12

PRESBYOPIA AND THE VERGENCE SYSTEM

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Throughout life, the ability to obtain and maintain a fused and focused binocular percept of objects of interest over a range of far and near distances, both along and off one's midline, involves the interaction of 4 vergence components.[1] These include (1) disparity, or fusional, vergence driven by retinal disparity—this is likely to be the primary component,[2] (2) accommodative vergence driven by retinal blur—this is likely to be the secondary component, as accommodative gain falls off precipitously with retinal eccentricity,[3] (3) proximal vergence driven by perceived target nearness, and (4) tonic vergence driven by baseline midbrain neural innervation. Tonic and proximal vergence are tertiary components to the overall vergence response under naturalistic viewing conditions.[1] These components and related aspects are depicted in a typical static, dual-mode interactive model of the human vergence system (Figure 12-1). The figure shows how the inputs provided by retinal defocus, target proximity, retinal illuminance, and retinal disparity interact (nonlinearly) to produce the 3 response outputs of the near triad: accommodation, pupil diameter, and vergence.[4,5]

The blur drive from the accommodative system to the vergence system through its neural crosslink (see Figure 12-1, green lines) conceptually constitutes the response accommodative convergence/accommodation (AC/A) ratio.[3,4] That is, the accommodative controller gain (ACG) and its related motor response, when multiplied by this crosslink gain (AC), provide an additional drive to the vergence system, namely "accommodative vergence." The ratio of the change in the accommodative vergence response (prism diopters; Δ) per unit change in the accommodative response (diopters; D) represents the response AC/A ratio (Δ/D). The typical response AC/A in the visually normal population is 4.4:1, whereas the stimulus AC/A ratio is 4:1.[3,4] The nonlinear interaction of accommodative vergence, primarily with disparity vergence but also with proximal and tonic vergence, provides the aggregate vergence response to a newly acquired target in 3-dimensional binocular visual space within the constraint of Panum's fusional areas.[1] Just as accommodation helps to drive vergence, vergence (meter angles; MA) can drive accommodation (D), through the link (red lines) labeled convergence accommodation/convergence (CA/C [D/MA]) in Figure 12-1. As stated previously, disparity vergence is likely to be the dominant component, and as such, its drive to accommodation is likely to be the (or a) dominant component. The typical CA/C ratio ranges from approximately 0.40 to 0.50 D/MA, although some may

Pallikaris IG, Plainis S, Charman WN.
Presbyopia: Origins, Effects, and Treatment (pp. 103-110).

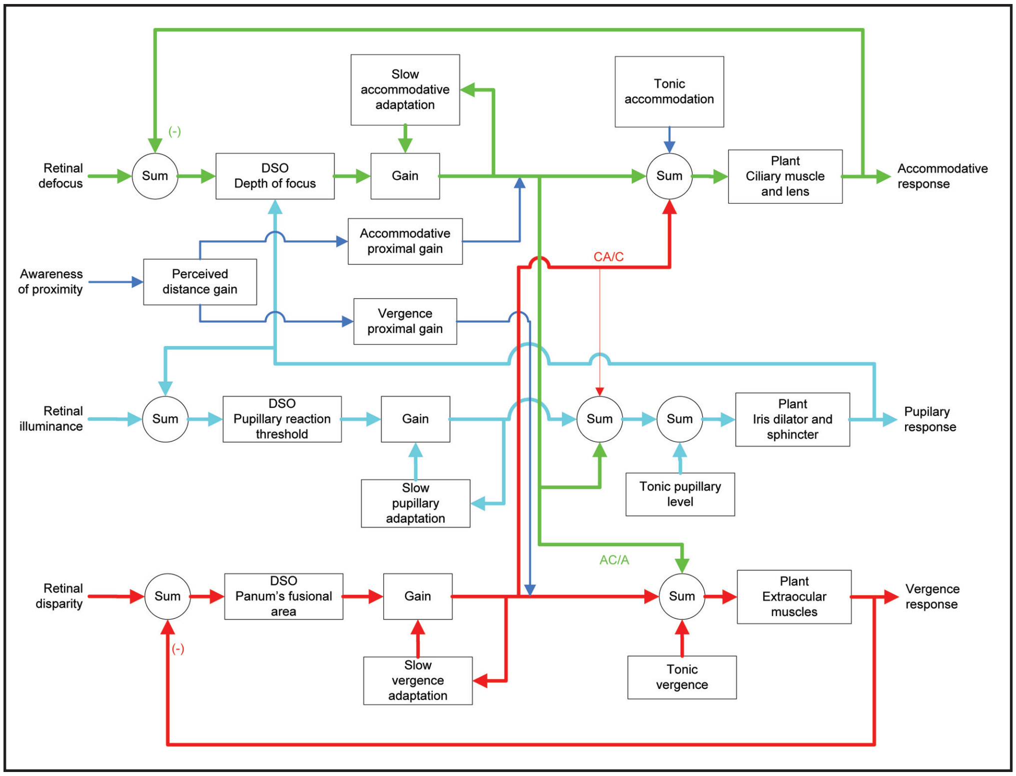

Figure 12-1. Comprehensive static dual-mode interactive model of the vergence and accommodative systems with added pupil component. AC/A = convergence/accommodation ratio; DSO = dead space operator; CA/C = convergence accommodation/convergence ratio. (Adapted by George A. Zikos, OD, MS from Hung GK, Ciuffreda KJ, Rosenfield M. Proximal contribution to a linear static model of accommodation and vergence. *Ophthalmic Physiol Opt.* 1996;16(1):31-41. Reprinted with permission of George A. Zikos, OD, MS.)

be considerably higher (eg, 1.00 D/MA).[6] Thus, if the CA/C ratio is 0.50 D or more, then most of the initial drive to accommodation would come from vergence accommodation, which we conceptualize as a modulator to vergence accommodation to derive the overall accommodative response under normal closed-loop viewing conditions.[1,7]

The purpose of this chapter is to succinctly review the major studies in the area of vergence as related to age and presbyopia. It will be couched as a series of 4 questions:

1. Do the parameters and components of accommodation and vergence change with age and presbyopic onset?
2. Does the AC/A ratio change with age and presbyopia, and what are its basic and clinical implications?
3. Does the CA/C ratio change with age and presbyopia, and what is its relation to the AC/A ratio?
4. What are the newer approaches for clinical presbyopic correction?

Do the Parameters and Components of Accommodation and Vergence Change With Age and Presbyopic Onset?

A comprehensive investigation of the static and dynamic vergence and accommodative components is essential to obtain a global assessment of these 2 systems with their many complex and nonlinear interactions. For such an investigation, we used a static model (see Figure 12-1), as well as the basic aspects of a dynamic model, in a series of detailed experiments.[8-13]

The results are presented in Tables 12-1 and 12-2. Table 12-1 presents those parameters that either increased, decreased, or remained relatively constant with age and presbyopic onset, and Table 12-2 presents the rates of change in the relevant parameters. Of particular interest to this chapter are the stimulus and response AC/A ratio findings—these ratios remained relatively constant, despite the predictable reduction in accommodative amplitude with age (~0.30 D per

TABLE 12-1. *OCULOMOTOR PARAMETERS WITH INCREASING AGE*

INCREASE	DECREASE	CONSTANT
Disparity vergence (relative contribution)	Accommodative amplitude	Near point of convergence
"Fast" vergence latency	Tonic accommodation	Tonic vergence
Subjective depth of focus	"Fast" vergence peak velocity	Objective depth of focus
Accommodative latency	Accommodative adaptation	Vergence adaptation
	CA/C ratio	Stimulus and response AC/A ratios
	Proximal accommodation	Proximal vergence
	Accommodative microfluctuations	Open and closed-loop accommodative gains
	Positive and negative fusional vergence recovery values at distance	Positive and negative fusional vergence break values at distance

TABLE 12-2. *RATE OF PARAMETER CHANGE PER YEAR WITH INCREASING AGE*

PARAMETER	ANNUAL RATE OF CHANGE
Accommodative amplitude	0.34 D decrease
Subjective depth of focus	0.027 D increase
Accommodative latency	2.5 msec increase
"Fast" vergence latency	1 msec increase
Tonic accommodation	0.04 D decrease
Accommodative adaptation	0.034 D decrease
CA/C ratio	0.006 D/pd decrease
Proximal accommodation	0.008 D decrease

year).[3] Constancy of the response AC/A ratio suggested that the accommodative controller gain and its crosslink gain did not change with age, whereas constancy of the stimulus AC/A ratio implied that the neural innervation to vergence and to accommodation, as well as the "effort" to accommodate, were invariant with age. These results will be discussed in more detail later in this chapter in relation to theories of presbyopia.

It is well known that the accommodative amplitude and its relative contribution via the AC crosslink decline with age due to the biomechanically based reduction in crystalline lens responsivity. To compensate for this effective loss in AC, the remaining components of the vergence system would be expected to increase their output and relative response contribution to maintain the net vergence response accuracy within Panum's fusional areas and achieve sustained and symptom-free binocular vision. The aggregate vergence response maximum does not show any age-related decrease, as is evident from the invariance of the near point of convergence (NPC) as seen in Table 12-1.[14] Furthermore, laboratory investigations have demonstrated the constancy of the proximal[12] and tonic[13] vergence components with age. Together, these results suggest that, due to the constant reduction in the AC response, the disparity vergence response must increase concomitantly and proportionally with age to ensure oculomotor balance and response accuracy. Evidence to support this notion arises from investigations that have demonstrated reduced fixation disparity (ie, reduced steady-state vergence error) in absolute presbyopes when compared to younger adult prepresbyopes,[15] despite the marked and progressive increase in near exophoria in the former group with increased age. This reflects the increased dominance and relative contribution of disparity vergence, as the contribution from the accommodative component and its interactions progressively decline with age. The overall vergence response in absolute presbyopia under naturalistic viewing conditions eventually becomes almost solely due to the disparity vergence contribution.

Investigation of the dynamics of the disparity vergence components ("fast" and "slow" components) revealed a small, age-related increase in latency (1 ms/y) and a small, age-related decrease in peak velocity (1 degree/s/y) for the "fast" component in response to a step disparity stimulus. These age-related changes are too small and subtle to be noticed clinically with gross visual observation, or even with the dynamic prism flipper flexibility test.[3] However, the changes are important for laboratory investigations in this area, as well as for the clinical research assessment of older patients using high-resolution objective recording eye movement techniques. For example, in the specialty eye-movement clinic, one would not want to send a 75-year-old patient for an MRI because his vergence peak velocity was decreased by 50 degrees/sec when compared to a 25-year-old individual, as such a decrease would be expected due to the normal age-related changes in the neurocontrol properties of the vergence system.

In contrast to these age changes in the "fast" dynamics, no significant age-related changes were observed with respect to "slow" vergence dynamics.[16]

DOES THE AC/A RATIO CHANGE WITH AGE AND PRESBYOPIA, AND WHAT ARE ITS BASIC AND CLINICAL IMPLICATIONS?

The question of change in the response AC/A ratio with age has been one of the most controversial topics in the accommodative literature for decades.[3,4,11] One reason for this controversy is that the 2 primary theories of presbyopia predict very different results. Furthermore, many of the earlier findings have been equivocal.[11,17] The Hess-Gullstrand Theory, which suggests that the accommodative effort per diopter of accommodative response remains unchanged with age, would predict that AC/A remains relatively constant, whereas the Duane-Fincham Theory, which hypothesizes that progressively more effort is required per diopter of response as the amplitude reduces with age, would predict that AC/A increases with advancing age and presbyopia (see Chapter 11).[3]

The early clinical and laboratory studies yielded mixed results, as mentioned earlier. Namely, all possibilities were found.[17] In those clinical and laboratory studies involving the stimulus AC/A ratio, it was found to either increase slightly, decrease slightly, or remain relatively constant. Thus, the findings were equivocal. If the stimulus AC/A ratio was found to remain relatively constant, this would suggest that the "effort" to focus at near was invariant with age, despite the progressive reduction in accommodative amplitude. Such a finding would be consistent with most clinical reports of patients being asymptomatic, except for the presence of blur at near. If the stimulus AC/A ratio increased, the opposite would be suggested, which is neither typically found nor reported clinically.

In the mid-1990s, 2 independent and well-conducted studies on this topic yielded remarkably similar results,[10,18] which was highly desirable to resolve such a long-standing controversy. Both studies found that the response AC/A ratio increased only slightly with age ($\sim 0.10\Delta/D/y$) over a sufficiently wide age range (~20 to 45 years) and number of patients (n=42). The results for the entire group of patients from Ciuffreda et al[10] are presented in Figure 12-2. Two aspects of the controversy became evident from these findings. First, after the age of 45 years, the residual accommodation was too small to provide an accurate measurement, and hence the ratio was found to be either positive or negative with a huge range of values ($\sim +60$ to $-70\Delta/D$).

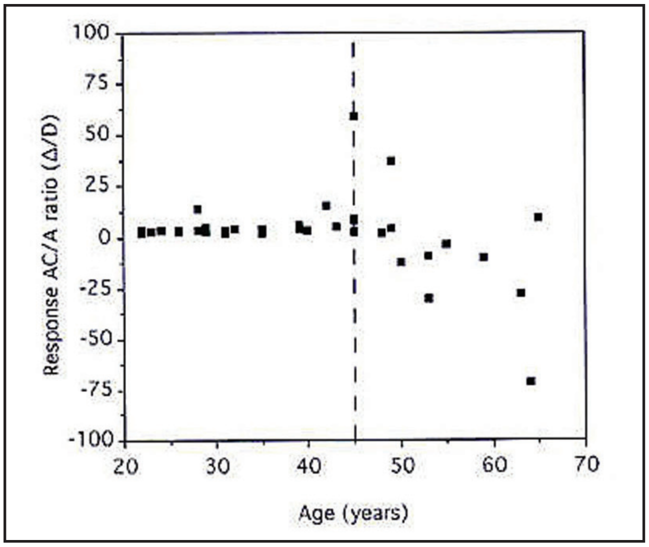

Figure 12-2. Response accommodative convergence/accommodation (AC/A) ratio as a function of age. (Adapted with permission from Ciuffreda KJ, Rosenfield M, Chen HW. The AC/A ratio, age and presbyopia. *Ophthalmic Physiol Opt.* 1997;17(4):307-315.)

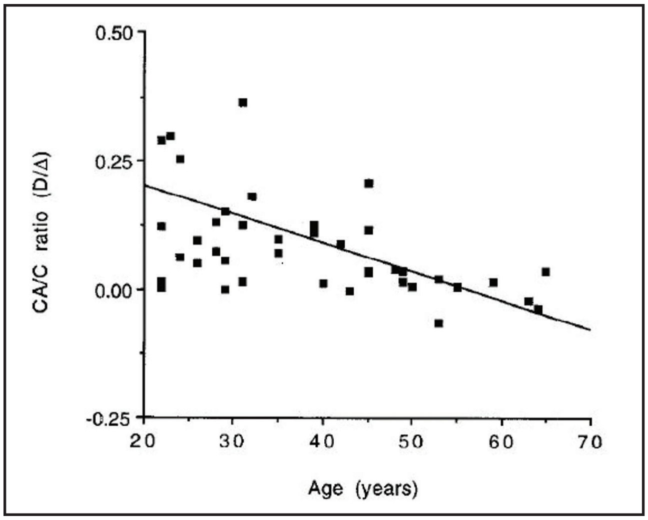

Figure 12-3. Stimulus convergence accommodation/convergence (CA/C) ratio as a function of age. (Adapted with permission from Rosenfield M, Ciuffreda KJ, Chen HW. Effect of age on the interaction between the AC/A and CA/C ratios. *Ophthalmic Physiol Opt.* 1995;15(5):451-455.)

This suggested the presence of a measurement "noise" phenomenon. Second, if the patient data from only the ages of 20 to 35 years were analyzed with linear regression, the ratio did not change significantly with age. Perhaps those values in the presbyopic "gray zone" of 36 to 45 years encroached on the nonlinear region of the patient's accommodative stimulus/response function,[3] which would result in an "apparent" increase in the AC/A ratio. Thus, the best evidence is in favor of the Hess-Gullstrand Theory (see Chapter 11).

DOES THE CA/C RATIO CHANGE WITH AGE AND PRESBYOPIA, AND WHAT IS ITS RELATION TO THE AC/A RATIO?

The answer to this question is simpler and more direct than is the case for its response AC/A counterpart. Because the accommodative amplitude reduces progressively with age, the CA/C ratio should also decrease (see Table 12-2), as the effective accommodation available from the vergence drive decreases. This rate of change was assessed in a group of 42 patients aged 22 to 65 years using a static haploscope optometer.[19] The CA/C ratio progressively decreased by 0.006 D/Δ/y (Figure 12-3). When compared with the response AC/A ratio in this same population, there was a trend for these 2 ratios to be inversely related, but not reciprocal. Such a relation would be expected in visually normal, asymptomatic individuals for oculomotor interactive "balance," or steady-state stability, between the 2 systems to be present. Absence of such a relationship would probably lead to an abnormal gain-related binocular vision anomaly, such as convergence insufficiency.[20]

What would be the functional impact of an age-related change in the CA/C ratio? That would depend on its value. If it was low,[18] then a considerable degree of the overall vergence response would be derived from blur-driven accommodation and correlated accommodative vergence. In contrast, if it was high,[20] the vergence-accommodation would be sufficient to account for all or most of the necessary accommodation for clarity of focus, and hence the blur-driven accommodation and correlated accommodative vergence would be minimal.

WHAT ARE THE NEWER APPROACHES TO CLINICAL PRESBYOPIC CORRECTION?

With advances in vision science and in modern technology, optical and surgical methods for the clinical correction of presbyopia have improved and have provided patients with better quality of vision over the years (see Sections V and VI). Optical correction with progressive addition lenses (PALs) to compensate for the loss of accommodation with advancing presbyopia has been a preferred choice of management over the past decade or so. Research continues to improve PAL design, fitting procedures, and functional outcomes assessment (see Chapter 13). As mentioned previously, with the progressive age-related loss of accommodation and its associated reduction of accommodative vergence, disparity vergence becomes dominant and eventually provides maximal contribution to the overall vergence response under normal binocular viewing conditions. Related to this, recent experiments showed that patients with faster vergence dynamics adapted better to PALs. This adaptation was related to changes in the disparity vergence transient component.[21] Thus, disparity vergence plays a critical role in both the age-related adaptive aspects, as well as motor adaptation in general.

A more contemporary, but still somewhat experimental, approach is to compensate surgically for the age-related accommodative loss. Implantation of a unifocal IOL is the most widely adopted surgical technique to replace a cataractous lens. With such implants providing correction for distance vision, the older individual will typically need to wear a near spectacle addition of +3.00 D for clarity of near vision. Although this method remains conventional and works well, multifocal (refractive and diffractive) and accommodating IOLs (AIOLs) are constantly evolving in an attempt to render the use of supplementary reading spectacles for near work unnecessary (see Chapters 17 and 18). Although reduced contrast sensitivity is a major pitfall with these lenses due to their simultaneous and overlapping multiple optical images across the retina, studies have shown considerable patient satisfaction and good stereopsis with these lenses.

A further advance in the surgical management of presbyopia is the development of AIOLs. These have received special interest over the past decade in an attempt to mimic the natural process of human accommodation. Deformable AIOLs that change shape with alteration in ciliary muscle force are currently being researched and clinically tested.

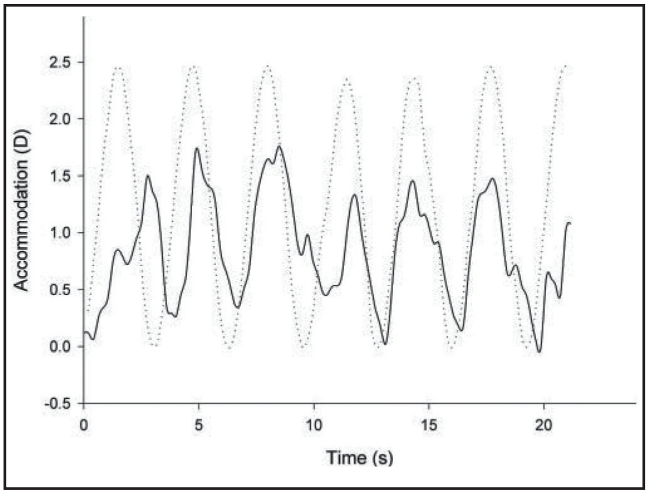

Figure 12-4. Dynamic accommodative responses of a subject fitted with 1CU accommodating intraocular lens (IOL) showing reduced accommodation and high variability. (Adapted with permission from Wolffsohn JS, Hunt OA, Naroo S, et al. Objective accommodative amplitude and dynamics with the 1CU accommodative intraocular lens. *Invest Ophthalmol Vis Sci.* 2006;47(3):1230-1235.)

While deformable AIOLs are a major new direction in presbyopia management, there are several factors that will influence their functional vision outcome and eventual success. One of the major concerns is the dynamic range of focusing that an AIOL can provide. Typically, 5.00 D of residual accommodation is needed to attain and maintain comfortable, blur-free near viewing (ie, 40 cm; 2.50 D dioptric demand) without symptoms (ie, the "half-in-reserve" rule).[3] This is not achieved with currently available AIOL designs, which only provide a more limited effective amplitude,[22] typically no greater than 2.00 D. Second, and related to the above, an important concern is the neuromuscular adaptive control involved with use of a newly implanted AIOL. The biomechanical properties of the implanted lens play a critical role in its degree of flexure during an effort to accommodate. Hence, a potential key problem is that the lens material does not match that of the human crystalline lens. AIOLs in current use have less viscosity than the natural lens. Based on the Hess-Gullstrand theory of presbyopia, the amount of neuromuscular force required to change 1.00 D of accommodation remains constant with age over the linear response range. Because the calibration of the accommodative neural signals is based on the crystalline lens viscosity for a given amount of dioptric change, implantation of a lens material, whose viscoelastic properties are different, would likely initially cause a mismatch in the previously learned force-response equation. This imposed mismatch between the adapted neural signals and the newly implanted lens viscoelastic properties in an older individual would likely cause instability of accommodation, at least initially. This instability is shown in Figure 12-4, in which the resultant accommodative responses to a relatively slowly changing stimulus (0.3 Hz) have greater-than-normal lag and are highly variable, even several months after surgery.[22] Use of an accommodative training protocol should help these individuals learn to use their accommodation more effectively for time-optimal focusing—this possibility deserves careful consideration and future testing.[23]

Although the effective accommodation provided by AIOLs and their effects on DOF, aberrations, etc, are being researched[23]; crosslink interactions and their influence on the overall vergence response have not yet been comprehensively tested experimentally. It would be interesting to ascertain how, in AIOL-implanted eyes, the disparity and blur signals interact through the CA and AC crosslinks, respectively. For example, for a given accommodative stimulus, the accommodative response of the newly implanted lens will be overdriven due to its reduced viscosity. However, its associated AC drive would be expected to be the same as for natural lens accommodation because neither the neural signal nor the extraocular muscles have changed. Thus, it would not affect the initial accommodative convergence contribution to the overall vergence response per se. However, subsequent accommodative response changes will probably be needed to attain steady-state accommodation, and such changes would in turn influence the amount of accommodative vergence output. With repetition and training, however, neural adaptation should occur, thereby resulting in more time-optimal responsivity and interactive stability.

SUMMARY

Based on this brief overview, it is clear that the vergence system plays several critical roles, both directly via disparity vergence and indirectly via vergence accommodation and the related CA/C ratio as one ages. Although the overall degree and magnitude of vergence responsivity remain relatively constant (eg, NPC constancy with age), the vergence and accommodative interactions are considerable and change dynamically with age to provide the resultant vergence response constancy and accuracy. Fortunately, this age-related adaptive process is very slow in nature. Future investigations in this area should be conducted with both PAL and AIOL lenses, especially over the course of adaptation within the first few minutes, hours, and days of lens introduction.

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