muscle and thus contribute to the rapid restoration of the tension in the anterior zonule. This helps to minimize the time required to complete the response. Although some have suggested that the iris[6] and vitreous body[7] may also be of importance, the occurrence of accommodation in aniridic individuals[8] and those lacking a vitreous[9] suggests that these factors can, at best, play only subsidiary rather than major roles in the overall accommodative mechanism. Similarly the confirmation of a decrease in lens diameter during accommodation by such methods as magnetic resonance imaging of normal subjects[10] and observations in albinos[11] appears to

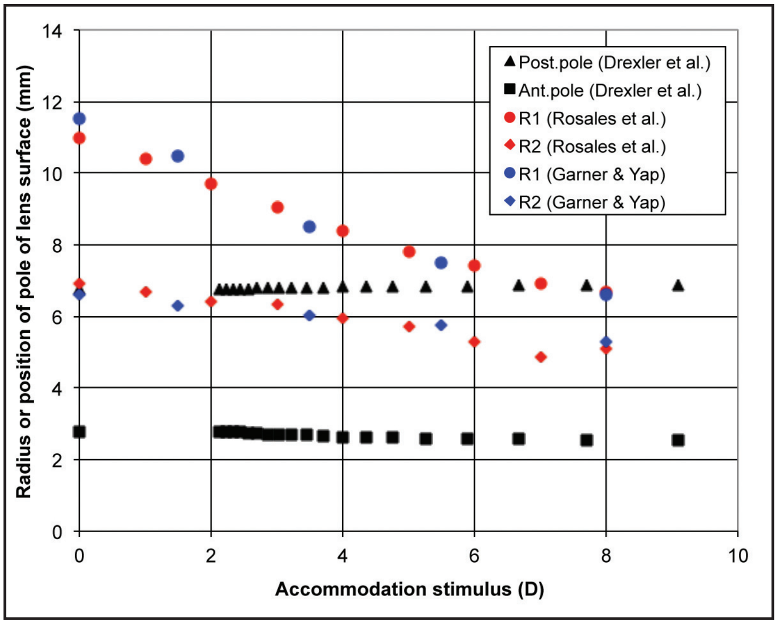

Figure 4-3. Changes with accommodation stimulus in the radii of curvature of the surfaces of the crystalline lens (anterior R1, posterior R2) and the positions of the poles of the surfaces, as measured with respect to the posterior surface of the cornea.[14-16] It is probable that the higher stimuli lay outside the objective amplitude of accommodation of some young adults.

rule out those theories of accommodation according to Tscherning,[12] Schachar,[13] and others who suggest that the reverse is true.

CHANGES IN LENS PARAMETERS

The changes in lens radius with accommodation are greater for the anterior surface of the lens[14,15] (Figure 4-3), possibly because the tensional changes are greater in the more anterior zonule and the anterior capsule is thicker and hence capable of exerting a greater elastic force on the lens substance. Note, however, that, because surface power is inversely proportional to surface radius, the smaller radius of the rear surface means that a given change in radius causes a greater change in power than the same change in the radius of the flatter anterior surface. Thus, although the change in radius of the rear surface is only approximately one-third of that in the front surface, its contribution to the change in lens power is roughly half that of the anterior surface.[14]

As the lens thickens during accommodation, its anterior pole undergoes marked forward movement, with a consequent reduction in the depth of the anterior chamber, and there is only a minor posterior movement of the rear lens surface.[16] Some have suggested that this lack of posterior movement is perhaps due to resistance by the vitreous body, although, as noted previously, the presence of the vitreous does not seem to be a prerequisite for accommodation to occur. Some typical data for these changes are shown in Figure 4-3.[14-16] Exact values vary somewhat with the individual, age, and other factors.

LINKAGE TO OTHER ASPECTS OF NEAR VISION AND NEURAL CONTROL OF THE NEAR RESPONSE

The maintenance of binocular single vision requires not only that accommodation should be matched to the viewing distance but also that the eyes should converge appropriately. The accommodation and convergence control systems are therefore closely linked, as discussed in Chapter 12. Because the pupil usually contracts during near vision (accommodative miosis), it is common to refer to the “near triad” formed by the accommodation, vergence, and pupil systems. It is, however, doubtful as to whether the pupil is directly linked to the other systems. Near pupil constriction appears to be almost absent in preteen patients,[17] and in adults there are wide variations between different individuals. It may be, therefore, that it is a comovement in near vision that is under independent control and cannot directly drive, or be driven by, the other members of the near triad.

The neural basis of the near response has been discussed by Mays and Gamlin.[18] Contraction of the ciliary body is brought about primarily by the activity of the parasympathetic fibers of the third cranial nerve, which originates in the Edinger-Westphal nucleus.[19] Studies have shown that there are near-response neurons (that increase their firing rate for near viewing) located in the supraoculomotor area with input to the Edinger-Westphal nucleus.[20,21] Gamlin and Clarke[20] examined the dynamic behavior of the Edinger-Westphal nucleus during ocular accommodation and found that during near viewing, there is a linear relationship between firing rate and accommodation. Even when viewing at optical infinity, the Edinger-Westphal neurons have a spontaneous activity. The activity of the Edinger-Westphal neurons is also related to the velocity of accommodation. Anatomical studies have found connections between the oculomotor neurons and specific deep cerebellar nuclei (ie, neurons in the posterior interposed nucleus are involved in the control of far response), thus providing evidence for a role of the cerebellum in controlling vergence and accommodation.[21] The question of whether the sympathetic system plays any role in accommodation is still imperfectly resolved, although some weak supplementary inhibitory innervation is certainly present.

COMPONENTS OF ACCOMMODATION

A variety of factors influence the final accommodation response achieved when the eye is presented with a near object of interest. Heath[22] suggested that the response has several components:

1. Reflex accommodation is a quasiautomatic adjustment of refractive state over, perhaps, a 2.00-D range to maintain a sharp retinal focus of the object of regard. There are, however, some doubts as to whether a true involuntary reflex is present because many normal individuals fail to accommodate when presented with modest amounts of defocus, particularly under monocular conditions.
2. Proximal or psychic accommodation triggered by knowledge (or a belief of knowledge) of the distance of the object.
3. Convergence accommodation, driven by fusion disparity vergence (see Chapter 12).
4. Tonic accommodation, the slightly myopic refractive state to which the system reverts in the absence of an adequate accommodative stimulus (see next).

It seems fair to also include voluntary accommodation because many individuals can train themselves to suppress or enhance the normal accommodative response. Heath,[22] however, considered voluntary accommodation to be a form of proximal accommodation, contending that patients are effectively "thinking of near" to generate their response.

ACCURACY OF THE STEADY-STATE ACCOMMODATION RESPONSE

Because the accommodative control system generates a signal to minimize the image blur on the retina, it would be expected that optimal accommodative performance, resulting in an in-focus retinal image, would automatically be achieved for the full range of distances within the objective amplitude of accommodation. However, it is now well accepted that steady-state errors in focus are an idiosyncratic feature of the accommodation system as noted by Charman.[23] The system is characterized by overaccommodation for far targets, known as "lead" of accommodation, and underaccommodation for near targets, known as "lag" of accommodation. When the mean steady-state response is plotted as a function of stimulus vergence (ie, accommodative demand), then a quasilinear response/stimulus curve of the form of Figure 4-4 is found. In near vision, although the magnitude of the lag of accommodation can be as high as 1 to 2.00 D at high stimulus vergences, this error in focus may not lead to noticeable subjective image blur. This explains the lower levels of the objective amplitude of accommodation (ie, range of the actual accommodative response or change in power of the eye) compared with the subjective amplitude of accommodation (ie, range of stimulus vergence over which there is no noticeable image blur). The accuracy of accommodative response is increased with binocular viewing.[24]

As shown in Figure 4-4, the response/stimulus slope varies substantially among individuals. It is also age-dependent, even in prepresbyopic eyes, and is affected by inherent ocular characteristics such as spherical aberration, pupil size, and the nature of the stimulus (its contrast, form: letter versus grating, spatial size, and color).[23,25,26] All of these factors are known to influence ocular DOF (see Chapter 3). More specifically, the larger DOFs associated with small-diameter pupils or high amounts of spherical aberration (positive or negative) are expected to produce larger errors in accommodation.

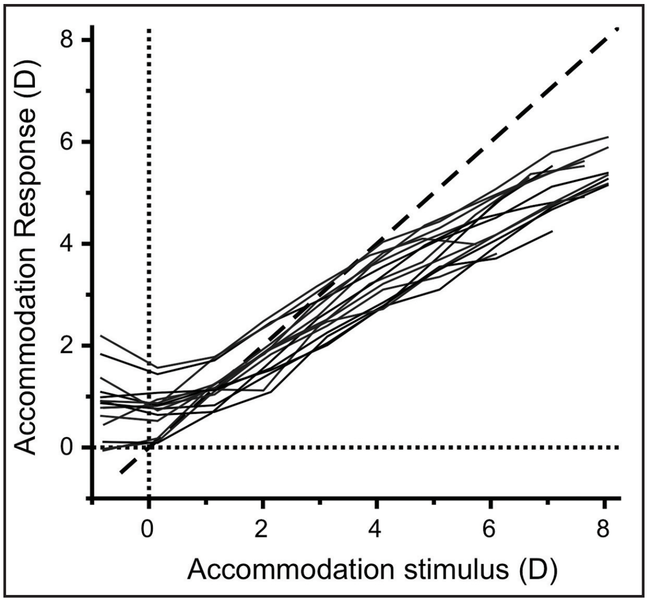

Figure 4-4. Accommodation response/stimulus curve from 13 young adult patients (age range: 23 to 33 years) under constant photopic conditions. The dashed line represents the ideal one-to-one relationship required for "perfect" focus. Accommodation was measured using a wavefront analyzer (Complete Ophthalmic Analysis System [COAS], AMO Wavefront Sciences Ltd, Albuquerque, NM) in conjunction with a purpose-built Badal optometer. Analysis was performed for natural pupils. Note the high intersubject variability. (Based on data compiled from Plainis S, Ginis HS, Pallikaris A. The effect of ocular aberrations on steady-state errors of accommodative response. *J Vis.* 2005;5(5):466-477 and Plainis S, Plevridi E, Pallikaris IG. Comparison of the ocular wavefront aberration between pharmacologically-induced and stimulus-driven accommodation. *Ophthalmic Physiol Opt.* 2009;29(3):272-280.)

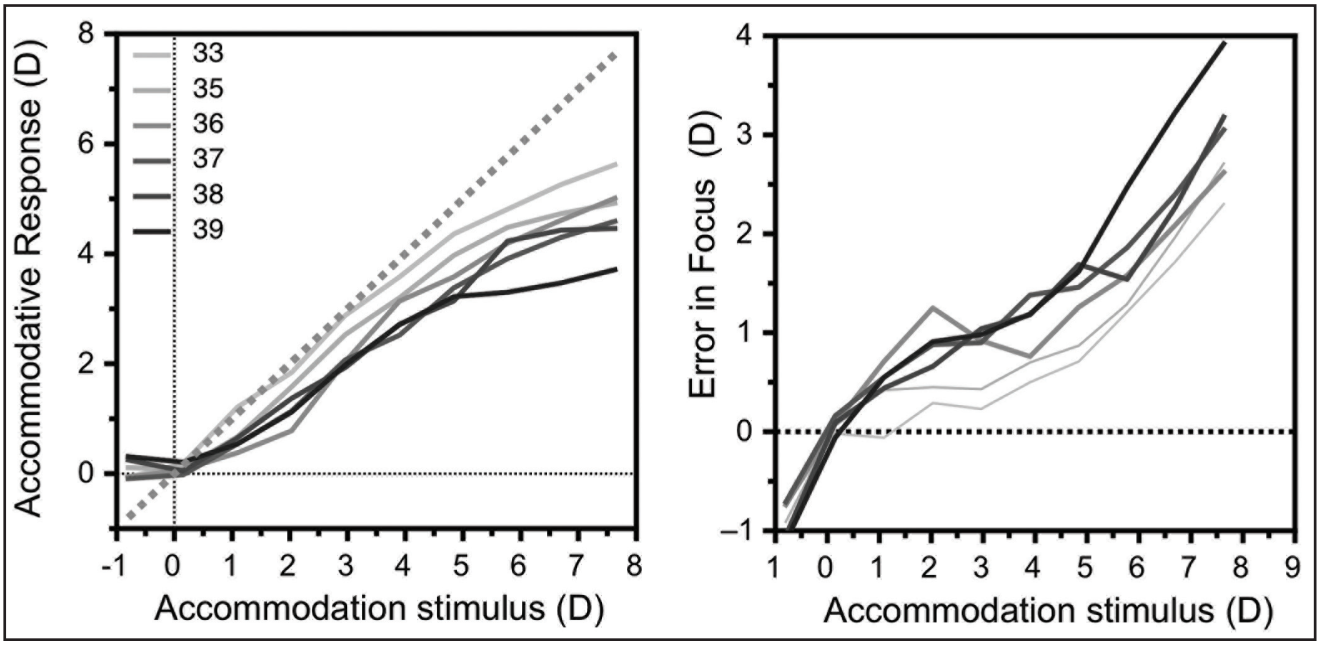

Figure 4-5. Age-related changes in accommodative response (left) and errors in focus (right) as a function of stimulus vergence under photopic conditions for a single patient. Accommodation was measured using a wavefront analyzer (COAS, AMO Wavefront Sciences Ltd) in conjunction with a purpose-built Badal optometer. Analysis was performed for a pupil diameter of 3.5 mm (Plainis, unpublished data, 2012).

Figure 4-5 presents response/stimulus curves and the associated errors of focus for the same patient at different ages. It is evident that the slope becomes flatter (ie, errors in focus are more pronounced) as age increases. The observed increase in accommodative errors is mainly due to the decreased accommodation ability with age rather than to changes in higher-order ocular aberration because computations were performed for a constant pupil diameter (3.5 mm), and spherical aberration did not exhibit any age-related changes. Figure 4-5 shows that the patient approaches the limit of amplitude of accommodation by the end of his or her 30s, which undergoes a steady reduction with age.

Accommodation is driven by cone photoreceptors. Thus, it is expected to be less effective under low lighting conditions. It has been shown that the errors in focus in the accommodative response become

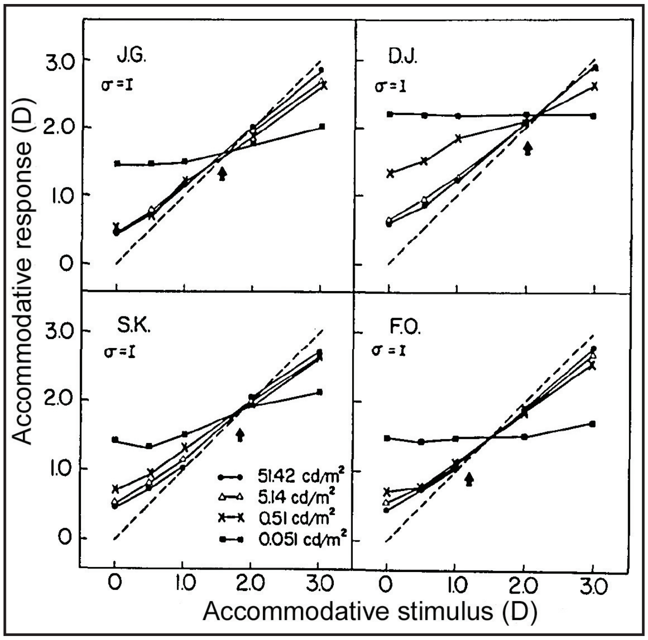

Figure 4-6. Accommodative response as a function of accommodative stimulus distance for 4 observers at 4 luminance levels. The dashed line represents a direct one-to-one correspondence between the accommodative stimulus and response, and the solid arrows indicate the mean response values of the accommodative response in darkness. (Reprinted with permission from Johnson CA. Effects of luminance and stimulus distance on accommodation and visual resolution. *J Opt Soc Am*. 1976;66(2):138-142.).

progressively higher as luminance is decreased (ie, the response/stimulus curve becomes flatter), thus pivoting about the point for which stimulus and response are equal (Figure 4-6).[27] At scotopic levels, when only the rods are active, the accommodative system ceases to function and the response remains constant at its myopic dark focus or tonic level, which is one of the components of accommodation as classified by Heath.[22]

Similarly, when illumination level is photopic but the stimulus field contains no spatial information, the accommodation response/stimulus curve becomes completely flat, the response again remaining constant at its resting state. The myopic refractive state of the eye at such conditions is known as empty field myopia and is well correlated with the tonic level of accommodation. Several studies have investigated the accommodation response in the absence of a stimulus or in complete darkness, suggesting that the tonic level has a mean value of approximately 1.00 D,[28] although it varies dramatically between patients (Figure 4-7). These observations lead to the concept that the tonic accommodation, which is also known as the resting state of response, forms the equilibrium level between parasympathetic and sympathetic innervations to the system.[29] This could imply that innervation of the parasympathetic system results in changes in accommodation from this level to view near targets, whereas innervation of the sympathetic system results in accommodation changes to view distant targets. However, it is more widely believed that sympathetic innervation acts relatively slowly and inhibits existing parasympathetic activity. Thus, its major role may be in the maintenance of sustained responses, as rapid response changes are governed by changes in the excitatory parasympathetic activity.[25] It is interesting that tonic accommodation levels correlate closely with the instrument myopia—the preference of observers to accommodate slightly when viewing objects or internal targets through optical instruments such as the microscope.[28]

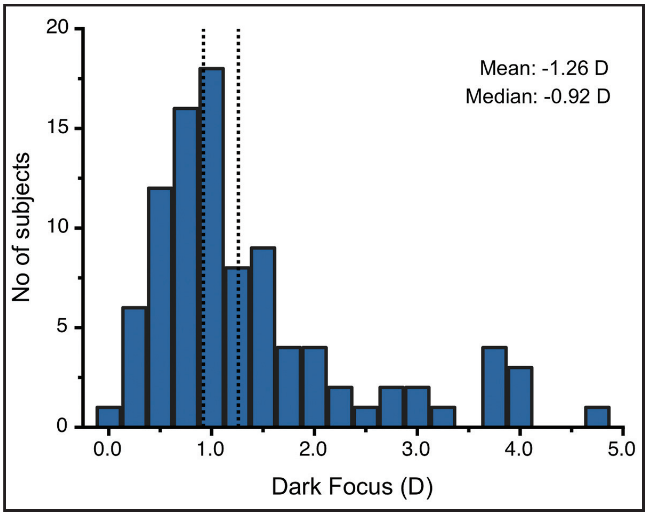

Figure 4-7. Frequency distribution of the dark focus (change in refractive error in total darkness) as measured with an infrared laser optometer for 96 eyes of university students (age range: 19 to 27 years) (Chauhan, Plainis, and Charman, unpublished data, 1999).

STABILITY OF THE STEADY-STATE RESPONSE

Under all conditions, the accommodation response is not steady but changes rapidly and continuously. These small oscillations in the dioptric power of the eye are called microfluctuations and have typical values of approximately 0.20 to 0.50 D.[30,31] They do not affect high-contrast acuity in white light, although they do have a small impact in monochromatic light.[32] Their main frequency spectrum consists of a low-frequency component, which is thought to be at least partly under neural control, and a higher-frequency component associated with factors such as heartbeat and breathing (see Chapter 5). The magnitude of the fluctuations, while varying considerably among patients, tends to increase in conditions under which perceived contrast is decreased, such as at low luminance or with low or high spatial frequency targets, for small pupils and as the target approaches the eye.[25,33] Under the same stimulus conditions, microfluctuations are slightly reduced in older as compared with younger eyes, perhaps due to reduced elasticity in the lens zonules and/or capsule.[34]

It is thought that the temporal changes in the retinal image contrast produced by accommodative microfluctuations may provide a vital feedback signal, which is used by the accommodation control system.[31,35,36] For the same magnitude of fluctuation, the associated change in image contrast is increased in the presence of small lags in accommodation. Larger lags and fluctuations of higher magnitude are required to maintain the system at higher levels of response. The magnitude of the microfluctuations would be expected to be related to the DOF under the conditions in use, which appears to be true of the lower-frequency components but not of the high. Of note is that oscillations in pupil diameter may also contribute to the microfluctuations of accommodation. This is expected to be more significant for near targets, as pupil noise is found to be maximal for small diameters while independent of the mean accommodation response level.[37]

It is apparent that any small changes in accommodation will also be of clinical importance. For example, the changes might affect the precision of refractive measurement by increasing the effective DOF of the eye. Recent studies have shown that the amplitude of microfluctuations is higher in myopic compared with emmetropic eyes, consolidating the theory that myopes have a higher threshold for retinal image blur.[36]

DYNAMICS OF THE ACCOMMODATION RESPONSE

Change in focus is when increasing or relaxing accommodation is not achieved instantaneously. In the presence of a step stimulus (Figure 4-8), there is a reaction time (latency) of approximately 300 to 400 msec before the accommodation response begins, which depends mainly on stimulus characteristics, but also on any anticipation of the changes in vergence. In addition, there is a response time of approximately 400 to 1000 msec (see Table 5-1 in Chapter 5) during which the accommodation is changing before stabilizing at its new level. Response times depend on the amount of positive accommodative but not negative demand; reaction time is fairly constant for similar levels of accommodation/relaxation, whereas response time is shorter for relaxation when the only cue to accommodation is blur (see Figure 4-8).[38] Studies with sinusoidally changing stimuli suggest that, within the amplitude of accommodation, the dynamic characteristics decline only modestly with age.[39]

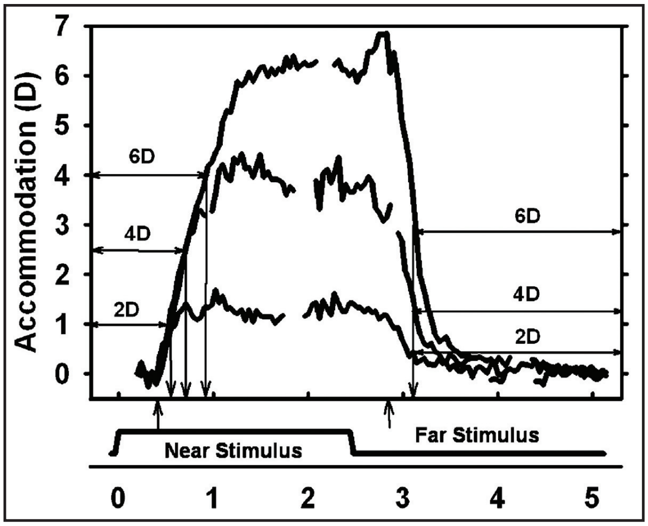

Figure 4-8. Accommodative step responses for accommodative demands of 2.00, 4.00, and 6.00 D. The solid line at the bottom of the graph shows the time course of the near and far targets, stimulating accommodation and disaccommodation, respectively. Horizontal drop lines are at 63% of amplitude, and vertical drop lines (arrows) show the time constant for each amplitude of accommodation and disaccommodation. Time constants of accommodation (0.11, 0.26, and 0.47 s) increase with amplitude (2.00, 4.00, and 6.00 D), but time constants of disaccommodation (0.24, 0.24, and 0.25 s) are similar for different amplitudes (2.00, 4.00, and 6.00 D). (Reprinted from *Vision Res*, vol 43(27), Kasthurirangan S, Vilupuru AS, Glasser A, Amplitude dependent accommodative dynamics in humans, pp 2945-2956, Copyright 2003, with permission from Elsevier.)

EFFECTS OF ACCOMMODATION ON WAVEFRONT ABERRATIONS AND RETINAL IMAGE QUALITY

Accommodation changes the shape (ie, both surface curvatures increase), the refractive index gradient, and the position of the crystalline lens. Thus, it is not surprising to find that, as the level of accommodation changes, alterations occur in both focus and higher-order ocular aberrations. The most prominent transition occurs for spherical aberration, which changes in the negative direction with increasing accommodation demand from an average positive value for far vision (Figure 4-9).[25] Figure 4-9 shows that, although there is a substantial individual variation on the amount/sign of spherical aberration when unaccommodated, the magnitude of its change with accommodation is fairly consistent among young adults. These changes in spherical aberration may be relevant to the changing second-order focus errors (ie, lags/leads of accommodation) with stimulus vergence.[25]

No evidence has been found for substantial systematic changes in other ocular aberrations. For example, coma-like aberrations exhibit a complex pattern of change that varies across individuals, with horizontal coma showing a weak tendency to change to more positive values with accommodation. Some patient-dependent changes in ocular astigmatism have been found with, on average, second-order astigmatism changing in the with-the-rule direction by approximately 0.04 D per diopter of accommodation.[40]

The small, somewhat erratic changes in coma and secondary astigmatism may be attributable to the lateral displacement or tilt of the lens relative to the cornea, as the zonule slackens during the accommodation process and hence provides a weaker constraint against such movements. Another possible explanation may be a lack of rotational symmetry in the cornea and/or the lens, which could induce asymmetric aberrations of variable magnitude on the forward movement of the accommodating lens.

Given that there are changes in higher-order ocular aberrations with the level of accommodation, it would be expected that these changes would in turn cause some changes in retinal image quality. Although there is some disagreement among the results of other authors, probably due to the wide variation in the aberrations of individual eyes, it appears that best image quality for the average eye is found at the resting point of accommodation.[25] However, because monochromatic aberrations play an important role only when the pupil diameter is large, it is expected that pupil constriction at near would ameliorate any degradation to retinal image quality the aberrations may cause. In any case, most retinal image blur will usually be the result of errors in focus (lags and leads of accommodation).[32]

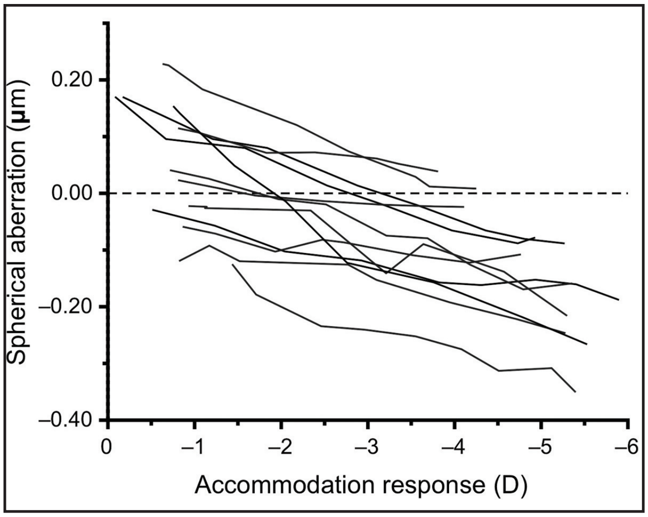

Figure 4-9. Plot of spherical aberration (Zernike C40 aberration coefficient for natural pupil diameter) as a function of accommodation response for 13 young adult patients (age range: 23 to 33 years). Accommodation and monochromatic aberrations were measured using a wavefront analyzer (COAS, AMO Wavefront Sciences Ltd) in conjunction with a purpose-built Badal optometer. (Based on data compiled from Plainis S, Ginis HS, Pallikaris A. The effect of ocular aberrations on steady-state errors of accommodative response. *J Vis.* 2005;5(5):466-477 and Plainis S, Plevridi E, Pallikaris IG. Comparison of the ocular wavefront aberration between pharmacologically-induced and stimulus-driven accommodation. *Ophthalmic Physiol Opt.* 2009;29(3):272-280.)

SUMMARY

The youthful accommodation system allows the eyes to vary focus to obtain reasonably clear retinal images of objects at different distances. Nevertheless, such focus is rarely exact (lags and leads of accommodation), nor is it stable (microfluctuations). The dynamic aspects of performance will be discussed more fully in Chapter 5, while the cues that trigger an accommodation response will be considered in Chapter 6.

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