

ORIGINAL ARTICLE

# Static and Dynamic Accommodation Measured Using the WAM-5500 Autorefractor

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## ABSTRACT

**Purpose.** This study was undertaken to compare static and dynamic accommodation measurements using the Grand Seiko WR-5500 (WAM) in young, phakic subjects.

**Methods.** Fifteen subjects, aged 20 to 28 years ( $23.8 \pm 0.58$  years; mean  $\pm$  SD years) participated. Accommodation was stimulated with printed text presented at various distances. In static mode, three measurements were taken for each stimulus amplitude. In dynamic mode, 5-Hz recordings were started, and subjects alternately looked through a transparent near chart and focused on a letter chart at 6 m for 5 seconds and then focused on the near letter chart for 5 seconds for a total of 30 seconds. After smoothing the raw data, the highest three individual values recorded in each 5-s interval of focusing at near were averaged for each stimulus amplitude. Analysis of variance and Bland-Altman analysis were used to compare the static and dynamic measurements. A calibration was performed with +3.00 to -10.00 D trial lenses behind an infrared filter, in 1.00 D steps in 5 of the 15 subjects.

**Results.** Stimulus-response graphs from static and dynamic modes were not significantly different in the lower stimulus range ( $<5.00$  D,  $p = 0.93$ ), but differed significantly for the higher stimulus amplitudes ( $p = 0.0027$ ). One of the 15 subjects showed a significant difference between the static and dynamic modes. Corresponding pupil diameter could be recorded along with the accommodation responses for the subjects, and pupil diameter decreased with increasing stimulus demand. Calibration curves for static and dynamic measurements were not significantly different from the 1:1 line or from each other ( $p = 0.32$ ).

**Conclusions.** Slight differences between the dynamically and statically recorded response amplitudes were identified. This is attributed to differences in the accommodative responses in this population and not to the instrument performance. Dynamic measurement of accommodation and pupil constriction potentially provides additional useful information on the accommodative response other than simply the response amplitude.

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Key Words: optometer, accommodation, refraction, pupil, clinical testing

Accommodation is the active and dynamic change in dioptric power of the eye when changing focus from far to near. Procedures aimed at restoring accommodation to the presbyopic eye are under investigation and undergoing United States Food and Drug Administration (FDA) clinical trials. Reliable and practical clinical methods of objective accommodation measurement need to be validated, implemented, and performed as part of routine clinical testing of these procedures. Accommodation restoration has yet to be fully realized with so-called “accommodating” intraocular lenses (A-IOL)<sup>1–3</sup> and has been shown to not occur with scleral expansion band surgery.<sup>4,5</sup> Although there are potentially many

effective methods for treating the symptoms of presbyopia, such as spectacles and monovision or multifocal IOLs, clearly, restoration of active and dynamic accommodation would provide the most effective treatment for presbyopia while minimizing potential side effects. True restoration of accommodation would provide a dynamic change in optical power of the eye with an effort to focus at near.

Although accommodation is a dynamic process, objective clinical accommodation measurement has typically relied on static measurements. Static measurement is a single instantaneous snapshot taken as the eye focuses on a near target, as opposed to dynamic measurement that is a continuous higher temporal frequency measurement as the eye changes focus from a far target to a near target or as the eye maintains focus on a near target. Recent experimental work has characterized the

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dynamic nature of the change in focus from far-to-near (accommodation)<sup>6–9</sup> and the change in focus from near-to-far (disaccommodation).<sup>6,10</sup> Recent studies have also examined the changes in accommodative dynamics with age.<sup>11–15</sup> Many of these studies use experimental, laboratory set ups and instrumentation that are not commercially available. Such laboratory and experimental methods would not generally be practical for routine clinical testing of dynamic accommodation in accommodation restoration procedures and A-IOLs. An easy to use, commercially available instrument that is capable of producing reliable, dynamic accommodation measurement is desirable for basic clinical testing and analysis.

An open-field autorefractor, the Shin-Nippon SRW-5000 (also the Grand Seiko WV-500), has been used for both static<sup>16</sup> and 60-Hz dynamic accommodation measurements<sup>17</sup> in testing some new A-IOLs. This open-field autorefractor has been validated for measuring refraction reliably in a young adult population<sup>18</sup> and modified for dynamic accommodation testing in laboratory studies.<sup>19,20</sup> These studies with the modified Shin-Nippon SRW-5000 are good examples of the use of a clinical instrument for accommodation measurements; however, the custom modifications required to convert this autorefractor to a dynamic instrument involve procedures that would invalidate manufacturer warranties and require technical capabilities beyond that of routine clinical practice and, therefore, would not be appropriate for multicenter FDA clinical trials. A similar instrument, the Grand Seiko WR-5100K autorefractor (with technical operating specifications similar to the Shin-Nippon SRW-5000), has also been validated for refraction<sup>21,22</sup> and accommodation measurements<sup>23</sup>; however, this instrument is only capable of static measurements.

A new version of the Grand Seiko WR-5100K autorefractor, the WAM-5500 autorefractor, is now commercially available, which, in addition to doing static refraction measurements, also allows dynamic refraction measurements (and hence dynamic accommodation measurements), as well as simultaneous, dynamic pupil diameter measurements. The measurement principle appears to be the same as in the WR-5100K, namely an infrared ring of light projected onto the retina with an internal motor-driven neutralizing optometer and the size and shape of the projected light ring analyzed for a sphere, cylinder, and axis. In dynamic mode, the instrument records only the spherical equivalent from the refraction measurement. The instrument writes the dynamic data to a Microsoft Excel file that records the time of measurement, eye measured (left or right), spherical equivalent refraction, and pupil diameter. These measurements are not shown by the recording software during data acquisition; so, blinks or other measurement errors can only be identified as missing data after the recording is completed and the recorded data file is opened for analysis. Because no customized modifications are required to accomplish the dynamic measurements, this is potentially a useful clinical instrument for aspects of dynamic accommodation measurement.

Because both static and dynamic accommodation measurements can be performed with the same commercially available autorefractor, it is of interest to understand if the static and dynamically recorded accommodative response amplitudes are the same. Differences could be attributable to: (1) differences in

how the instrument works in static and dynamic mode, (2) differences in the actual accommodative response of the subjects with a static or a dynamic task, or (3) differences in the refraction data captured by the instrument because of the fluctuations of accommodation. The third situation could arise when doing static accommodation testing if, when taking only three static measurements (as is often the case), the three measurements do not coincide with the moments in time when the eye is in its maximally accommodated state. If accommodation is recorded dynamically, the dynamically recorded data would necessarily include data points in close temporal proximity to when the eye is maximally accommodated. If this situation occurred, static measurements would underestimate the dynamically measured accommodative amplitude.

In this study, static and dynamic measurements of accommodation were compared using the Grand Seiko WAM-5500 in 15 young adults. A calibration was performed in both static and dynamic modes on the subjects with trial lenses to assess accuracy of the instrument. In addition, an adjustable focus model eye was measured with different refractive errors (REs) in static and dynamic modes to test the autorefractor. The aim of this study was to determine the suitability of the instrument for clinical dynamic accommodation measurements, to compare the ability of the instrument in static and dynamic mode, and to determine if the statically and dynamically measured accommodative amplitudes recorded are similar.

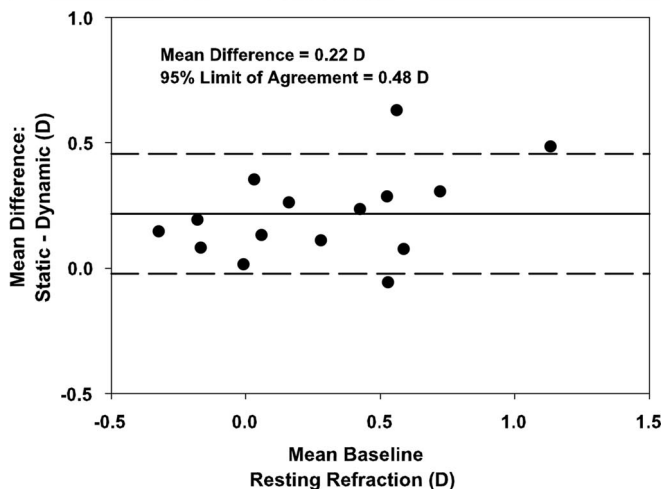
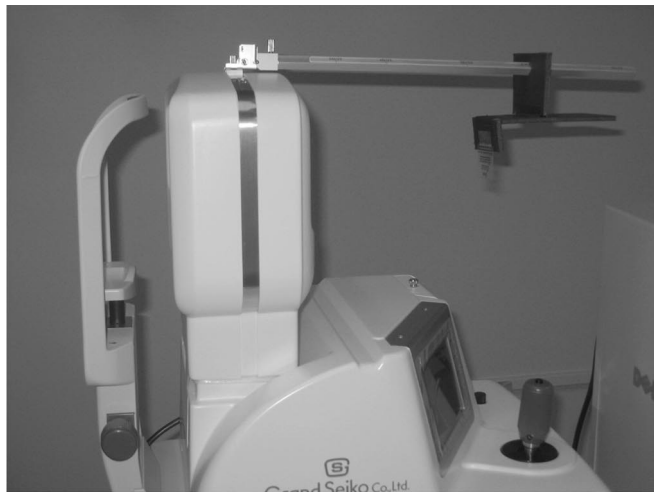
## METHODS

### Subjects

Fifteen subjects, aged 20 to 28 years (mean  $\pm$  SD years: 23.8  $\pm$  0.58 years), participated. Relatively young subjects were used for this testing because these subjects have relatively high accommodative amplitudes. The subjects were recruited from the students of the University of Houston. Informed consent was obtained in accordance with the Declaration of Helsinki and institutionally approved human subjects' protocols. All subjects had no known ocular pathology or strabismus and were correctable to 20/20 in each eye with soft contact lenses if correction was needed. Exclusion criteria included astigmatism  $\geq$  2.00 D and/or amblyopia (best-corrected visual acuity of better than 20/30). Subjects had had eye examinations within a year of the study and reported their best-corrected distance RE. To avoid problems with reflections from spectacle lenses and additional considerations of vertex distance (VD) or magnification/minification, all subjects wore their best correction in soft contact lenses for all the accommodation testing. Baseline distance refraction was the overrefraction with the subject wearing soft contact lenses if correction was needed.

### Near Target

The near target was near chart text of 0.8 to 0.4 M size (2 to 1.5 mm). The text was photocopied onto a 4.3-  $\times$  3.3-cm transparency film. This allowed the subjects to see the near text when focused on the transparency and also to see through the transparency to view a distant target along the same line of sight. The near chart was attached to a specially designed holder attached to the



**FIGURE 1.**

(Top) Grand-Seiko WAM-5500 with near-point rod and custom-made near-point target holder with printed, transparent near letter chart. The holder allows the near-point target to be moved closer to the eye under the instrument beam-splitter housing to stimulate up to 8 D of accommodation. (Bottom) Bland-Altman graph showing the difference between the statically and dynamically recorded distance refractions for all 15 subjects.

near-point rod (Fig. 1 upper panel). The holder permitted the transparency to be positioned closer to the eye than a standard near chart because the transparency text could be moved under the upper edge of the instrument beam-splitter housing, and up against the beam splitter to 12.5 cm (8.00 D stimulus) from the subjects' eyes. The instrument's standard near-point text holder only permits the near-point target to be positioned at 20 cm (5.00 D stimulus) from the subjects' eyes because of restrictions imposed by the instrument beam-splitter housing. During testing, the room lights were left on to allow the subjects to see the near chart clearly.

## Instrument and Set Up

### Alignment

Subjects viewed the far and near targets through the  $12.5 \times 22$  cm open-field beam splitter, monocularly with the eye being measured, while the contralateral eye was covered with the instrument's occluder. The instrument setting was set to a sensitivity of 0.25 D and a 0 mm

VD for all measurements described. The instrument setting only permits a 0 mm VD when set to do the dynamic measurements.

For the testing, the subjects were seated at the instrument with their head stabilized in the chin rest and forehead strap. Before accommodation testing, subjects were aligned to ensure on-axis measurements. For both static and dynamic modes, the subject was asked to fixate on the central letter of a distant Bailey-Lovie chart placed at 6 m. This corresponded to the 20/80 visual acuity line. An initial measurement was made, and the subject was asked if the central letter that they were fixating on was centered within the "just visible," red measurement light ring that the instrument projects to the retina during measurement. If the letter was not centered, the instrument was adjusted until centration and alignment was achieved. These preliminary measurements were discarded. In dynamic mode, measurements were recorded for 10 s during the alignment process and then discarded.

### Static Testing

When the subject was properly aligned, three baseline measurements were made with the subject viewing the distance (6 m) chart. The near target was then mounted on the near-point rod starting at 2.00 D (50 cm). The static alignment procedure described above was repeated. The subject was then instructed to focus on the near text while the three measurements were made. After each set of measurements, the subject was asked to sit out of the headrest while the three measurements were printed, and the subject name and stimulus amplitude were written on the printout. The near chart was then moved closer in 0.50 D steps, the subject was asked to sit back in the headrest, the alignment was repeated at each step, and the three measurements were made at each target distance (50, 40, 33, 29, 25, 22, 20, 18, 17, 15, 14, 13, and 12.5 cm, which corresponded to accommodative demands from 2.00 to 8.00 D in 0.5 D steps). From the refraction measurements made in static mode, the spherical equivalent (sphere +  $\frac{1}{2}$  cylinder) was used for comparison with the spherical equivalent measurements obtained in dynamic mode.

### Dynamic Testing

To measure in dynamic mode, the RS-232 serial cable provided was attached between a personal computer and the instrument. The WCS-1 software provided by the manufacturer was installed and run on the computer. To initiate measurements, the instrument was aligned with the pupil of the eye, the joystick button was pressed and released once, and the instrument started recording dynamic measurements at 5 Hz. During the dynamic accommodation measurements, the user ensured that the instrument remained aligned with the subjects' eye by observing the alignment with the pupil in the LCD monitor for the duration of the test. To stop the measurements, the joystick button was pressed and released again.

First, to record the baseline resting refraction, the subject was asked to focus on the distant target (without the near target present), and the refraction was recorded dynamically for 10 s. The 10 s of recorded data were averaged to calculate baseline distance refraction. The near chart was then suspended on the near-point rod and aligned with the distant target. Before starting the dynamic accommodation measurements, the subject was allowed to practice

changing focus from the far chart to the near chart and back again. When it was determined that the subject was able to do this, the near chart was set at 2.00 D (50 cm) in the same way as for the static testing. The subject was instructed to look at the central letter on the distance letter chart. The dynamic recording was started, and at successive 5 s intervals (using a timer), the examiner instructed the subject to change focus with the single command “near” or “far.” This cycle was repeated for a total of 30 s. After each recording, the subject was asked to sit out of the headrest, while the measurements were saved to the computer.

The near stimulus was then moved to the next testing distance, the subject was asked to sit back in the head rest, and the entire far and near cycle was repeated for the same stimulus amplitudes as with the static mode (from 2.00 to 8.00 D in 0.50 D steps). For comparison with the static measurements, the raw spherical equivalent (as is recorded by the instrument in dynamic mode) was used.

### Calibration With Trial Lenses and Infrared Filter

Trial lens-induced REs in unaccommodated eyes were measured as a calibration procedure with the WAM in static and dynamic mode to test the accuracy of the instrument. The trial lens calibration procedure was performed on 5 of the 15 subjects. The measured eye was selected as the eye with the least astigmatism. Distance-corrected subjects viewed a distant letter chart with one eye. An infrared pass, visible cutoff filter (Kodak Wratten 89B high pass 720 nm) encased in a plano glass lens (as a trial lens) was held in front of the other eye in a trial frame to prevent the subject from seeing through this eye but allowing the instrument to measure through the filter using infrared light. The non-seeing eye was systematically defocused with trial lenses from +3.00 D to -10.00 D in 1.00 D steps held behind the filter in a trial frame at the spectacle plane. This trial frame distance from the eye, varied with each subject based on the fit with the subject’s face, and the VD were measured for each subject with a ruler from the corneal apex to the trial lens. Three refraction measurements were recorded for each trial lens power (TLP). Refraction measurements through the trial lenses were calculated using the formula:

$$\text{Induced RE (D)} = \text{measured refraction (lens + eye) (D)} \\ - \text{distance (baseline) refraction (D)}.$$

Because the WAM will only measure at a 0 mm VD setting when in dynamic mode, the static measurements were also performed at 0 mm vertex setting.

### Model Eye Testing

A Heine (Heine US, Dover, NH) adjustable focus model eye was mounted in front of the instrument. Because only the spherical defocus of the model eye could be adjusted, a -1.00 D cylinder trial lens was placed in a well holder attached to the front of the model eye. The refraction of the model eye was adjusted in ~1.00 D steps from +1.00 to -6.00 D spherical power based on markings on the model eye. Refraction was measured statically 10 times and dynamic refraction was recorded five times, 5 s recordings for each dioptric power. The 10 static measurements were

averaged, and a SD was calculated. The five, 5 s dynamic recordings were averaged, and a SD was calculated.

### Statistical Analysis

The subjects’ accommodative response amplitudes from the static and dynamic measurements were compared. For static mode, the three individual static measurements were used to calculate a mean and a SD for each stimulus amplitude. For dynamic mode, the 30 s of dynamically recorded refraction measurements were converted to accommodation by subtracting each recorded refraction measurement from the mean value from the separate 10 s baseline recording. For each near stimulus measurement, the data were smoothed with a 5-point running average centered on the reference time point. From this smoothed data, the three largest accommodation values for each of the three near response intervals (i.e., three data points from each of the three accommodative responses and nine data points in total) were used to calculate a mean maximum accommodative response amplitude and a SD for each stimulus amplitude.

An analysis of variance was performed on the stimulus-response data from each individual subject, in addition for the group of subjects as a whole to compare the amplitudes of the static and dynamic measurements. Bland-Altman analysis was used to compare the mean differences between static and dynamic measurements for the accommodative responses and calibration measurements for the subjects.

To evaluate the possibility that the presence of the near target during distance viewing in the dynamic accommodation task reduced the accommodative response amplitude (the Mandelbaum effect),<sup>24</sup> an additional analysis was performed. Rather than using the previously and separately recorded 10 s baseline distance refraction measurement in which the near target was not present, the accommodative response amplitudes were calculated considering the local baseline distance refractions recorded before each individual accommodative response during the 30 s dynamic recording. In this analysis, the three minimum baseline data points were identified in each 5 s baseline recording before each accommodative response in the smoothed data. Nine data points (three data points before each response) were averaged, and the accommodative response amplitude was calculated considering this mean baseline.

A vertex calculation correction was applied to the calibration values from the autorefractor response for each TLP used in the calibration. The formula used was as follows:

$$= -1 \times \left[ \text{TLP} + \frac{1}{\left[ \frac{1}{\left[ \left( \frac{1}{\text{ARM}} \right) + \text{VD} \right] + \text{TLP}} \right] - \text{VD}} \right] - \text{RE}$$

where ARM, autorefractor response measurement; and TLP, ARM, and RE are in units of diopters, and VD is in units of meters.

### RESULTS

A Bland-Altman analysis of the baseline resting refraction measurements comparing static and dynamic measurements of all the subjects showed a mean difference of 0.22 D and a 95% limit of agreement of 0.48 D (Fig. 1 lower panel). This indicates that in

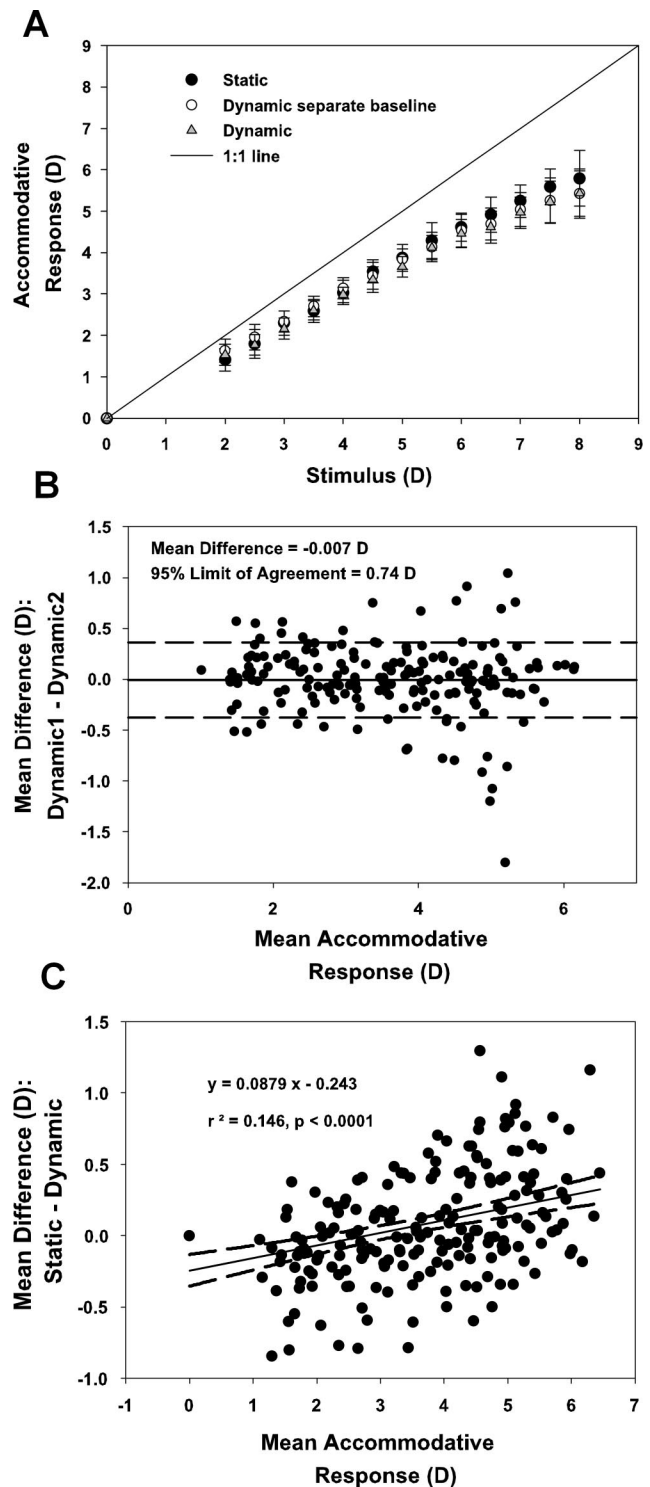
general, the static mode systematically measured baseline refractions to be almost 0.25 D more hyperopic.

As expected, the mean stimulus response graphs for all the subjects showed an increase in accommodative response with increasing stimulus amplitude as measured in both static and dynamic modes (Fig. 2A). When compared with the dynamic measurements, the results from the static measurements were slightly lower at lower stimulus amplitudes and slightly higher at higher stimulus amplitudes (e.g., 2 D stimulus: static = 1.41 D; dynamic = 1.54 D; 8 D stimulus: static = 5.79 D; dynamic = 5.34 D). An analysis of variance of the static and dynamic response (the dynamic analysis considering separate baselines) showed them to be significantly different overall ( $F = 17.37$ ,  $p = 0.0011$ ). A separate analysis of the responses to the lower stimulus amplitudes of 0.00 to 4.50 D showed no statistically significant differences between the static and dynamic responses ( $F = 0.01$ ,  $p = 0.930$ ). However, analysis of the responses to the higher stimulus amplitudes of 5.00 to 8.00 D showed the static and dynamic responses to be significantly different ( $F = 24.17$ ,  $p = 0.0027$ ). An analysis of variance of the two dynamic responses (the first using separate baseline and the second using the same baseline in the 30 s dynamic recording) showed no significant difference ( $F = 0.03$ ,  $p = 0.858$ ). A Bland-Altman plot comparing the two dynamic responses shows a mean difference of  $-0.007$  D and a 95% limit of agreement of 0.74 D (Fig. 2B).

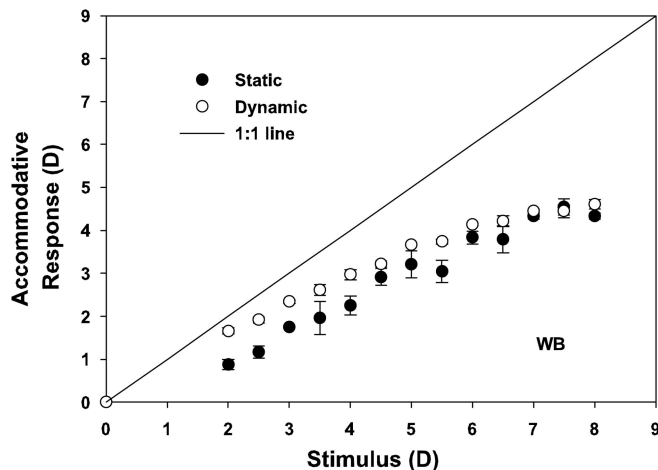
A Bland-Altman plot comparing the static and dynamic accommodation responses showed that the dynamic measurements overestimate the static measurements for low-response amplitudes but underestimate the static measurements for higher response amplitudes (Fig. 2C). A linear regression fitted to this Bland-Altman data shows a statistically significant slope of 0.0879 ( $p < 0.0001$ ). The linear regression line means that in general, for 6.00 D of accommodation, the statically measured accommodative response is  $\sim 0.284$  D greater than the dynamically measured accommodative response.

The Bland-Altman plots show limits of agreement of 0.48 D for the statically vs. dynamically measured baseline refractions and 0.74 D for the difference between the two dynamic measures (Fig. 2B). For the Bland-Altman plot comparing the static and dynamic measurements (Fig. 2C), because there is a slope to these data, to determine the limits of agreements between the methods, the data were corrected for the slope and the limits of agreement then calculated to be 0.79 D. These differences between the static and dynamic measurements are smaller than or comparable with the limits of agreements found between the WR-5100K autorefractor and the iTrace aberrometer for static baseline refraction (0.95 D) and static accommodative response amplitudes (0.70 D) measured previously.<sup>25</sup>

Separate analysis of data from the individual subjects showed that only one of the 15 subjects had a significant difference between the static and dynamic measurements. Subject WB was measured to have slightly higher accommodative responses at every stimulus amplitude with the dynamic mode vs. the static mode (Fig. 3). An analysis of variance showed a significant difference between the static and dynamic modes ( $p < 0.05$ ) in this one subject. The data from this one subject did not appreciably influence the overall result as shown in Fig. 2A.



**FIGURE 2.** (A) Mean and SD of static and dynamically recorded accommodative stimulus response curves for all subjects. Data showing dynamic measurements with the separate baseline with no near chart in place are represented by the open circles. Data showing dynamic measurements with the local baseline with the near chart in place throughout recordings are represented by the open triangles. (B) Bland-Altman graph comparing the two dynamic measurements. (C) Bland-Altman graph comparing the static and dynamic accommodation responses for all subjects.

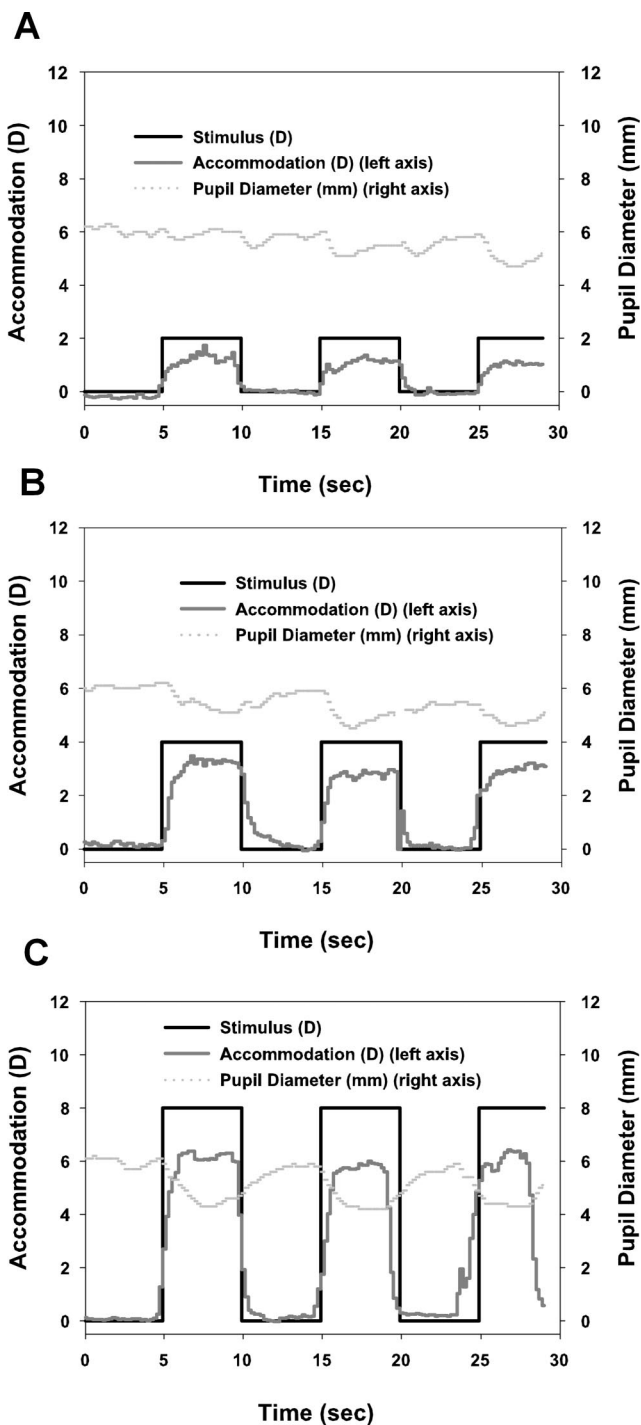


**FIGURE 3.** Stimulus response curve of mean and SD values for subject WB showing significantly different accommodative responses between the static and dynamic measurements.

Graphs of the raw, unsmoothed data plotted as a function of time from the dynamic measurements for a subject accommodating to 2.00-, 4.00-, and 8.00 D stimuli show the increasing accommodation response and increasing pupil constriction with increasing stimulus amplitude (Fig. 4). For this relatively young (aged 23 years) subject with a relatively low-stimulus demand (2.00 D), there is no systematic pupil response. The higher stimulus demands of 4.00 and 8.00 D elicited a stronger accommodation response, in addition to stronger and more systematic pupil constrictions. Although the frequency of dynamic measurements made with the instrument is relatively low (5 Hz) when compared with some of the modified instruments of previous studies (60 Hz),<sup>19,20</sup> variations in accommodation can be seen at all three stimulus amplitudes as the subject fixates on the near stimulus.

The WAM static and dynamic calibrations both showed linear fits, which were not significantly different from the ideal 1:1 line (static:  $p = 0.85$ , dynamic:  $p, 0.86$ ). An effectivity correction was applied to the data because of the VD of the lenses from the cornea. Comparison of the slopes of the static and dynamic calibration graphs showed that they were not significantly different from each other ( $t$ -test = 0.58;  $p = 0.95$ ; Fig. 5A). Bland-Altman analysis of the individual calibration data from the two modes for all subjects shows a mean difference of  $-0.13$  D and a 95% limit of agreement of 0.53 D (Fig. 5B).

The static and dynamic measurements of the Heine model eye (Fig. 6A) and the associated Bland-Altman analysis (Fig. 6B) comparing the static and dynamic measurements show that there is a bias in the instrument with the static measurements being more myopic than the dynamic measurements near  $-6.00$  D and the static measurements being more hyperopic than the dynamic measurements near  $+1.00$  D. This bias is in the same direction, but of a smaller magnitude, than the bias between the static and dynamic measurements of all the subjects shown in Fig. 2A. On the model eye, for a refraction of  $-6.01$  D sphere,  $-0.78$  D cylinder, the static measurement is  $-0.15$  D more myopic than the dynamic measurement.

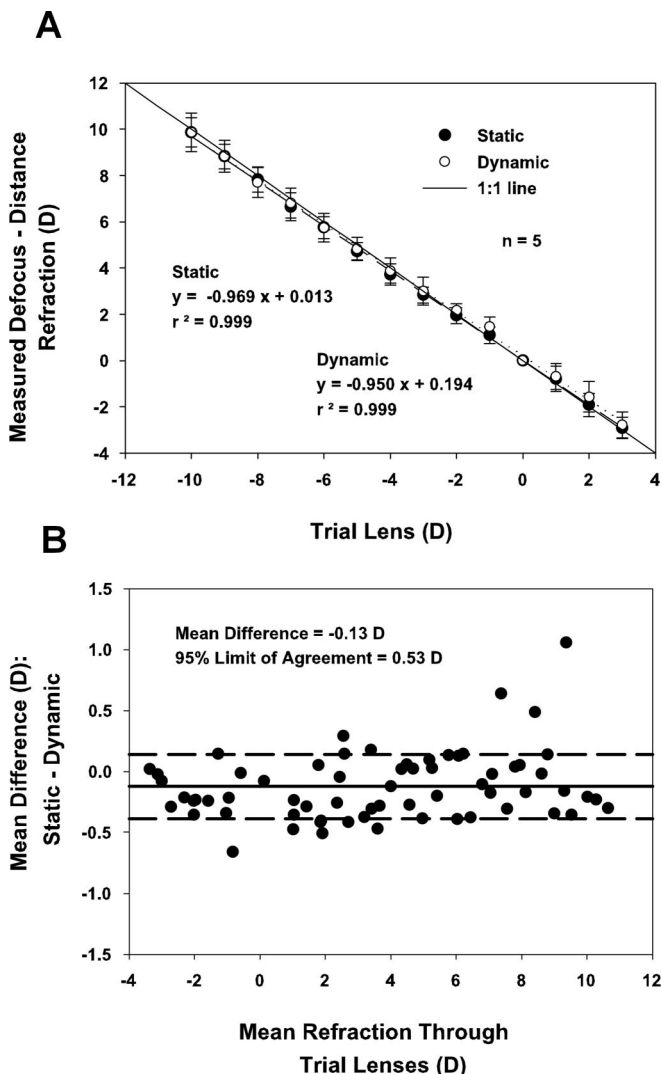


**FIGURE 4.** Sample dynamic measurements of accommodation and pupil responses for subject JB for (A) 2.00, (B) 4.00, and (C) 8.00 D stimuli.

**DISCUSSION**

In static mode, the operation of the WAM is identical to the WR-5100K. Because the WR-5100K has already been validated in several studies to be reliable and repeatable for static accommodation measurements, the purpose of this study was to test the reliability of the accommodation measurements of the WAM in dynamic and static modes.

The method chosen to compare the static and dynamic recordings was to extract the three largest values from the smoothed,

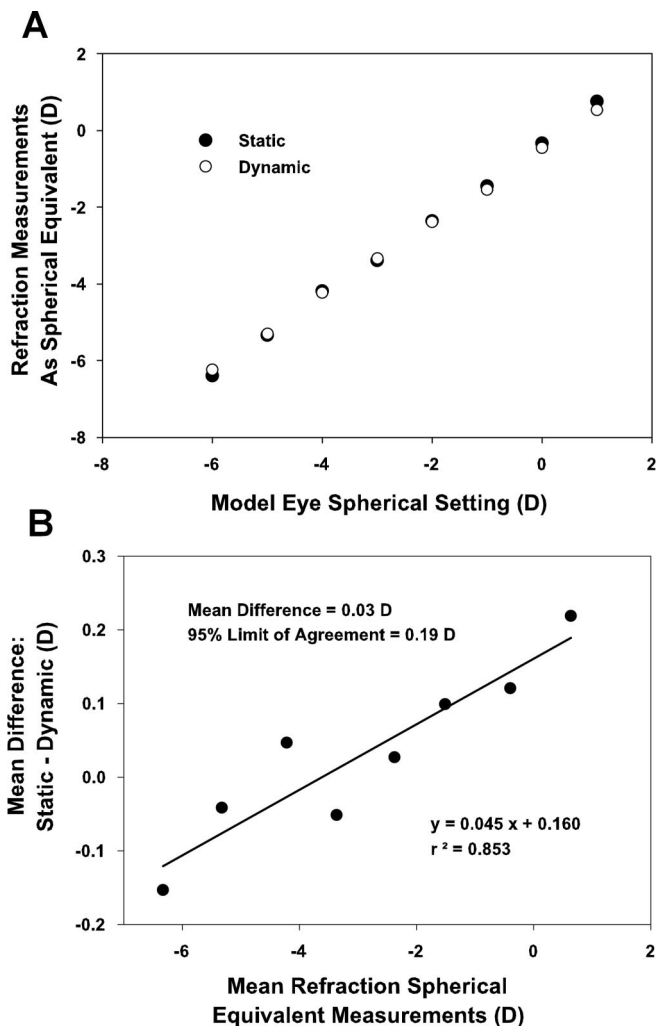


**FIGURE 5.** (A) Calibration curve of mean and SD values for static and dynamic measurements through trial lenses +3.00 to -10.00 D for five subjects. (B) Bland-Altman graph of the static and dynamic measurements through trial lenses for calibration of the instrument.

dynamic recordings during each 5 s accommodative response. A formula calculation in Microsoft Excel allows this analysis to be done objectively for each interval of data extending from before an accommodative response begins until after it ends:

$$\text{Formula} = \text{Average} [\text{Large}(\text{D2:D31}, 3), \text{Large}(\text{D2:D31}, 2), \text{Large}(\text{D2:D31}, 1)]$$

where, e.g., Large(D2:D31, 3) is the third largest number in the range of cells extending from D2 to D31 as specified. This method was chosen because it provided a relatively simple, objective method to extract three data points during the period when the eye was accommodated. An alternative analysis might be to, for example, use the average of all the data collected during the accommodation phase. However, this is not appropriate because there is a period of time when the eye is transitioning from unaccommodated to accommodated, and the data recorded during the transition phase must be excluded. As can be seen from the dynamic accommodation recordings, because



**FIGURE 6.** (A) Refraction measurements with a model eye and -1.00 D cylinder trial lens for a range of spherical refractions of the model eye from +1.00 to -6.00 D, measured in static and dynamic mode. (B) Bland-Altman graph of the static and dynamic measurements taken on the model eye.

this transition is not instantaneous and can be variable between responses and subjects, it is not clear exactly when the eye can be considered to have reached the fully accommodative state. Using only the three (e.g.,) largest data points avoids this source of error. Using only the three largest dynamically recorded data points also provided a similar analysis as was used for the static measurements in which three individual measurements were taken. The dynamic data were smoothed with a centered, 5-point running average to ensure that the three maximum points averaged could not be simply considered as outliers. Doing the analysis on smoothed data will reduce the accommodative response amplitudes slightly. Using only three data points is a diminished data set from the 5-Hz dynamic recordings. Certainly, a similar Microsoft Excel analysis could be done to consider more than three data points. It might be expected that using only the three largest values from each smoothed response in the dynamic recordings would overestimate the amplitudes compared with static mode. It is extremely unlikely that when taking only three individual measurements in static mode that these three instantaneous measurements would coincide exactly with when the eye happened to be maximally accommodated. However, interestingly, averaging only the three largest data

points from the smoothed dynamic data resulted in a slight, but not statistically significant, overestimation at lower response amplitudes of the dynamic response relative to the static response and a slight, statistically significant, underestimate for higher amplitudes of the dynamic response relative to the static response. It is not completely clear why the static and dynamic responses differed. The comparison of the static and dynamic analysis on the Heine model eye show a bias of  $-0.16$  D for a  $-6.40$  D spherical equivalent refractive state. This is in the correct direction but of a smaller magnitude than the difference between the statically and dynamically recorded accommodative response amplitudes in the subjects. However, interestingly, the static and dynamic calibrations on the subjects' eyes with trial lenses showed no systematic difference between static and dynamic recordings. It is possible that the method of stimulating accommodation in the dynamic testing resulted in lower responses being elicited to the higher stimulus demands compared with the static task. In other words, the difference could, in part, be because of how accommodation is stimulated rather than being because of how the instrument measures or how the analysis was performed. It is also possible that because the dynamic testing was done after the static accommodation testing and from lower to higher stimulus amplitudes, fatiguing could have resulted in lower responses to higher stimuli. However, prior dynamic accommodation testing with considerably more rigorous accommodation tasks than used here showed no evidence for lower response amplitudes attributable to fatigue.<sup>9</sup> Several of the individual subjects showed this same general trend of slight (but not statistically significant) difference between the dynamic and static accommodation measurements, but this trend did not occur in all subjects. This overall result could also be attributable to the performance of the individual subjects in this study. However, some subjects had slightly lower overall dynamic responses compared with the static results, and the reverse occurred in other subjects. Only one subject showed a systematically higher response amplitude with this dynamic analysis compared with the static measurements (Fig. 3).

Another important aspect of the accommodative response is the lag of accommodation. The nature of the lag can clearly be seen in Figs. 2A and 4. The response amplitudes approaching 6.00 D but not yet reaching an asymptote for stimuli up to 8.00 D and the lags observed of  $\sim 1.50$  D for a 6.00 D stimulus or approaching 2.00 D for a 7.00 D stimulus are similar in magnitude to the amplitudes and the lags observed in other recent studies in which accommodation was measured dynamically.<sup>26,27</sup> Other studies of lag in younger humans (mean, 11.7 years), which used an autorefractor of similar open-field design (Canon R-1) showed a lag of as much as 1.15 D for myopic and 0.66 D for emmetropic subjects for a 4.00 D stimulus.<sup>28</sup> In a study by Seidemann and Schaeffel,<sup>29</sup> lag of accommodation was measured with a photorefractor, and they found their lag to be 0.35 D (monocular viewing) and 0.37 D (binocular viewing) for a 4.00 D stimulus. In this study, for a 4.00 D stimulus, the lag was 0.97 D (static testing) and 0.86 D (dynamic testing).

If more than just the three maximum response data points were considered in the dynamic analysis, the dynamic responses would decrease further. This is because any further data points included after the three maximum points must necessarily be smaller. Increasing the number of data points analyzed from 3 to 20 systematically decreases the dynamic accommodative response and more so for the larger accommodative responses. The larger accommodative responses may be subject to a greater decrease because they are less stable as the subjects

have to exert greater effort to achieve the accommodative response nearing the limits of their abilities. Greater variability in the accommodative response means that including more data points in the analysis results in a lower mean accommodative response and greater variance. Although using only three data points from each accommodative response in the dynamic measurements is a considerably reduced data set, based on the methodology used in this study, three data points provided an appropriate comparison with the static measurements.

As originally reported by Mandelbaum<sup>24</sup> and shown by others,<sup>30</sup> the presence of a mesh screen between the subject and a distant target can induce some tonic accommodation despite the subjects' effort to focus on a distant target. Because the subjects in this study were asked to alternate viewing between a near chart printed on a transparency and a distance chart seen through the transparent near chart, there was a potential for the Mandelbaum effect to prevent the subjects from completely relaxing their accommodation to the distant target. However, this was not found to occur by comparing the subjects' responses between a separate baseline recording with no intervening near chart and baseline recordings with the intervening near chart in place (Fig. 2A, B). Letters printed on a transparency occur at a relatively low spatial frequency relative to strands of a mesh screen, and this may be the reason for the absence of the Mandelbaum effect with this near target.

Calibration of the WAM with trial lenses in both static and dynamic modes showed no significant deviation from the ideal 1:1 line. Other studies have shown that measurements through trial lenses, particularly higher powered positive lenses ( $> +4.00$  D), are inaccurate because the instrument was not designed to take measurements through spectacle lenses.<sup>31</sup> However, our effectivity corrections because of the VD of the lenses from the cornea showed that the instrument can measure correctly in static and dynamic modes through negative-powered trial lenses. Trial lenses affect the focal point of the eye lens combination determined by the instrument and produce a minified/magnified image of the ring that is projected through the cornea and reflected off the retina and captured by the instrument. Kimura et al.<sup>31</sup> performed trial lens calibrations with the Grand Seiko WV-500 using human and model eyes and reported a small but systematic measurement error (0.30 D at most) with negative lenses (up to  $-5.00$  D), but a systematically increasing error (maximum of  $\sim 1.50$  D) with positive lenses (up to  $+5.00$  D). Other studies with the Shin-Nippon SRW-5000 (or Grand Seiko WV-500) did not perform calibrations on subjects but used model eyes.<sup>19,20</sup> Although the calibration through trial lenses is similar between the static and dynamic modes, it does not provide a calibration of the instrument's performance on eyes without lenses. The best calibration for the WAM may be well done by systematically altering the refraction of the eyes with soft contact lenses. Calibration with contact lenses was performed in a previous study with the WR-5100K on pseudophakic subjects and yielded linear 1:1 calibration curves,<sup>32</sup> but a contact lens calibration was not performed in this study.

The trial lens calibrations were performed in this study to compare the static and dynamic performance of the instrument. However, the calibrations were performed through mostly minus lenses that produce hyperopic refractions. Therefore, unfortunately, the trial lens calibrations cannot be used to address the differences observed between the static and dynamic measurements on the subjects, because the differences occurred during accommodation when the refractive



state was in the myopic range. However, the calibrations performed in static and dynamic mode on the Heine model eye were in the myopic range and did show similar differences between static and dynamic mode to the differences between static and dynamic modes observed in the subjects. However, the extent of the differences was smaller in the Heine model eye than in the subjects. Therefore, the differences between the static and dynamic accommodative measurements in the subjects (Fig. 2A, C) may be partly because of not only the instrument but also the differences in the accommodative response attributable to the nature of the differences between the static and dynamic accommodative tasks.

Although calibration of the pupil diameter measurements was not done in this study, observing the pupil measurements that were made with the WAM shows that it agrees with previous studies of pupil responses with accommodation where clear pupil responses did not necessarily occur for low-stimulus amplitudes in a young (23 to 26 years) adult population at 1.00 D and 2.00 D.<sup>33</sup> A clinical instrument that is capable of simultaneous accommodation and pupil diameter measurements is useful for showing that an accommodative effort, which will cause a pupil constriction, is being exerted even if an associated accommodation change in dioptric power of the eye does not occur.<sup>5</sup>

In populations where the accommodative amplitudes will be low (such as with near presbyopic and pseudophakic subjects), a compelling accommodative stimulus is necessary to attempt to elicit maximum accommodation. Therefore, in this study (unlike in previous studies with the Shin-Nippon SRW-5000<sup>16,17</sup>) real targets were presented at different distances. The previous studies used optical targets, such as in a Badal optical system, where blur is the only cue to accommodation. A real target offers the opportunity to present blur, proximity, and vergence cues if viewed binocularly in an effort to present the strongest accommodative stimulus possible.<sup>34</sup> The WAM offers the opportunity to present a compelling accommodative stimulus that can be viewed binocularly while measuring monocularly. For lower accommodative stimulus demands, <5.00 D, the dynamic measurements are similar to and, therefore as reliable as the static measurements, which means that the WAM is a suitable instrument for measuring accommodation in a near-presbyopic population with low accommodative amplitudes.

Dynamic measurements of accommodation and associated pupil constriction offer several advantages over static measurements. Static measurements provide one measure of accommodation at one moment in time without information on the stability or velocity of the response or without indicating if that is the maximal response or not. Many aspects of the dynamics of accommodation and disaccommodation, such as latency, peak velocity, acceleration, and microfluctuations, have been measured in previous studies.<sup>6,14,15,33,35</sup> These dynamic characteristics of the accommodative response are of higher speeds and frequencies than can be measured with recordings of a frequency as low as 5 Hz. However, the ability to sustain an accommodative response over time could be determined effectively with a 5-Hz recording.

Future FDA clinical testing of accommodation restoration concepts will need to include objective measurements of accommodation such as described here to evaluate if accommodation is restored. There are potentially many instruments available that are capable of doing such measurements, either statically or dynamically. These include autorefractors and aberrometers. A few of these instruments do

permit dynamic measurements of accommodation, but the authors are not aware of other studies that have systematically tested commercially available instruments to compare their abilities to do both static and dynamic clinical accommodation testing. This study demonstrates a simple protocol with a clinically available instrument that can be used for both static and dynamic clinical accommodative measurements.

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