The Physiologic Mechanism of Accommodation

A youthful accommodation system allows the eye to vary its focus in order to obtain reasonably clear retinal images of objects at different distances, but this focus is rarely exact or stable.

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Presbyopia is the age-related loss of accommodation—the ability of the eye to focus on objects at close distances—and is the most common ocular affliction in the world. Accommodative ability falls almost linearly with age from at least the early teenage years, with presbyopic symptoms starting to occur at the age of 40 to 45 years. This is in contrast to most other aspects of visual performance, which typically start to decline only after the age of about 50 years.[1]

AMPLITUDE OF ACCOMMODATION

Subjective amplitude of accommodation is a measurement of the focusing range of the eye: that is, the dioptric difference between the far point (optical infinity for emmetropes or fully corrected ametropes) and the near point where an object can be focused clearly over a range of distances. In young eyes, it is usually interpreted as an index of maximum accommodative effort, although it is well known that subjective amplitudes of accommodation are higher than objectively measured optical changes due to the inclusion of depth-of-focus effects.[2]

Amplitude of accommodation declines progressively with age, and the onset of presbyopia is generally defined as the point where one's subjective amplitude of accommodation falls below 3.00 D.[3] When assessed monocularly in healthy eyes, the subjective amplitude decreases to a minimum value of 1.00 to 2.00 D at about age 55 years,[4] although notable intersubject variability has been observed (Figure 1).

Subjective amplitude of accommodation is an inadequate measure to assess whether any true accommodation is present in the presbyopic eye. This is because subjective recordings of accommodative amplitude fail to differentiate between passive depth of focus and an active accommodative power change in the eye (see below).[5]

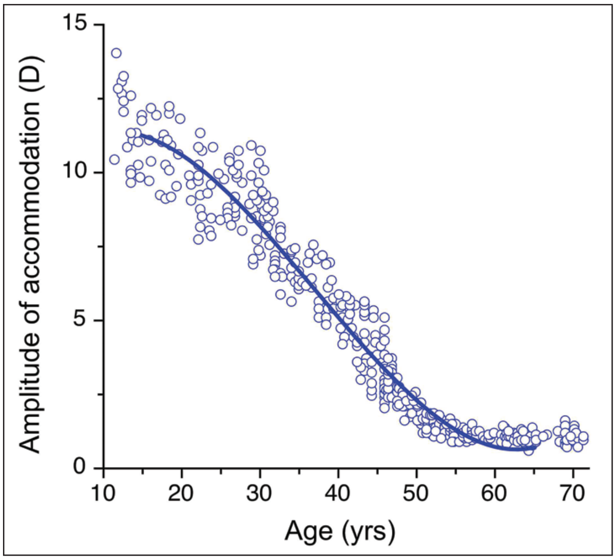

Figure 1. Monocular amplitudes of accommodation as a function of age, based on data compiled and replotted from Duane.[4]

BASIC MECHANISM OF ACCOMMODATION

It has been well recognized for more than 250 years that accommodation involves a lens-based change in the refractive power of the eye. Previous hypotheses by

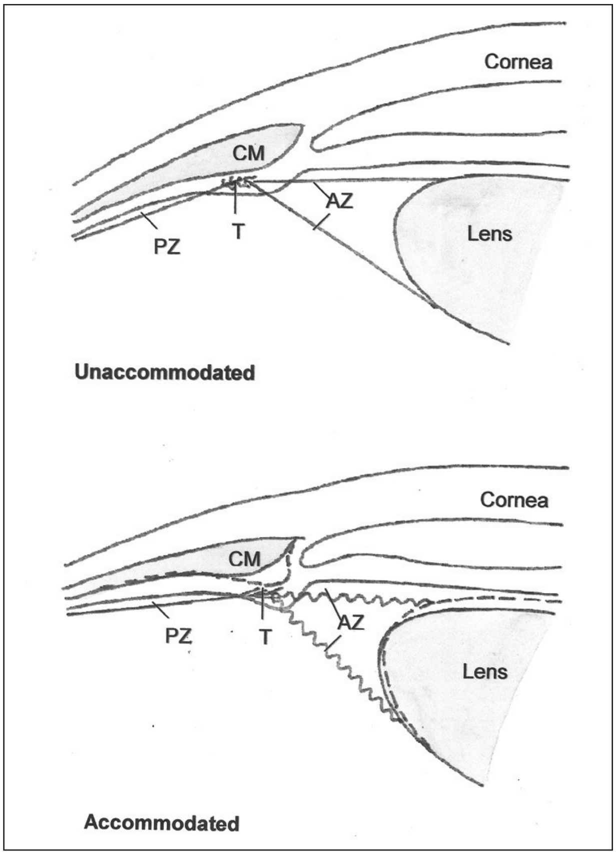

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Figure 2. Schematic view of the mechanism of accommodation as visualized by Rohen.[10] In the unaccommodated eye (top), the ciliary muscle (CM) is relaxed and the anterior zonular fibers (AZ) are stretched by traction from the posterior pars plana zonular fibers (PZ). The resultant tension in the anterior fibers flattens the lens for distance vision. In the accommodated state (bottom), the forward and inward movement of the ciliary muscle (dashed curve) allows the tension fiber system to take up the tractional force from the posterior zonular fibers and releases the tension in the anterior zonules. The lens and its capsule can then take up their natural, more powerful, accommodated form.

Descartes[6] and others on the changes in the shape and power of the crystalline lens were confirmed by Young's elegant studies[7] and have been supported by subsequent experimentation, although there is still disagreement as to whether minor changes in corneal curvature, axial length,[8] and lens position occur during accommodation.

According to the classical view, as described by Helmholtz,[9] accommodation occurs by contraction (forward and inward movement) of the ciliary muscle and relaxation of the zonules that attach the ciliary body to the lens; as a result, the lens thickens and becomes more steeply curved, increasing the refractive power of the eye.

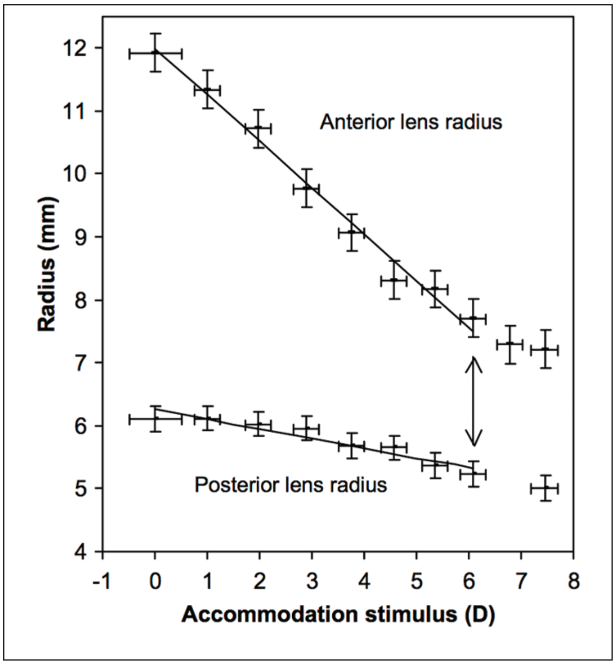

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Figure 3. Changes with accommodation stimulus in the radii of curvature of the anterior and posterior surfaces of the crystalline lens in a 29-year-old woman. Note that there is no significant change in radius at the highest accommodation level, which probably exceeds the patient's accommodation range (from Dubbelman et al[13]).

The elastic lens capsule molds the lens into the accommodated state. However, within the eye, the lens is supported by the zonular fibers, attached in the region of the lens equator (Figure 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[10] suggested that the anterior zonular fibers are attached near the lens equator

TAKE-HOME MESSAGE

- Accommodative ability falls almost linearly with age, with presbyopic symptoms starting to occur at the age of 40 to 45 years.
- It has been well recognized for more than 250 years that accommodation involves a lens-based change in the refractive power of the eye.
- Accommodation is driven by cone photoreceptors, and, thus, it is expected to be less effective under low light conditions.
- The youthful accommodation system allows the eye to vary its focus to obtain reasonably clear retinal images of objects at different distances, but such focus is rarely exact or stable.

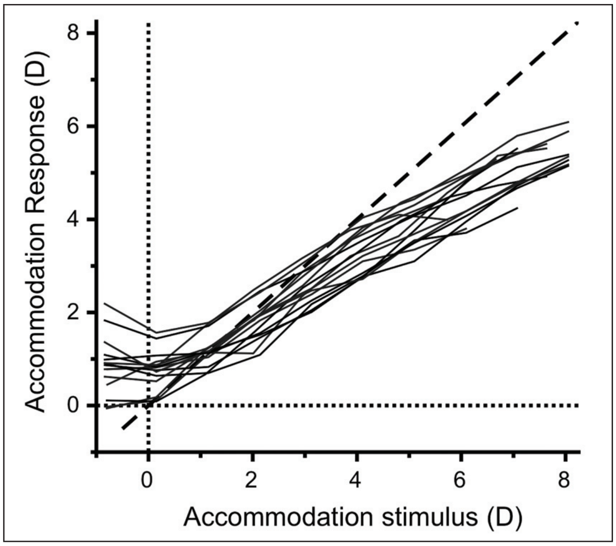

Figure 4. Accommodation response and stimulus curve from 13 young patients under constant photopic conditions. The dashed line represents the ideal one-to-one relationship required for perfect focus. Analysis was performed for natural pupils. Note the high intersubject variability (data adopted from Plainis et al[20,23]).

in three distinct sets, of which two are attached about 1.5 mm anterior and posterior to the lens equator and the third, finer set is attached along the equator itself.

When accommodation is relaxed (ie, the unaccommodated state) for distance vision, the apex of the ciliary muscle is of 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 lens flattens, and its power decreases to the value appropriate for distance vision. Accompanying these changes, the lens diameter increases and its thickness decreases.

The accommodation required for near vision results from contraction of the ciliary muscle. This reduces the tension in the anterior zonular fibers, while tension is placed on the posterior elastic tissues as the muscle moves forward and inward (Figure 2).[10] Thus, the combined lens-capsule system can change to the more powerful form that it assumes when isolated in vitro. The surface curvatures and lens thickness increase and the lens diameter decreases, with a consequent increase in lens power.

It has also been suggested that the vitreous supplies support to the lens periphery and facilitates the shape change in the lens in combination with a change in the vitreous/anterior chamber pressure gradient.[11] Others have argued against a role for the vitreous, which at best plays only a subsidiary rather than a major role in accommodation.[12]

CHANGES IN LENS PARAMETERS

The changes in lens radius with accommodation are greater for the anterior surface of the lens (Figure 3).[13] This is possibly because the tensional changes are greater in the more anterior zonules and because the anterior capsule is thicker and, thus, capable of exerting a greater elastic force on the lens substance. However, 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 flatter radius of the anterior surface. Therefore, although the change in radius of the rear surface is only about one-third that of 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. There is only a minor posterior movement of the rear lens surface.[15] Some have suggested that this lack of posterior movement is due to resistance offered by the vitreous body.

ACCURACY OF THE ACCOMMODATIVE RESPONSE

Because the accommodative control system generates a signal to minimize retinal image blur, 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 an individual's objective amplitude of accommodation. However, it is now well accepted that steady-state errors in focus are an idiosyncratic feature of the accommo-

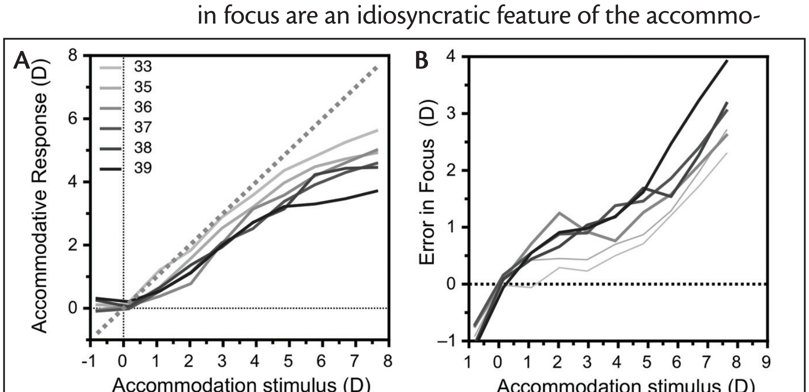

Figure 5. Age-related changes in accommodative response (A) and errors in focus (B) as a function of stimulus vergence under photopic conditions for a single patient. Analysis was performed for a pupil diameter of 3.5 mm.

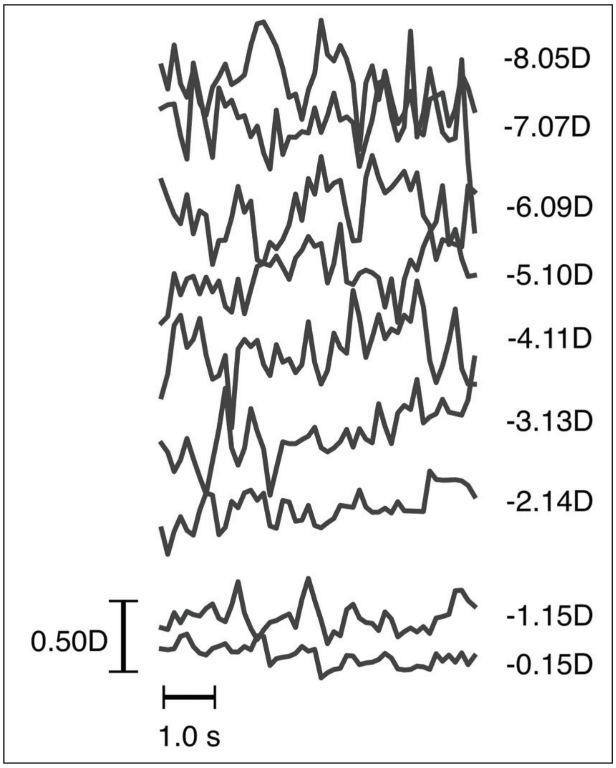

Figure 6. Temporal changes (fluctuations) in the accommodative response of a single patient for a range of accommodative stimuli (data replotted from Plainis et al[20]).

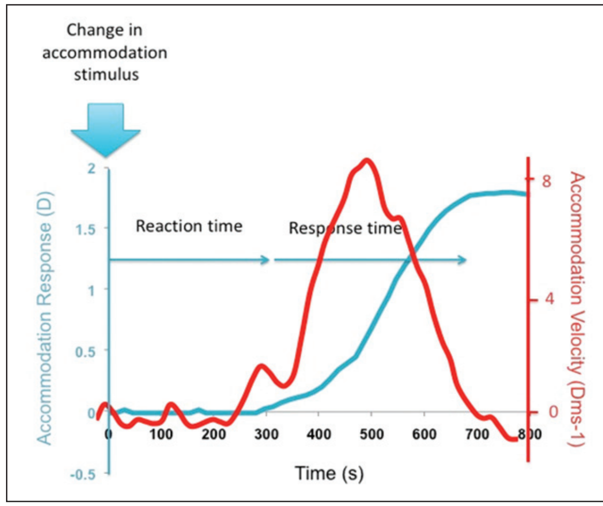

Figure 7. A typical dioptric accommodation response (blue curve) and the corresponding rate of change with time (ie, its velocity; red curve) for a 2.00 D accommodation step stimulus, the onset of which occurs at 0 seconds (from Strang and Day[24]).

dation system.[16] The system is characterized by over-accommodation for far targets, known as *lead of accommodation*, and under-accommodation for near targets, known as *lag of accommodation*. When the mean steady-state response is plotted as a function of accommodative demand, a quasi-linear response/stimulus curve of the form shown in Figure 4 is recorded.

In vision at near distances, although the magnitude of the lag of accommodation can be as high as 1.00 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).

As shown in Figure 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 and pupil size, and by the nature of the stimulus (its contrast, form [letter vs grating], spatial size, and color).[16] All of these factors are known to influence ocular depth of focus. More specifically, the larger depths of focus associated with small-diameter pupils or high amounts of positive or negative spherical aberration are expected to allow larger errors in accommodation.

Figure 5 presents response/stimulus curves and the associated errors of focus for the same individual at different ages. It is evident that the slope becomes flatter—that is, errors in focus are more pronounced—as age increases. The observed increase in accommodative errors is mainly due to the decreased accommodative ability with age, rather than to changes in higher-order ocular aberration, as computations were performed for a constant pupil diameter (3.5 mm), and spherical aberration did not exhibit any age-related changes. Although the range of stimuli in Figure 5 does not include the near point of the individual at young ages, it can be seen that, by the end of the individual's 30s, the limits of amplitude of accommodation are approached. The amplitude of accommodation undergoes a steady reduction with age (Figure 1).

Accommodation is driven by cone photoreceptors. Thus, it is expected to be less effective under low light conditions. It has been shown that errors in focus in accommodative response become progressively higher as luminance is decreased; the response/stimulus curve becomes flatter, pivoting about the point for which stimulus and response are equal.[17] 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*. Similarly, when the illumination level is photopic but the stimulus field contains no spatial information, the accommodative response/stimulus curve becomes completely flat, the

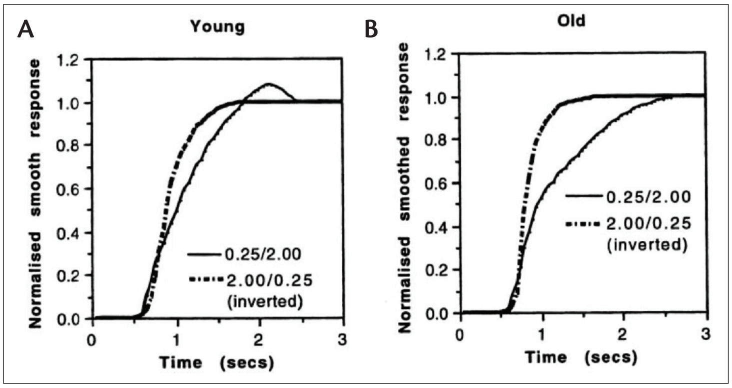

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Figure 8. Responses of young (A) and old (B) patients to both directions (accommodation, far to near [FN], vs relaxation, near to far [NF]) of stimulus change between 0.25 and 2.00 D. The NF responses are shown inverted to allow direct comparison of their temporal profile with the FN responses (from Heron and Charman[22]).

response again remaining constant at its resting state.

The myopic refractive state of the eye in such conditions is known as *empty field myopia* and is well correlated with the tonic level of accommodation. Studies have investigated accommodative response in the absence of a stimulus or in complete darkness, suggesting that the tonic level has a mean value of around 1.00 D,[18] although it varies dramatically from patient to patient. These observations lead to the concept that the tonic state of accommodation, also known as the *resting state of response*, forms the equilibrium level between parasympathetic and sympathetic innervations to the system.[19] It is of interest that tonic accommodation levels (dark focus and empty field myopia) correlate closely with instrument myopia, the preference of observers to accommodate slightly when viewing objects or internal targets through optical instruments, such as the microscope.

STABILITY OF ACCOMMODATIVE RESPONSE

Under all conditions, the accommodative response is not steady but changes rapidly and continuously. These small oscillations in the dioptric power of the eye, called *microfluctuations*, typically have values of about 0.20 to 0.50 D.[20,21] Their main frequency spectrum, which mainly extends up to a few hertz, shows two distinct peaks, corresponding to a low- and a high-frequency component. The low-frequency component is thought to be at least partly under neural control, and the higher-frequency fluctuations are associated with factors such as heartbeat and breathing. The magnitude of the fluctuations, although varying considerably among individuals, tends to increase in conditions in 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 (rising to approximately 0.50 D for a stimulus of 6.00 D vergence; Figure 6). The increased level of fluctuation for very near stimuli may result from increased instability of the lens as the lens zonules relax during accommodation. Under the same stimulus conditions, microfluctuations are slightly reduced in older as compared with younger eyes, perhaps because of reduced elasticity in the lens zonules and/or capsule.

It is thought that the temporal changes in the retinal image contrast produced by accommodative microfluctuations may provide a vital feedback signal that is used by the accommodation control system.[21] 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 a higher level of response. The magnitude of the microfluctuations would be expected to be related to the depth of focus under the conditions in use; this appears to be true of the lower-frequency components but not the high.

DYNAMICS OF THE ACCOMMODATIVE RESPONSE

Changes in focus when accommodating (far to near, or FN) or disaccommodating/relaxing (near to far, or NF) are not achieved instantaneously. In the presence of a typical 2.00 D step stimulus, there is a reaction time (latency) of about 300 to 400 ms before the accommodative response begins. This depends mainly on stimulus characteristics but also on any anticipation of the changes in accommodation (Figure 7).

On top of this, there is a response time of about 400 to 1,000 ms, during which the accommodation changes before stabilizing at its new level. Response times depend on the amount of accommodative but not disaccommodative demand. Reaction time is fairly constant for similar levels of accommodation/relaxation, whereas response time is shorter for relaxation in both young and old patient groups, when the only cue to accommodation is blur.

This can be appreciated more readily if one of the relative step responses is inverted for direct comparison (Figure 8). Although studies suggest that, within the amplitude of accommodation, the dynamic characteristics decline only modestly with age,[22] as Figure 8 suggests, the FN is faster in young patients (and more sluggish in older), while the NF response is faster in older patients.

SUMMARY

The youthful accommodation system allows the eye to vary its focus to obtain reasonably clear retinal images of objects at different distances. Nevertheless, such focus is rarely exact (with lags and leads of accommodation), nor is it stable (with microfluctuations). ■

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