Accommodation measurements in a prepresbyopic and presbyopic population

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Purpose: To study the efficacy of several subjective and objective methods of accommodation measurement in normal prepresbyopic and presbyopic populations to identify appropriate methods for measuring the outcome of accommodative restorative procedures.

Setting: University of Houston, College of Optometry, Houston, Texas, USA.

Methods: Thirty-one normal subjects with a mean age of 43.7 years (range 31 to 53 years) participated. Accommodation was measured monocularly using 3 subjective approaches—the push-up test, minus lenses to blur, and a focometer—and 2 approaches measured with a Hartinger coincidence refractometer, in which accommodation was stimulated with minus lenses to blur and topical pilocarpine 6%.

Results: The push-up method overestimated accommodative amplitude relative to objective measures in 28 subjects. Two subjective methods, minus lenses to blur and the focometer, produced comparable results, but with lower amplitudes in younger subjects and higher amplitudes in older subjects compared with objective methods. Comparable results were obtained when accommodation was stimulated in 1 of 2 ways and measured with the Hartinger. Pilocarpine elicited stronger accommodative responses than distance blur for subjects with low accommodative amplitudes. Pilocarpine 6% produced stronger responses in subjects with light irides than in those with dark irides.

Conclusions: Hartinger-measured accommodation provides more realistic measurement of accommodative amplitude than the subjective methods tested, especially in the presbyopic population. In presbyopic subjects, the subjective tests resulted in accommodative amplitudes up to 4.0 diopters greater than those measured with objective tests. Measurements of accommodative amplitude are best achieved with objective methods to stimulate and measure accommodation.

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Accommodation is a change in focus of the eye from distant to near objects. This is defined as a dioptric change in the eye's optical power.[1] Accommodation decreases with age, leading to presbyopia, which begins to affect near visual tasks around 40 years. Around 55 years, little or no accommodative ability remains.[2]

Accommodation is mediated by parasympathetic innervation of the ciliary muscles of the eye from the Edinger-Westphal nucleus of the midbrain.[3] According to the classically described and generally accepted Helmholtz theory of accommodation, the ciliary muscle contracts, moving the apex of the ciliary body toward the lens equator.[4,5] This releases resting zonular tension at the lens equator, allowing the capsule to mold the lens into a more spherical and accommodated form. With accommodation, the lens diameter decreases, the lens equator moves away from the sclera, and the curvature of the anterior and posterior lens surfaces increases, resulting in dioptric power increase in the lens and eye.

Clinically and experimentally, accommodation is often measured with the subjective push-up method.[6–8] A near reading chart is moved toward the distance-corrected subject until blur is first detected. The recipro-

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cal of the measured distance from the eye to the near reading chart is suggested to represent accommodative amplitude.

The push-up technique suffers from confounding factors and generally overestimates true accommodative amplitude.[9] It relies on subjective endpoint criteria (blur) and patient interpretation of the task and is confounded by depth-of-field effects (ie, range of object distances over which there is no detectable change in visual acuity),[10] which are accentuated by accommodative pupil constriction.[11] As target distance decreases, the angular subtense of a given letter size increases, contributing to overestimation of true accommodative ability.[12] The push-up technique can overestimate accommodation in a patient with low visual acuity and poor blur detection. When tested with the push-up test and a near acuity chart, a patient with a multifocal intraocular lens (IOL) may appear to have functional accommodation when none exists.[13] The push-up test does not unequivocally measure accommodation and can lead to the suggestion that active accommodation is present when it is not.

There is much interest in the prospects for restoring accommodation in presbyopia.[14–16] Scleral expansion is said to restore the dynamic accommodative capacity of the lens by expanding the scleral diameter overlying the ciliary muscle,[15] although the theory of accommodation on which this surgical procedure is based is refuted.[5] Other methods of restoring accommodation include implantation of accommodating IOLs designed to allow the optic to translate forward in the eye with an accommodative effort.[16,17] This is also said to restore dynamic accommodative ability. Limited objective testing of accommodation has been done in pseudophakic eyes.[18,19] Subjective tests suggest that some short-term near reading ability may be restored with accommodating IOLs[17] and scleral expansion.[20] Objective dynamic accommodative testing after scleral expansion shows no evidence of accommodation restoration.[21]

Standardized objective methods of measuring accommodation are needed to unequivocally demonstrate that accommodation can be restored. In this study, a variety of methods were tested in normal prepresbyopic and presbyopic subjects to assess methods of measuring accommodation in the target population for accommodative restoration procedures.

Pilocarpine is a parasympathomimetic agent that directly stimulates cholinergic receptors on the iris sphincter and ciliary muscles to cause miosis and accommodative spasm.[22] Pilocarpine 2% and 6% have been used to stimulate accommodation.[23,24] Refraction was measured at 60 minutes after pilocarpine in 1 report,[23] and subjective measurements of accommodation were made in the other.[24] The pupil dramatically constricts soon after pilocarpine administration, making prolonged objective accommodation measurements difficult. Phenylephrine, a sympathomimetic, can be used to dilate the iris without appreciably affecting accommodation.[25] Topical application of phenylephrine before pilocarpine administration can slow the miotic effects of pilocarpine, allowing easier and prolonged refraction measurements. Refraction measurement with an instrument such as a Hartinger coincidence refractometer, which allows measurement through 1.0 to 2.0 mm diameter pupils,[26] enables refraction measurements to be performed over longer post-pilocarpine intervals.

When accommodation is pharmacologically stimulated, an involuntary accommodative response ensues that is not accompanied by convergence eye movements that are usually coupled with voluntary accommodation. Even if little accommodation is present, it can be stimulated with pilocarpine. When accommodation is pharmacologically stimulated and measured with an objective instrument, minimal cooperation and no voluntary accommodative effort are required from the subject. This method of stimulating and measuring accommodation may be important for testing the results of accommodative restorative procedures and characterizing the changes that occur in the aging process.[27]

Iris pigmentation affects the pilocarpine-stimulated accommodative response[28] and is a confounding factor in the hypotensive effects of pilocarpine from melanin binding of the drug.[29] In this study, we also characterize the differential effects of iris color on the pilocarpine-induced accommodative response.

Subjects and Methods

Thirty-one subjects with a mean age of 43.7 years (range 31 to 53 years; 19 Caucasian, 7 Hispanic, and 5 African American) participated. The pharmacological stimulation protocol was developed in accordance with that used previously and in consultation with an ophthalmologist.[23,27] The University Eye Clinic director, a medical doctor listed as an

investigator on the approved human subjects protocol and involved with the development of the human subjects and drug stimulation protocols, was available in a clinical capacity for medical consultation during the experiments, if necessary. The study was performed in accordance with a University of Houston institutionally approved human subjects protocol under supervision of the clinic director. Fully informed consent was obtained from the participants.

All subjects were in good physical and ocular health and completed a questionnaire to ascertain any contraindications for participation or predisposition to complications (eg, heart or respiratory conditions, migraines, high myopia, ocular or systemic medications, or ocular surgeries). All subjects had a fully dilated eye examination within the previous 6 months by a qualified clinician under the direct supervision of a board-certified clinician before they were considered eligible for the study. The examination screened for contraindications to the drugs, susceptibility to retinal detachment, ocular pathology, or peripheral retinal degeneration.

Exclusion criteria included astigmatism greater than 0.5 diopter (D), a refractive error greater than 2.5 D, anisometropia greater than 2.0 D, amblyopia, ocular surgeries, ocular disease, and medications that would interact unfavorably with phenylephrine, pilocarpine, proparacaine, or cyclopentolate. Subjects were screened for known sensitivities to the drugs or conditions that would preclude the use of phenylephrine or pilocarpine. During the experiments, the subjects were closely monitored and regularly asked to report on any ocular, systemic, or physiological reactions they experienced. Atropine was available in the event of adverse effects, although none was reported.

Procedures

Five monocular methods (3 subjective and 2 objective) were used to measure accommodative amplitude in each subject. Accommodation was determined subjectively with 1 of the following: (1) the push-up technique; (2) the maximum negative lens power introduced monocularly in a phoropter while trying to maintain clear, sharp focus on a distant letter chart; and (3) finding the maximum negative defocusing power that could be introduced over the subject's distance correction with a focometer (In Focus) while trying to maintain clear sharp focus on a distant letter chart. For subjective measurements, room lights were left on and the near and distant Snellen charts had 100% contrast. The white part of the charts had a luminance of 90 cd/m^2 (near) and 41 cd/m^2 (distant).

Accommodation was also measured with a Hartinger coincidence refractometer (Zeiss) in the right eye when accommodation was stimulated with negative-powered lenses presented before the left eye or by topical application of pilocarpine 6% to the right eye. For objective measurements, room illumination was turned off and the Snellen chart at 20 feet, illuminated by a 60 W lightbulb at 3 feet, had a luminance of 37.6 cd/m^2.

Method 1: Subjective Push-Up Technique The subject wore distance correction determined from the results of a subjective refraction at the full eye examination, in which the most plus prescription for 20/20 acuity was established, and focused on the 20/20 line of a near Snellen chart with the right eye while the left eye was occluded. The subject was instructed to focus on a letter as the near chart was moved closer, until the letter could no longer be held in clear focus. The inverse of the final distance in meters was recorded as the subject's accommodative amplitude.

Method 2: Subjective Minus to Blur The left eye was occluded, and the subject viewed an illuminated distant letter chart with the right eye through a phoropter. With distance correction in place, minus lens power was added in front of the right eye in 0.25 D steps. The subject reported when the 20/20 line could no longer be held in clear focus. The minus-lens power added over the distance correction was recorded as the accommodative amplitude.

Method 3: Subjective Focometer-Induced Accommodation With the left eye occluded, the subject viewed the distant letter chart through a focometer with the right eye. The focometer is a monocular, Badal optometer similar to a handheld telescope.[30] A manual focusing ring allows the spherical optical power to be increased or decreased, but unlike the stepwise change in power and magnification induced with trial lenses, the Badal principle allows a smooth transition in power with near constant angular subtense. A linear scale on the focusing ring allows the spherical power to be recorded in 0.25 D steps from −8.00 to +10.00 D. As minus power is increased, the subject tends to accommodate to overcome the induced defocus. Maximum plus defocus (+10.00 D) was first introduced into the focometer. The subject was instructed to slowly reduce the defocus by adjusting the power with the focus ring until he or she could clearly see the 20/20 line on a distant letter chart. This spherical power of the focometer was recorded as the distance refraction. The subject was instructed to continue to add minus power until the 20/20 line could no longer be held in clear focus. This spherical power was recorded, and the difference in power between the 2 readings was taken as the accommodative amplitude. This process was repeated 3 times, and a mean of the accommodative amplitude was calculated.

Method 4: Trial Lens-Induced Accommodation Measured with the Hartinger Coincidence Refractometer The subject's head was placed in a chin rest, and a Hartinger coincidence refractometer was aligned to measure the right eye. The Hartinger is a Scheiner principle optometer that measures through a fixed-entrance pupil aperture and is frequently used in human and animal accommodation experiments.[23,31,32] The examiner uses a subjective vernier alignment task to align light mires to measure refraction that is objective with respect to the patient and accurate to within 0.25 D in a variable-focus model eye (Heine). Accommodation was stimulated with minus trial lenses placed in a lens holder in front of the left eye as the subject viewed a distant letter chart. Consensual

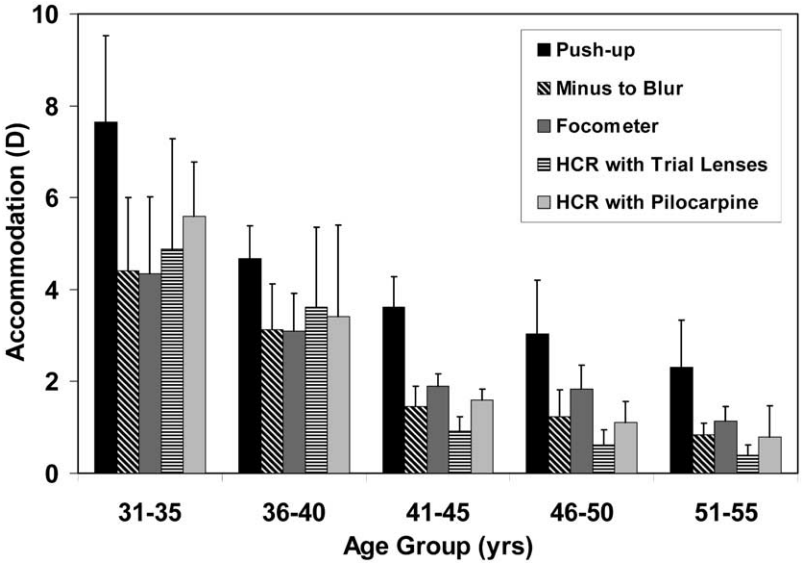

Figure 1. (Ostrin) Mean maximum accommodative amplitudes and SD for the various methods of accommodation measurement for all subjects as a function of age groups.

accommodation was measured in the right eye with the Hartinger. With the left eye corrected for distance, a +0.50 D lens and then lenses of increasing minus power (plano −0.50 D, −1.00 D, −2.00 D, etc.) were placed before the left eye until 3 consecutive increasing lens powers resulted in no further increase in Hartinger measured accommodative amplitude or the subject reported that the letter chart could no longer be held in focus. Three Hartinger measurements were recorded for each lens power to generate an accommodation stimulus response curve and to find the maximum accommodative amplitude.

Method 5: Pilocarpine-Induced Accommodation Measured with the Hartinger Coincidence Refractometer Baseline refractions were measured with the Hartinger in both eyes. One drop of phenylephrine hydrochloride 2.5% (AK-Dilate®) was instilled to dilate but not cycloplege the right eye. One drop of cyclopentolate hydrochloride 1% (AK-Pentolate®) was instilled to dilate and cycloplege the left eye. Thirty minutes after the initial drug instillations, a second baseline refraction was measured in each eye. One drop of proparacaine followed by 1 drop of pilocarpine hydrochloride 6% (Isopto-Carpine®) were instilled into the right eye. Proparacaine anesthetizes the eye and facilitates diffusion of pilocarpine across the cornea.[33] The refraction in both eyes was measured with the Hartinger 3 times every 5 minutes for 60 minutes after instillation of pilocarpine. Subjects were asked to view the distant letter chart with the eye that was not being measured.

To describe the differential responses that pilocarpine may have because of different iris colors, irides were classified on a scale of A to E by color and pigmentation.[34] Class A includes the most lightly pigmented irides, including grays, greens, and blues. Class B includes slightly more pigmented irides, including darker greens and hazels. Classes C, D, and E include various pigmentations of brown irides.

Pupil diameter was measured before the refraction measurements every 5 minutes for 1 hour after pilocarpine instillation. An image of the eye illuminated with an infrared light source was captured with an infrared sensitive video camera and stored on a computer. The camera was placed at a fixed distance from the eye, and the image magnification was calibrated. Pupil diameters were later measured from the images offline.

The entire experiment was repeated in 1 subject on 2 occasions to ascertain the variance in the amplitudes measured. The order in which the various tests were done was changed, except for the pilocarpine stimulation, which was performed last.

Results

Figure 1 and Table 1 show the accommodative amplitudes measured with the various methods in all subjects. For analysis, subjects were grouped in 5-year age groups. Higher accommodative amplitudes were recorded with the push-up method at all ages. Minus to blur, focometer, and Hartinger measurements showed similar amplitudes, although with considerable variability among subjects.

Figures 2, *A* through *E*, show the change in accommodation with time after pilocarpine administration for light (iris classification of *A*, *B*, or *C*) and dark (*D* and *E*) irides. As shown in Figure 2, *A*, *B*, and *D*, a greater response was recorded in subjects with light irides. Maximum accommodation was achieved within 25 minutes of pilocarpine administration, and amplitude decreased as a function of age. The relative decrease in pupil diameter as a function of time after pilocarpine 6% administration is shown in Figure 3. The rate of

Table 1. Mean accommodative amplitudes (diopters ± SD) measured with the various methods in all subjects.

Type of Measurement	Method of Measurement	Age Group (Y)				
		31–35	36–40	41–45	46–50	51–55
Subjective	Push-up	7.64 ± 1.88	4.68 ± 0.71	3.62 ± 0.66	3.04 ± 1.16	2.30 ± 1.04
	Minus to blur	4.4 ± 1.61	3.13 ± 1.00	1.45 ± 0.45	1.24 ± 0.58	0.83 ± 0.26
	Focometers	4.35 ± 1.67	3.10 ± 0.81	1.90 ± 0.27	1.83 ± 0.53	1.13 ± 0.33
Objective	HCR with trial lenses	4.88 ± 2.41	3.62 ± 1.73	0.92 ± 0.32	0.62 ± 0.32	0.40 ± 0.21
	HCR with pilocarpine	5.60 ± 1.18	3.42 ± 1.99	1.60 ± 0.23	1.10 ± 0.46	0.79 ± 0.68

HCR = Hartinger coincidence refractometer

iris constriction was faster for light irides, reaching maximum miosis within 25 minutes.

In Figure 4, each subjective measurement is plotted against Hartinger measured trial lens stimulation with linear regression and 1:1 lines. Hartinger measurement with trial lens stimulation is plotted on the *x*-axis, and the 3 subjective methods—push-up technique, minus to blur, and focometer-induced accommodation—are plotted on the *y*-axis. The push-up method overestimated the Hartinger measured amplitude in 28 subjects. All 3 subjective methods tended to overestimate accommodation in subjects with lower amplitudes (typically older subjects), as the regression lines are flatter than the 1:1 line. For the 2 subjective tests—minus to blur and focometer-induced accommodation (Figure 5)—the linear regression line is close to 1:1, indicating that these 2 methods result in similar accommodative responses. Figure 6 shows the 2 Hartinger measurements with trial lens stimulation and pilocarpine stimulation plotted against each other. The regression line is shown for all subjects. One subject (circled) showed a difference of almost 6.0 D between pharmacological and trial-lens-stimulated accommodation. With this subject excluded, the regression equation is:

$$y = 0.967x - 0.165;\ r^2 = 0.70$$

Figure 7 shows accommodative amplitude as a function of age for all the measurement methods.

Table 2 shows the results in 1 subject (age 35) in whom the experiment was repeated on 2 occasions with the tests conducted in a different order, except for the pilocarpine stimulation, which was done last. The subjective minus-to-blur test showed the greatest difference and trial lens stimulation and objective measurement with the Hartinger showed the smallest difference.

Discussion

Although accommodation recorded with the push-up test appears high relative to the values for the other

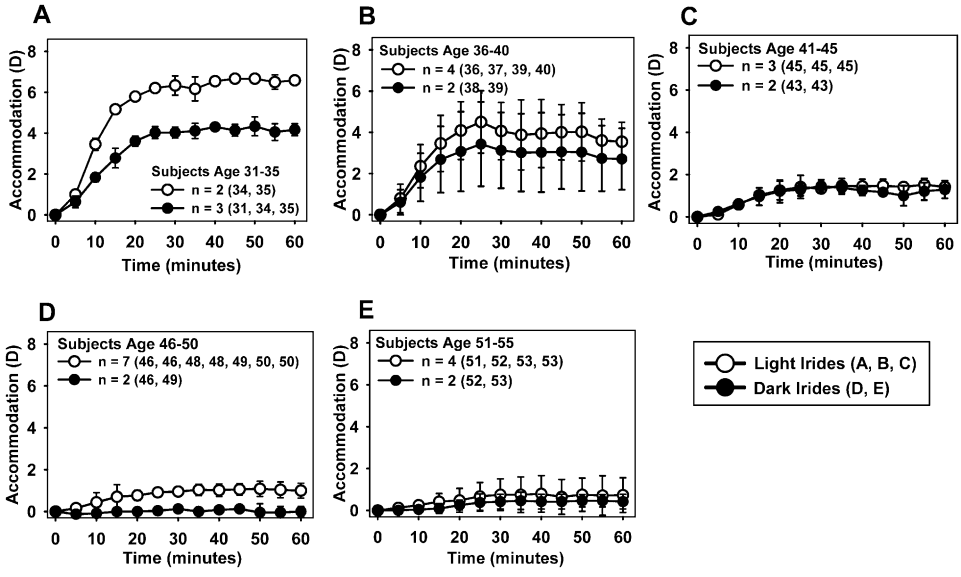

Figure 2. (Ostrin) Maximum accommodative amplitude after administration of pilocarpine 6%. Subjects are grouped in 5-year age groups and separated by iris color (light: open symbols; dark: solid symbols; ± SD). Light irides include A, B, and C, and dark irides include D and E.

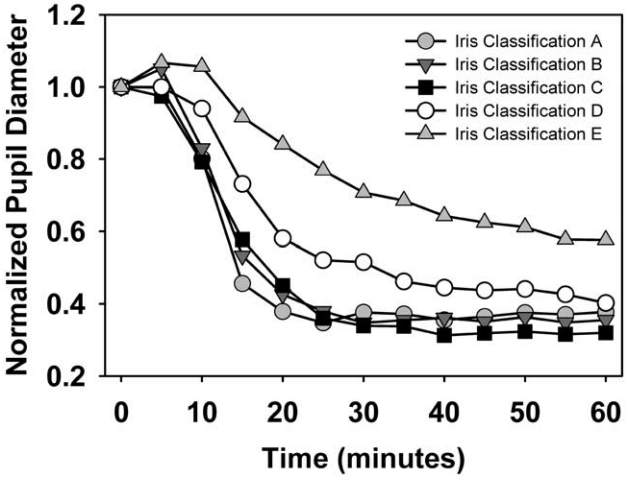

Figure 3. (Ostrin) The relative decrease in pupil diameter as a function of time after pilocarpine 6% administration in all subjects by iris color classification.

methods, the results are within the normal limits reported by Duane[7] (Figure 7, *A*). The other 2 subjective methods, monocular minus to blur and focometer, require a similar task of the subject. Increasing minus power is presented to the subjects, who attempt to minimize the imposed defocus by accommodating and report when the target can no longer be held in focus. Similar results were found for these 2 tests, although differences in image magnification (focometer: constant; minus lenses: minification) and blur presentation (focometer: smooth; minus lenses: step-wise) exist. For many older subjects with little accommodation, the amplitudes recorded with subjective methods are higher than those measured with the Hartinger. These subjective measurements overestimate true accommodative amplitude, especially in the presbyopic population, possibly because of increased depth of focus in older subjects as a result of smaller pupil diameters.[35] Hartinger measurements for subjects aged 51 to 55 with pilocarpine 6% stimulation (mean 0.79 D ± 0.68 [SD]) were slightly higher than accommodative responses measured objectively by Hamasaki and coauthors[2] in subjects in the same age group (mean 0.23 ± 0.14 D).

The Hartinger was used to make objective (on the part of the subject) measurements of accommodation. A study in a younger population, ages 23 to 36, reports that accommodation stimulated with negative trial lenses resulted in more consistent and reliable results than pilocarpine stimulation.[28] In the present study, a similar result was found in the younger subjects. However, pilocarpine produced a stronger response than negative lenses in the older population with low accommodative amplitudes. When as little as 0.25 to 0.50 D

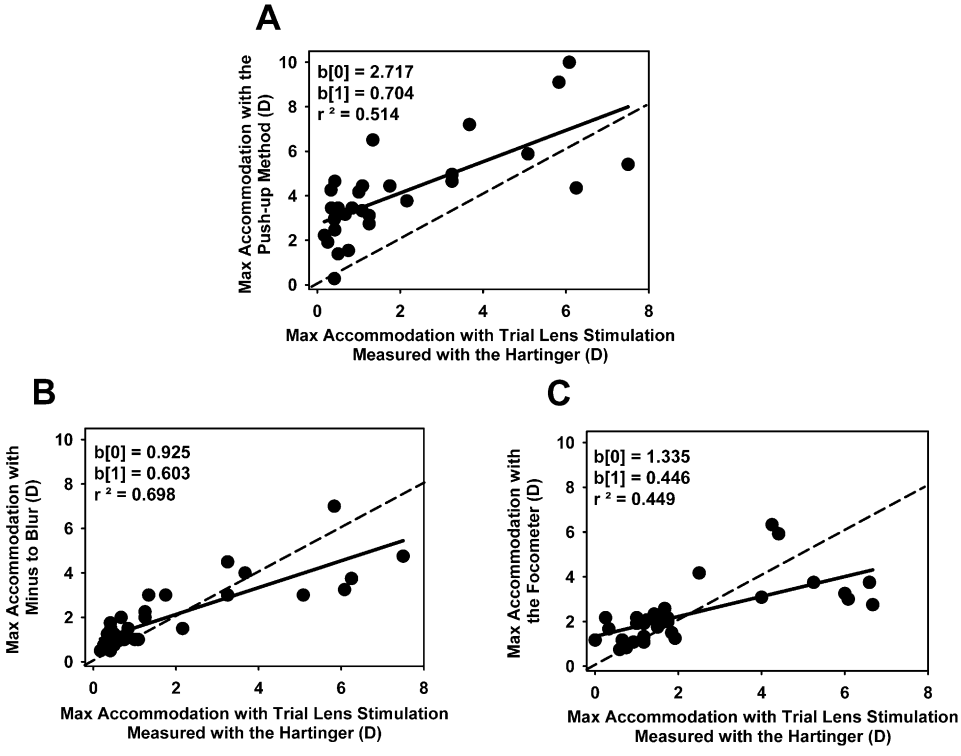

Figure 4. (Ostrin) Each subjective measurement plotted against Hartinger measured trial lens stimulated accommodation with regression (solid) and unity (dashed) lines (as in subsequent figures).

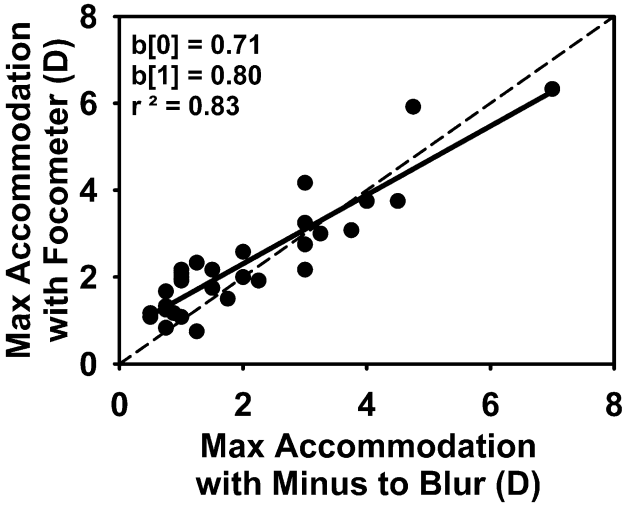

Figure 5. (Ostrin) Comparison of 2 subjective methods, minus to blur with trial lenses and the focometer.

of accommodation was present, it could be reliably measured with the Hartinger following pilocarpine instillation (Figure 2, *D* and *E*, and Figure 6).

In a previous study, accommodation measured with the subjective push-up method in 25 presbyopic patients, age range 60 to 80 years, after instillation of pilocarpine 2%, reportedly produced a mean of 7.0 D (range 2.0 to 13.0 D).[24] However, subjects were likely to have had pinhole pupils, greatly increasing depth of focus and resulting in an overestimation of true

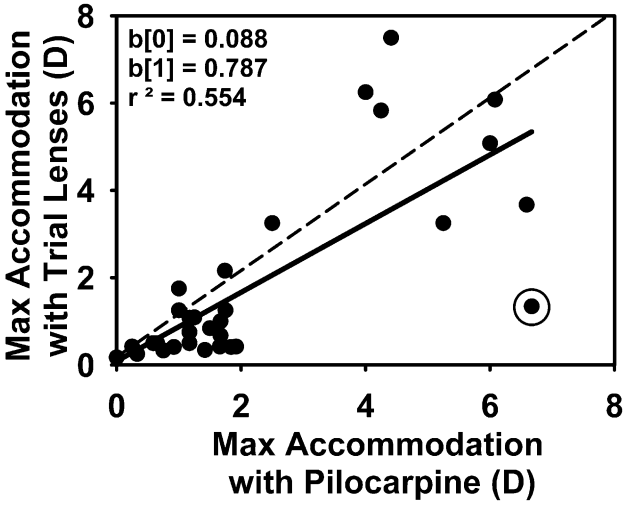

Figure 6. (Ostrin) Comparison of 2 Hartinger measurements of accommodative amplitude when stimulated with trial lenses and pilocarpine 6%. One subject (circled), age 35, shows an especially low voluntary accommodative response relative to the involuntary accommodative response. This data point is included in the regression.

accommodation. The Hartinger measurements reported in the current study using pilocarpine 6% showed less than 1.0 D of accommodation is achieved in subjects older than 51 years.

In the subject in whom the experiment was repeated, the results in the 2 trials were similar (Table 2), with most consistent results from the Hartinger measured trial lens stimulation, showing a difference of only 0.24 D. A large difference was recorded with the subjectively measured minus to blur (2.50 D). The variation could stem from a difference in blur interpretation or task interpretation by the subject from 1 occasion to the next. Ideally, repeated measures would be performed on all subjects to draw statistical conclusions about the repeatability of the testing methods.

Subjects with light-colored irides generally showed stronger accommodative responses to pilocarpine 6% than subjects with dark irides. Differences in the efficacy of cycloplegics and the amount of residual accommodation from differences in iris color are well known.[36–38] Similarly, significant differences in hypotensive effects of pilocarpine with iris color have been reported.[29,39] In the present study, many subjects with light irides achieved higher amplitudes of accommodation with pilocarpine stimulation than with the other methods. However, subjects with dark irides achieved lower accommodative amplitudes with pilocarpine than measured with the other objective method (trial lens stimulation). Thus, while pilocarpine-stimulated accommodation may be an effective method for stimulating and demonstrating the presence of accommodation, it is not always effective in determining maximum accommodative amplitude.

The most effective method to objectively determine true accommodative ability was by stimulating accommodation with negative lenses (in young subjects) or pilocarpine 6% (in older subjects) and measuring the accommodative response with the Hartinger coincidence refractometer. Some subjects were unable to use blurring of the distant letter chart as an effective accommodative stimulus, resulting in low amplitudes measured when stimulated with negative trial lenses. One 35-year-old subject achieved only 3.00 D with minus to blur, 2.75 D with the focometer, and 1.34 D with trial lens stimulation but achieved 6.67 D with pilocarpine (circle, Figure 6). A real proximal target that provides an active convergence stimulus may be a stronger

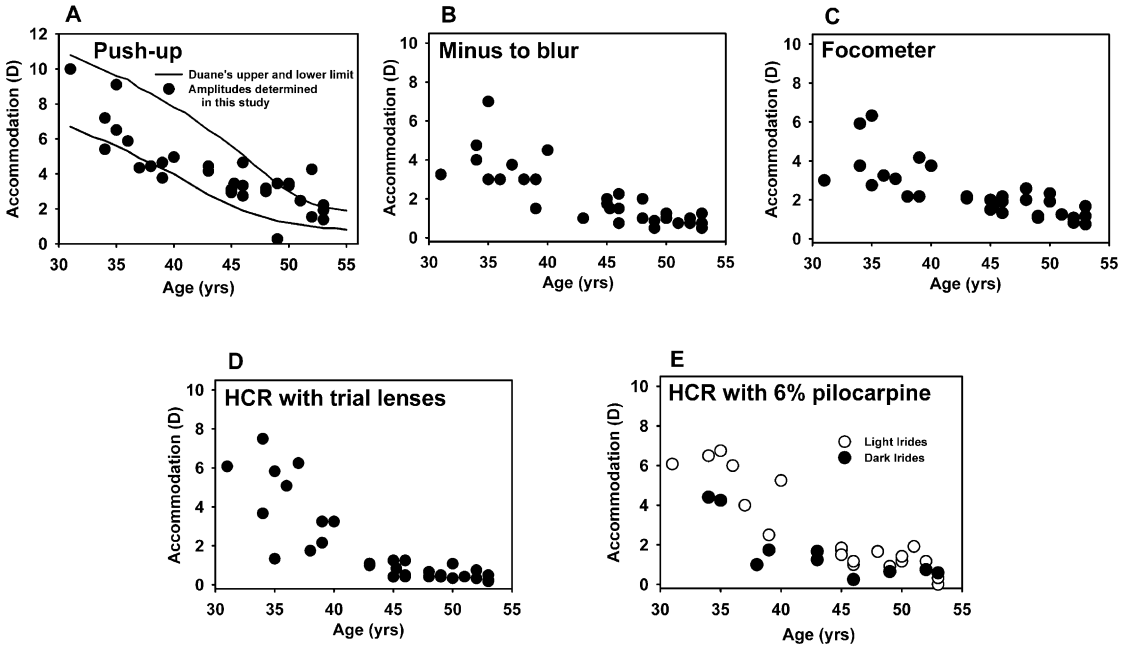

Figure 7. (Ostrin) Accommodative amplitude as a function of age measured with the push-up technique (compared to the values found by Duane[7]), minus to blur, a focometer, Hartinger when stimulated with negative trial lenses, and Hartinger when stimulated with pilocarpine 6% (●, dark irides; ○, light irides).

stimulus for accommodation than optical blur of a distant target,[40] as it actively stimulates a convergence response that may further accentuate accommodation.

The Hartinger coincidence refractometer is capable of measuring through very small pupil diameters that result from pilocarpine stimulation. In no case did the pilocarpine-induced miosis prevent refraction measurements. This may have been in part from predilation with phenylephrine. In a model eye with a pupil radius of 1.1 mm, the greatest Hartinger measured variation from the mean refraction was 0.016 D.[26] While the Hartinger is no longer generally available, it is commonly used in accommodation experiments.[23,32] Other refractometers are available, but objective infrared optometers and wavefront systems are not generally capable of measuring through the small pupil diameters that result from pilocarpine stimulation and would not allow the full pilocarpine-stimulated accommodative response to be measured.

Table 2. Accommodative amplitude measured in 1 subject, age 35 years. The experimental protocol was performed on 2 separate occasions in a different order to determine the variability inherent in each method.

Method	Trail 1 (D)	Trial 2 (D)	Difference (D)
Push-up	9.1	8.3	0.8
Minus to blur	7.0	4.5	2.5
Focometer	6.33	6.67	1.34
HCR with trial lenses	5.83	5.59	0.24
HCR with pilocarpine	4.25	5.00	0.75

HCR = Hartinger coincidence refractometer

The effect of measuring refraction off axis in the convergent eye was assessed by having a subject view distance targets at increasing off-axis positions up to 40 degrees. A variation in refraction of no more than 0.50 D was recorded for deviations up to 22.8 degrees. The highest accommodative amplitude measured with the Hartinger was 7.50 D (mean 1.90 ± 2.12 D). A subject with a normal accommodative convergence/accommodation (AC/A) ratio of 5/1[41] would converge in the measured eye no more than 20 degrees for 7.50 D of accommodation. Thus, convergence would not appreciably affect refraction as measured by the Hartinger with negative lens stimulation.

One goal of this study was to determine appropriate methods for measuring accommodation to evaluate patients who have had accommodative restorative procedures. The responses to pilocarpine 6% stimulation have been established in normal subjects based on age and iris pigmentation. If this method is used in the

future to test the performance of accommodative restorative procedures, preoperative test results could be compared with postoperative results and results compared with those in normal subjects of the same age and iris pigmentation. Ideally, patients receiving accommodative restorative procedures should be tested preoperatively and postoperatively to establish the efficacy of these procedures to restore a dioptric change in power of the eye.[27,42]

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