ORIGINAL ARTICLE

Objective Accommodation Measurement with the Grand Seiko and Hartinger Coincidence Refractometer

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ABSTRACT

Purpose. Subjective push-up tests and dynamic retinoscopy are standard clinical accommodation tests. These are inadequate for assessing if accommodation can be restored in presbyopes. Commercially available clinical autorefractors offer potentially reliable methods for objective accommodation measurement. This study evaluated accuracy and reliability of the Grand Seiko WR-5100K autorefractor for objective accommodation measurement in young adults.

Methods. Twenty-two subjects, aged 21 to 30 years (mean 25.6 ± 2.26) participated. Three methods were used to stimulate and measure accommodation: (1) subjective push-up test in free space, (2) a near target pushed-up on a near-point rod and the response measured with the WR-5100K and a Hartinger coincidence refractometer (HCR), and (3) a distant target viewed through increasing powered negative trial lenses and the response measured with the WR-5100K and the HCR. Trial lens calibration procedures were also used to test the accuracy of the instruments.

Results. Average maximum accommodative amplitude with the subjective push-up test was 7.74 D ± 0.36 D (mean ± SE). For a 5 D stimulus, accommodation of 4.68 D ± 0.10 D (mean ± SE) and 4.13 D ± 0.09 D was measured with the WR-5100K and the HCR, respectively. With a distant target viewed through a −5.00 D trial lens, the WR-5100K measured 4.07 D ± 0.09 D and the HCR measured 4.05 D ± 0.09 D of accommodation. Maximum mean response measured with trial lens-induced accommodation was 5.67 D ± 0.15 D with the WR-5100K and 5.77 D ± 0.18 D with the HCR.

Conclusions. The subjective push-up test overestimated accommodative amplitude relative to the objective measures. The WR-5100K showed good agreement in the responses measured for both pushed-up near targets and a distant target viewed through trial lenses with the HCR, a widely used laboratory instrument. The Grand Seiko WR-5100K, a commercially available instrument, has been demonstrated to be well suited for clinical, objective accommodation measurement using a population of normal young adults.

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A ccommodation is defined as an increase in dioptric power of the eye with an effort to focus at near.[1,2] Clinically, accommodative amplitude is usually measured using a subjective push-up test. Although a subjective test provides important information about near visual ability, it does not unequivocally measure the accommodative optical change in the eye. For example, a multifocal intraocular lens (IOL) is not designed to allow accommodation to occur, but to provide simultaneous distance and near vision from the multifocality. When a patient with a multifocal IOL is tested with a subjective push-up test, the patient may have similar distance and near acuity without a perceptible change in blur. However, this "range of vision" would clearly not be because of accommodation, but rather a consequence of increased depth of field of the eye caused by multifocality due to astigmatism or higher order aberrations and decrease in pupil size. Subjective measurements typically overestimate objectively measured accommodative amplitude.[3,4] A truly objective measurement of accommodation requires no subjective assessment from either the clinician or the subject.

Accommodation can be measured objectively by measuring the change in refraction of the eye with an autorefractor when the subject accommodates from a distant to a near target. The difference between the distance and near refraction as measured by the autorefractor is the accommodative response. This is an objective measure of the dioptric change in the power of the eye and excludes subjective factors such as depth of focus of the eye. The maximum change in power that is achieved as the near target is brought progressively closer to the subjects' eye is the accommodative amplitude.

Accommodative amplitude diminishes with increasing age with the progression of presbyopia.[5] As the mechanisms of accommodation and presbyopia are elucidated,[6–12] ocular surgeries have emerged that are claimed to "restore" accommodation to the presbyopic eye.[13–16] These surgeries include implanting scleral bands,[13] replacing the natural, presbyopic lens with a soft polymer,[15,17] or introducing so-called accommodative IOLs.[16,18,19] These approaches aim to restore active accommodation, i.e., a dynamic increase in dioptric power of the eye with an effort to focus from far to near. New surgical devices and procedures are not without risks, and a thorough cost/benefit analysis is warranted.[20,21] One accommodative IOL, the eyeonics Crystalens, has received United States Food and Drug Administration approval, and clinical trials are currently underway for other such IOLs and accommodation restoration procedures. However, few of these procedures are undergoing rigorous objective testing to determine if they truly accomplish what is claimed of them, namely restoring accommodation. Distance corrected near visual acuities,[14,16] subjective accommodative amplitudes measured with the standard clinical push-up test,[22,23] and patient satisfaction[22] have generally been used to evaluate clinical outcomes. Although these tests may be important for understanding functional near vision, they are inappropriate, inadequate, and inconclusive for evaluating the ability of an accommodation restoration procedure to restore an active and dynamic accommodative change in optical power of the eye.[24–26]

A number of studies have done objective, clinical accommodation testing of patients who have had accommodation restoration surgical procedures or so-called accommodative IOLs.[19,25–28] However, on the whole, these studies have used instruments that are not generally available, require special laboratory setups or have undergone modifications. However, studies are beginning to include more routine clinical procedures appropriate for clinical trials.[26,29] Further, small pupil diameters in older subjects and bright Purkinje images reflected from the relatively flat, high refractive index IOL surfaces can cause variability in the instruments and difficulty with routine clinical use. These clinical challenges, or lack of general availability of the instruments, present impediments to the use of these methods in routine clinical practice.

The Hartinger coincidence refractometer (HCR) has long been used to measure refraction and accommodation in humans and animals.[3,4,7–9,25,30–34] It is a Scheiner principle instrument in which two mires projected onto the retina are aligned or displaced laterally with respect to each other depending on the refraction of the eye. The HCR is objective with respect to the subject, but requires a simple, subjective vernier alignment task from the examiner which is accomplished readily and accurately.[4,31] The HCR is capable of measuring through pupils as small as 1.1 mm.[3,4,31] Although the HCR has proved to be a reliable and useful instrument for accommodation studies, it is no longer commercially available and so cannot be used in clinical trials.

Accommodation can be accurately and objectively measured with an autorefractor; however, several special requirements exist. The instrument should allow: (1) the subject to view a distant and a near target while the refraction is measured; (2) the use of real letter charts (as opposed to an internal target viewed through an optical system); (3) the dioptric demand of the near target to be adjustable to stimulate different accommodative demands; (4) the far and near targets to be viewed binocularly; (5) refraction to be measured on-axis, along the same line of sight as the targets are viewed (because the eyes converge during accommodation); (6) measurement through relatively small pupils (because pupils constrict during accommodation); (7) measurement without need for a bite-bar or pupil dilation. Few commercially available autorefractors meet these fundamental requirements. So far as the authors are aware only the Shin-Nippon SRW-5000 and the Grand-Seiko WR-5100K open-field autorefractors meet all these requirements. The instruments are nearly identical in design although the internal optics of the Shin-Nippon SWR-5000 have recently undergone modification by the manufacturer.[35] The WR-5100K analyzes the diameter and shape of a ring of light projected onto the retina. A myopic change in the eye increases the ring diameter and astigmatism distorts the ring elliptically.

Distance refraction measurements with open-field autorefractors have been shown to be reliable.[36–38] Some accommodation studies have been done with these open-field autorefractors,[35,39,40] although, none have systematically compared accommodative measurements with another instrument recognized for accommodation measurement or conducted testing with different accommodation protocols and systematically validated these autorefractors for accommodation measurement.

In this study, the WR-5100K and HCR were used to measure accommodation in a young adult population. Young adults, as opposed to prepresbyopes, were used because they have relatively high, stable, and measurable accommodative amplitudes. This is an appropriate subject population to determine if the instruments are able to measure accommodation accurately. Accommodation was stimulated using real near targets and trial lens-induced defocus. Trial lens-stimulated and objectively measured accommodative amplitudes were compared with the accommodative amplitude measured subjectively with the "push-up" test. A trial lens calibration was performed with both instruments to verify their accuracy. The two instruments were tested on the same subjects using the same protocols to allow the WR-5100K to be compared with the HCR, an instrument widely used for accommodation testing. These tests were directed at understanding if the WR-5100K, a commercially available, clinical autorefractor is suitable for objective accommodation studies. If the WR-5100K is verified to be accurate, if the accommodative amplitudes measured in a young adult population are similar between the two instruments, and if the variance of the two instruments is similar in the same population, this would serve to validate the commercially available WR-5100K as an appropriate instrument for objective, clinical accommodation studies for future clinical trials of accommodation restoration concepts.

MATERIALS AND METHODS
Subjects

Twenty-two subjects, ranging in age between 21 and 30 years (mean: 25.6 ± 2.26) participated. Subjects, recruited from the student body of the University of Houston, College of Optometry, consisted of 12 women and 10 men and were required to have had a full eye exam within a year. Informed consent was obtained in accordance with the Declaration of Helsinki and institutionally approved human subjects protocols. All subjects had no ocular pathology, strabismus, or prior ocular surgeries and were correctable to 20/20 in each eye with contact lenses. Spherical refractive errors ranged from +2.75 D to −5.75 D with a maximum of −1.75 D astigmatism. Although the WR-5100K can measure through spectacles, placing a trial lens over spectacles causes reflections that can affect refraction measurements. To avoid this, subjects were required to wear contact lenses if correction was needed. Subjects with refractive errors wore their habitual correction in soft contact lenses (except one, who wore gas permeable lenses) to fully correct refractive errors including astigmatism.

Instruments and Setup

WR-5100K Open-Field Autorefractor.   Subjects were seated at the instrument with their head stabilized in the instrument chin rest and forehead strap. Room illumination was dimmed. Subjects viewed far or near targets through the 12.5 × 22 cm open-field beam splitter. The distant target was a printed Snellen equivalent letter chart at 6 m illuminated with an adjacent desk lamp. The near target was a star-like image suspended on a calibrated near-point rod mounted on the instrument and illuminated with a book light. Measurements were performed with 6.28 to 10.12 lux illumination. Although this instrument allows a binocular open field of view, for comparison with the other tests, subjects viewed the targets monocularly with the contralateral eye patched. The WR-5100K is able to measure through pupils 2.3 mm or larger in diameter.[39] The instrument software was set to a sensitivity of 0.01 D and a 12 mm vertex distance for measured refractions. For each far or near target presentation, five consecutive measurements were made. Occasional questionable measurements were detected by large amounts of cylinder. Because refractive errors were corrected, large amounts of cylinder suggested off-axis viewing or spurious reflections. If this occurred, the measurement was repeated.

HCR.   The subjects were seated in front of the instrument with their head stabilized in a chin rest and forehead strap. Room illumination was dimmed. The HCR is a monocular instrument that is aligned with the eye to be measured, with no internal fixation target, but a visible measurement mire. An infrared (IR) pass filter (Kodak Wratten filter 89B, high pass at 720 nm) was fixed in front of the instrument to cut off most of the visible light entering the eye, although the dim red measurement mires projected onto the retina remained faintly visible. An IR-sensitive video camera was inserted into the eyepiece of the instrument and the video output fed to a video monitor, so measurements were made using IR light. To present an external fixation target, a front silvered beam splitter was mounted in front of the HCR at 45°. The distant target was a printed Snellen equivalent letter chart at 6 m, illumi-nated with an adjacent desk lamp. The near target was a near letter chart mounted on a track illuminated with a book light. The images of the far and near targets were seen, by the measured eye, reflected off the beam splitter, and aligned with the HCR measurement axis. The contralateral eye was patched. The HCR has a resolution of 0.25 D[3,4,25,31] and is calibrated to measure refraction at a 14-mm vertex distance.

Procedures.   Distance and near visual acuities were determined monocularly for each subject. Three methods were used to stimulate and measure accommodation: (1) a subjective push-up test in free space; (2) a push-up stimulus and the response measured objectively with the WR-5100K and the HCR; and (3) a distant target viewed through increasing powered negative lenses and the response measured objectively through the trial lenses with the WR-5100K and HCR.

Calibration with Trial Lenses and IR Filter.   Trial lens calibration procedures were performed with both instruments to test their accuracy. This was done by measuring trial lens-induced refractive errors in unaccommodated eyes. For example, a −1 D trial lens placed in front of the eye should produce a 1 D hyperopic refractive change. Distance corrected subjects viewed a distant letter chart with their left eye. An IR pass, visible cutoff filter (Kodak Wratten 89B high pass 720 nm) was held in front of the right eye to prevent the subject from seeing through the right eye, but allowing the instruments to measure through the filter using IR light. The nonseeing right eye was systematically defocused with trial lenses from −6 D to +6 D in 1 D steps held in front of the filter at the spectacle plane (vertex distance of 12 to 15 mm). The distance refraction was subtracted from the refraction measurements through the filter and trial lenses. For each trial lens power, five measurements were made with the WR-5100K and three measurements were made with the HCR.

Method 1: Subjective Push-Up in Free Space.   Distance corrected subjects were asked to focus on a 20/20 line of a near letter chart at 40 cm, one eye at a time with the other eye occluded. The subjects moved the chart slowly toward their eye while maintaining fixation on the same letters until first sustained blur was perceived. The distance of the letter chart from the eye was measured with a ruler. The reciprocal of this distance was recorded as the amplitude of accommodation. Three measurements were made for each eye.

Method 2: Objectively Measured Push-Up–Stimulated Accommodation—WR-5100K Open-Field Autorefractor. Distance corrected subjects were seated at the WR-5100K and viewed the distant letter chart binocularly. Five baseline refraction measurements were made over 5 to 10 s in the right eye. Then with the left eye occluded, the near target was mounted along the line of sight of the right eye on a near-point rod at 50 cm, 33 cm, 25 cm, 20 cm (corresponding to 2.00 D, 3.00 D, 4.00 D, and 5.00 D accommodative demands). The subject was asked to focus on the target and keep it clear and five refraction measurements were made for each stimulus demand over 5 to 15 s. Push-up dioptric demands higher than 5 D could not be presented with the instrument's standard near-point rod. This limitation has been overcome by modification of the standard near-point rod, but was not used here.[41]

HCR.   Distance corrected subjects were seated at the HCR. The left eye was occluded. Baseline refraction was measured three

times in the right eye as the subject viewed the distant letter chart reflected off the beam splitter in front of the instrument. The subject viewed the near letter target mounted on a track reflected off the beam splitter at 50 cm, 33 cm, 25 cm, 20 cm. The subject saw the HCR mires superimposed on the image of the near chart, and this remained so as the eye accommodated. At each distance, the subject was asked to focus on the target and keep it clear while three refraction measurements were made. HCR measurements were read off an internal scale calibrated in 0.25 D steps. Although this setup allows stimulus demands higher than 5 D, only push-up amplitudes of up to 5 D were used to test the same conditions as used with the WR-5100K.

Method 3: Objectively Measured Trial Lens-Stimulated Accommodation—WR-5100K Open-Field Autorefractor. Distance corrected subjects were seated at the WR-5100K with their head in the chin rest. Room lights were dimmed. The subjects wore a light weight, trial lens frame. With the left eye occluded, increasing negative powered trial lenses were placed in the trial lens frame at a 12-mm vertex distance in front of the right eye. The trial lens powers were started at −1.00 D and increased in −1.00 D steps up to −10 D. The subjects were asked to focus on and attempt to clear the smallest line of letters they could see on the illuminated distant letter chart through the trial lens. Subjects were instructed to look at the larger letters in the letter chart as necessary to maintain acuity because of minification of the letters. The refractive state of the eye was measured five times each through the trial lens.

HCR.   Distance corrected subjects were seated at the HCR with their head in a chin rest. With the left eye occluded, subjects viewed the distant letter chart reflected off the beam splitter mounted on the front of the HCR. The subject saw the HCR mires superimposed on the image of the far chart, and this remained so as the eye accommodated. The subjects were asked to focus on the relatively brightly illuminated near chart and ignore the dim mires. The right eye was then progressively defocused by having the subjects hold increasing powered negative trial lenses at approximately 12 mm in front of the eye. This was reliably accomplished, with stability, as the subjects rested their elbow on the table and their hand against the head rest. The trial lens powers started at −1.00 D and increased in −1 D steps up to −10.00 D. The subjects were asked to focus on and attempt to clear the smallest line of letters they could see on the distant letter chart through the trial lens. Subjects were instructed to look further up the letter chart as necessary to maintain acuity because of minification of the letters. The refractive state of the eye was measured three times through each trial lens as the subjects viewed the letter chart.

Analysis.   Only spherical refractions were used for analysis. Although the WR-5100K provides sphere, cylinder, and axis, the HCR generally only measures spherical power in the horizontal meridian. Cylinder and axis can be determined with a separate measurement from the HCR, but this was not done. For the WR-5100K, cylinder measurements generally changed only minimally (<0.25 D) with on-axis accommodation measurements. For the objectively measured push-up test, accommodation was calculated by subtracting the mean refraction measurement for each near target distance from the mean baseline refraction measurement from the distant target. For the negative trial lens-induced accommodation, if the subjects accommodated to exactly overcome the trial lens power, then the refraction measured through the trial lens

should be close to the baseline (distance) refraction. Any positive power (hyperopic refraction) measured through the trial lenses represents a lag of accommodation. Accommodation was calculated as:

Baseline refraction − (trial lens power + lag)

$$= \text{accommodative response}$$

The WR-5100K and HCR measurements were compared using Bland-Altman analysis.[42]

RESULTS

The WR-5100K and the HCR both showed linear calibration curves through the trial lenses from −6 D to +6 D which were close to the ideal 1:1 line. The slopes for the calibration curves were significantly different from one (WR-5100K: −1.065; p = 0.0001; HCR: −1.025; p = 0.0189). The deviation from the 1:1 line at higher negative trial lens powers is slightly greater for the WR-5100K than for the HCR. The intercepts for these regression lines were significantly different from zero (WR-5100K: 0.072; p = 0.0062; HCR: −0.105; p = 0.0038;) (Fig. 1A). The individ-
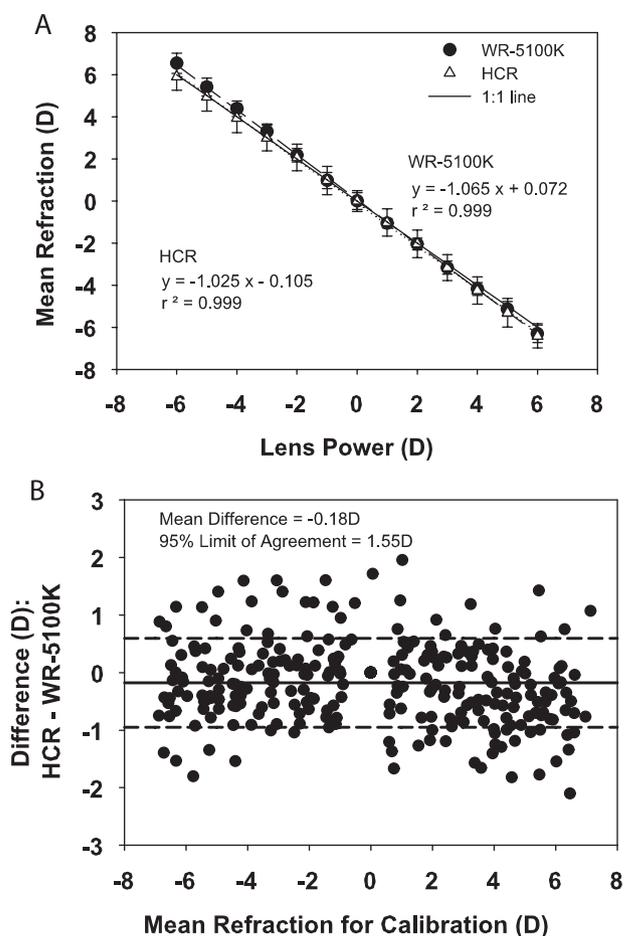
FIGURE 1.

(A) Calibration of the WR-5100K and the HCR. Both instruments show a relatively linear (close to the 1:1) line over the range of −6 D to +6 D. (B) Mean vs. difference plot of refraction measured through the trial lenses and infrared filter during the calibration procedure for the HCR and the WR-5100K for all subjects.
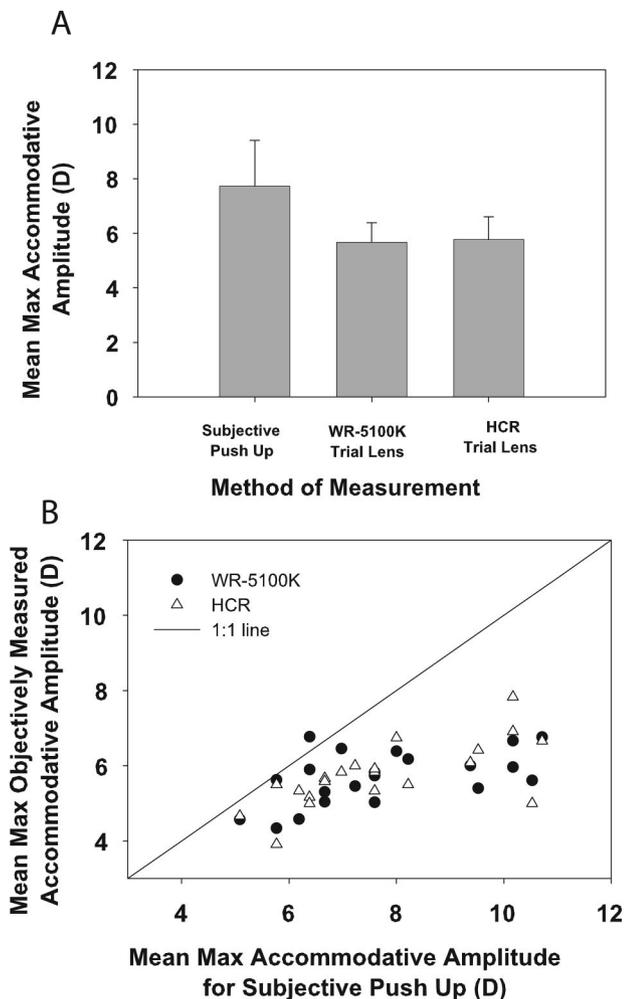
A

B

FIGURE 2.

(A) Mean subjectively measured push-up accommodative amplitude and mean maximum objectively measured accommodative amplitude measured with the WR-5100K and the HCR when accommodation was stimulated with trial lenses. Error bars represent one standard error of the mean. (B) Mean subjectively measured push-up accommodative amplitude compared with mean maximum objectively measured amplitudes measured with the WR-5100K and the HCR when accommodation was stimulated with trial lenses.

A

B

FIGURE 3.

(A) Stimulus response functions showing the mean accommodative responses to push-up and negative trial lens stimulated accommodation measured with the WR-5100K and the HCR for all subjects. (B) Comparison of accommodative responses for the WR-5100K and HCR for a 5 D stimulus. Paired t test results are a: $p = 0.581$; b: $p = 0.002$; c: $p = 0.0005$; d: $p = 0.926$. The * denotes statistically significant differences.

ual calibration data for all subjects compared using a mean vs. difference plot for the calibration procedure with the two instruments shows a mean difference of -0.18 D and a 95% limit of agreement of 1.55 D.

The subjectively measured push-up accommodative amplitude was compared with the WR-5100K and the HCR objectively measured, trial lens-stimulated accommodative amplitudes (Fig. 2A, B). The subjective push-up amplitude of 7.74 D $\pm$ 0.36 D overestimates the objective trial lens-stimulated measurements and the two objective measurements agreed well (Fig. 2A). The subjective push-up test showed a large range of accommodative amplitudes from 5.08 D to 10.71 D. The objective measurements showed smaller ranges (WR-5100K: from 4.34 D to 6.77 D; HCR: from 3.92 D to 7.93 D) (Fig. 2B).

The objective stimulus response functions from all subjects for the push-up and trial lens-stimulated accommodative responses measured with the WR-5100K and HCR showed similar results (Fig. 3A, B). As
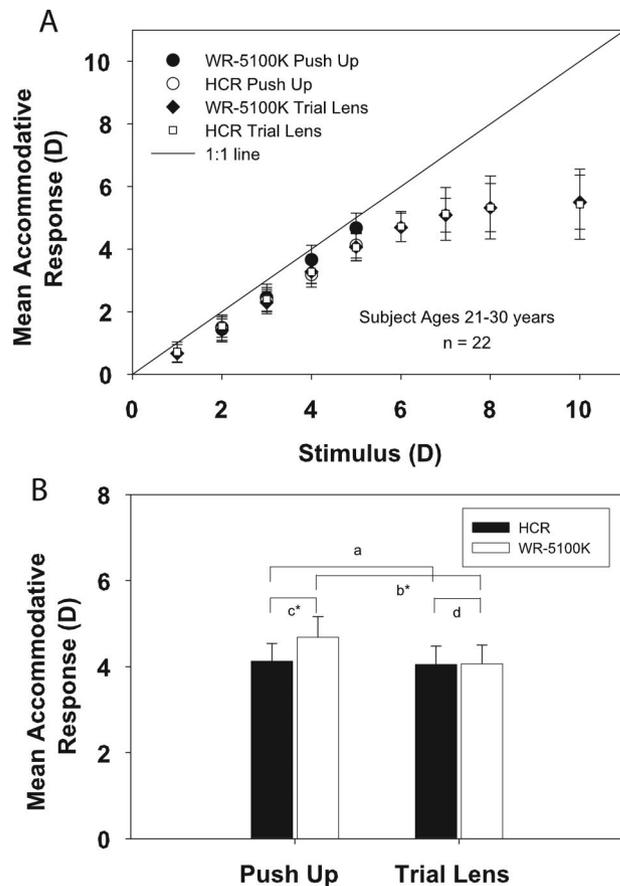
is classically described, objectively measured response amplitudes progressively lag behind the stimulus amplitude with increasing stimulus demand for both trial lens and push-up–induced accommodation (Fig. 3A). For trial lens-induced accommodation, an average maximum response amplitude of 5.67 D $\pm$ 0.15 D (mean $\pm$ SE) was recorded with the WR-5100K and 5.77 D $\pm$ 0.18 D was recorded with the HCR (not significantly different; paired t test: $p = 0.9903$).

Push-up stimuli of up to only 5 D were used for both instruments because of the inability to present a closer near target in the WR-5100K. A comparison of the WR-5100K and HCR measured response to the 5 D push-up and trial lens stimulus is shown in Fig. 3B. The results showed higher amplitudes of accommodation with a 5 D push-up stimulus (WR-5100K: 4.68 D $\pm$ 0.10 D; HCR: 4.13 D $\pm$ 0.09 D) than for the -5 D trial lens stimulus (WR-5100K: 4.07 D $\pm$ 0.09 D and HCR: 4.05 D $\pm$ 0.09 D). There was a significant difference between the two methods of stimulating accommodation (push-up vs. trial lenses) for the WR-5100K (paired t test: $p = 0.002$) but not for the HCR (paired t test: $p = 0.581$). There was a significant difference between the two instruments (WR-5100K vs. HCR) for the push-up stimulus (paired t test: $p = 0.0005$), but not for the trial lens stimulus (paired t test: $p = 0.926$).

Comparisons were made between the WR-5100K and the HCR for push-up and trial lens-stimulated accommodation and for the distance corrected refractive errors in all subjects. The mean vs. difference plot for the push-up stimulus measured accommodation with both instruments showed a mean difference of -0.24 D and a 95% limit of agreement of 1.17 D (Fig. 4A). On average, the HCR measurements show less accommodation for each near push-up stimulus amplitude when compared with the WR-5100K. The mean vs. difference plot for the two instruments for trial lens-stimulated accommodation shows a mean difference of 0.03 D with a 95% limit of agreement of 1.26 D (Fig. 4B). The variability in the accommodative responses measured by the two instruments increased with increasing powered negative trial lenses. In addition, the ability of both instruments to measure the baseline, distance corrected resting refractions was compared. The mean vs. difference plot for the two instruments for baseline, distance refraction (as measured through the contact lens distance correction) showed a mean difference of 0.18 D and a 95% limit of agreement of 1.18 D (Fig. 4C). The circled point in Fig. 4C is the subject wearing a gas permeable contact lens. Measurements were more variable and difficult to measure because of excessive movement of the contact lens.

DISCUSSION

Open-field autorefractors have been used to measure accommodation in prior studies and accuracy of refraction measurements have been compared with retinoscopy, subjective refraction, and closed system autorefractors.[36–39,41] However, to our knowledge, no prior study has compared the accuracy and precision of the WR-5100K for accommodation measurement with another instrument using different accommodation testing protocols.

The trial lens calibration procedure is important for two reasons. First, it is useful (and sometimes necessary) to verify the absolute accuracy of an instrument. Second, to measure accommodative amplitude with the trial lens protocol requires that the instrument measure accurately through trial lenses as well as measuring the accommodative response accurately. The slopes and intercepts of the HCR and WR-5100K calibration lines are similar and close to, although significantly different from, the 1:1 line. This means that an emmetropic eye would be measured to have a resting refractive error of $+0.07$ D by the WR-5100K and -0.11 D by the HCR, that for a 6 D accommodative response there would be an overestimate of 0.32 D for the WR-5100K and 0.26 D for the HCR and that accommodation measured through a -6 D lens would be overestimated by 0.46 D for the WR-5100K and 0.04 D for the HCR. These are relatively small errors as far as accommodation testing is concerned, especially in young subjects with high accommodative amplitudes. The differences from the 1:1 line reach statistical significance, in part, because the variance in the measurements from both instruments is small. The calibration lines allow corrections to be applied to the measured data if more accurate clinical results are desired. The differences from the 1:1 line may stem from variations in the internal calibrations of each instrument and/or small differences in the vertex distance of the trial lenses and the instrument measurement planes. Although the calibration pro-
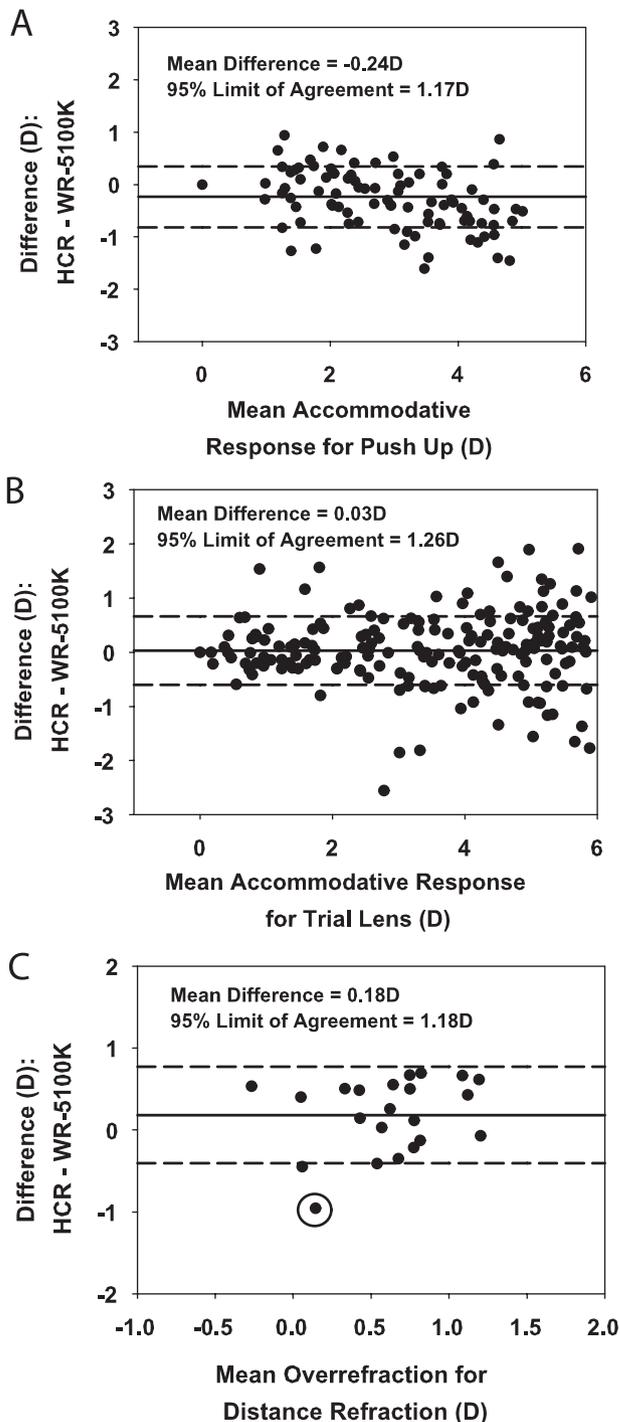
FIGURE 4.

(A) Mean vs. difference plot of HCR and WR-5100K measured mean accommodative response for objective push-up stimulated accommodation. (B) Mean vs. difference plot of HCR and WR-5100K measured mean accommodative response for objective trial lens stimulated accommodation. (C) Mean vs. difference plot of HCR and WR-5100K measured baseline, resting refraction for each subject as they viewed the distant letter chart. The circled symbol represents the one subject wearing gas permeable contact lenses.

cedures described here may be clinically laborious, performing them in conjunction with routine accommodation testing provides important information on the performance, reliability, and accuracy of an instrument and serves as a valuable verification procedure.

The WR-5100K and the HCR do not permit the stimuli to be presented in the same way. The binocular, open field of view of the WR-5100K allows presentation of a real far and near target. This affords naturalistic viewing that may represent an ideal case for an accommodative stimulus. To permit comparisons between the two instruments, testing was restricted to monocular viewing with both instruments and on-axis measurements of the viewing eye for the real targets and trial lens stimulation. Responses to the 5 D push-up stimulus are significantly greater for the WR-5100K than for the HCR and the WR-5100K measured a greater response to the push-up stimulus than to the trial lens stimulus. These differences may reflect the more naturalistic, open-field viewing conditions afforded by the WR-5100K when used with the push-up stimulus and the fact that the body of the HCR is in front of the measured eye. The greater response measured by the WR-5100K is not attributable to the calibration inaccuracies, which would predict an overestimate with the trial lens stimulus. The WR-5100K used a near IR ring of light projected around the fovea,[35,37,38,40] whereas the HCR used a set of three vertical lines of IR light projected onto the fovea.[31] A dim image of the mires is visible in each case. The HCR mires are on the fovea and superimposed on the visual stimulus. As the eye accommodates, the subject sees the mires separate and defocus. The HCR mires may present a distraction, whereas the ring of IR light from the WR-5100K is less perceptible as it is around, rather than on, the fovea. Sensory cues in the different experimental setups could influence how the subjects accommodate and could account for some of the differences observed.

A different near target was used with each instrument; a black star-like target on a white background for the WR-5100K and black printed text of constant size on a white background for the HCR. A near letter chart consisting of letters of decreasing angular subtense may present a more compelling accommodative stimulus than the constant size letters or the star-like target used here and may result in higher amplitudes being recorded. The responses measured to the push-up stimulus with the WR-5100K and star-like target were higher than the responses measured with the HCR and text target. It is unclear if this difference is because of the characteristics of the target or differences between the target presentation in the two instruments. However, the intention was to simply stimulate accommodation and to measure the response with the two instruments, so the characteristics of the near target are not critically important in this case. In addition the size or the angular subtense of the target has been shown not to influence the accommodative response amplitude.[43]

Stimulating accommodation with a push-up stimulus or with negative trial lenses are both effective and easy to use. These approaches have been used in various studies of accommodation.[39,44–46]

The subjectively measured push-up amplitude overestimates the objectively measured trial lens-induced accommodative amplitude. This difference could be attributed to differences between the subjective vs. objective measurement; the different stimulus conditions (push-up vs. trial lens stimulated); and/or differences in pupil diameters between the different testing conditions. When measured objectively with the HCR, responses were not significantly different for the 5 D trial lens vs. the 5 D push-up stimulus, suggesting that this does not account for the difference. When measured objectively with the WR-5100K, although the 5 D push-up stimulus resulted in a significantly higher response than the 5 D trial lens stimulus, this difference was small (0.61 D) relative to the approximately 2 D difference between the subjective push-up test and the objective trial lens measured response amplitudes. Although pupil diameters were not measured and the illumination conditions were not identical for the objective and subjective testing, the illumination conditions are unlikely to account for the 2 D difference. Results strikingly similar to those reported here were found in another study from this laboratory in which the subjective and objective testing were performed with the same targets and under the same illumination.[47] The push-up stimulus includes proximity and blur cues and an increase in angular subtense of the target as it is moved closer. Minus trial lens-induced defocus of a distance target provides blur, but no proximal cues[48] and results in minification of the distant target. However, it has previously been demonstrated and is generally well recognized that subjective tests, which inherently include the depth of field of the eye, overestimate objectively measured accommodative amplitudes.[3,4] Subjectively measured accommodation also significantly overestimates the objectively measured responses in accommodation restoration procedures.[25,29]

It would have been better to compare the maximum subjectively measured push-up amplitude with the maximum objectively measured push-up amplitude. However, the standard near-point rod on the WR-5100K does not allow the near-point target to be pushed closer than 20 cm (5 D). This young adult population would require a stimulus of more than 5 D to elicit maximum accommodation. The WR-5100K standard near-point rod is attached to the top of the frame surrounding the beam splitter in front of the subjects' eyes. The beam splitter limits how close the near target can be positioned in front of the eyes. Modification of the near-point target can allow a stimulus of up to 8 D.[41]

The increased variability in the accommodative responses measured with the higher power minus trial lenses (Fig. 4B) may be because of nearing the maximum accommodative amplitudes in these subjects as well as because of the trial lens-induced minification of the image. Some subjects may find it difficult to accommodate to optically induced accommodative stimuli.[45,48] However, the otherwise relatively good agreement in the amplitudes measured by the two instruments suggests the performance of the two instruments is comparable when accommodation is stimulated with trial lenses.

Many types of presbyopia treatments are currently available that rely on optical principles other than an active dioptric change in power of the eye. Multifocal or diffractive contact lenses and IOLs provide "pseudo-accommodation" by providing simultaneous far and near vision to effectively increase the depth of field of the eye. This is clearly not accommodation as defined by a change in dioptric power of the eye. This study was directed at measuring a true, active change in power of the eye that occurs with natural accommodation or as would occur with a forward movement of an IOL in the eye, for example. It would, of course be inappropriate and impractical to attempt to apply the protocols and instruments described in this study for assessing other kinds of presbyopia treatments that do not rely on an active restoration of accommodation.

In conclusion, relatively simple, reliable, objective accommodation measurements can be performed with the WR-5100K, a com-

mercially available, clinical autorefractor. These tests demonstrate the validity of the clinical instruments for objective, clinical accommodation testing in a population of young subjects with high accommodative amplitudes. Because older subjects represent the target population of accommodation restoration concepts, additional testing should be conducted with the WR-5100K on older, near-presbyopic, phakic subjects to determine the ability of the instrument to measure low accommodative amplitudes when they are present in subjects with small pupil diameters.[49] The lower accommodative amplitudes expected will require smaller stimulus steps to be used and will require greater precision from the instruments to be able to detect small changes. The smaller pupil diameters in an older population may mean that the measurements are more variable. In addition, unique challenges may exist in measuring eyes with IOLs in which bright Purkinje image reflections can occur because of high refractive index IOL materials. However, excellent studies exist in which appropriate objective accommodation testing has been done using a Shin-Nippon clinical autorefractor that is very similar to the WR-5100K, in patients with so-called accommodative IOLs to demonstrate the viability of this kind of objective clinical accommodation testing.[26,29] Such tests will become increasingly important for future clinical trials of new accommodation restoration concepts for improving the efficacy and safety of these procedures.

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