AMERICAN ACADEMY
OF OPHTHALMOLOGY®

Introducing Dynamic Stimulation Aberrometry

Binocular Objective Accommodation versus Subjective Measures

Maximilian Hammer,[1,2] Yvonne Heggemann, MSc,[2] Gerd U. Auffarth, MD, PhD[1,2]

Purpose: The objective measurement of binocular accommodation remains a challenge. The dynamic stimulation aberrometry (DSA) system uses wavefront measurements to dynamically assess accommodation. In this study, we sought to introduce this method in a large number of patients of varying age and compared it with the subjective push-up method as well as the historical results of Duane.

Design: This study is an evaluation of diagnostic technology.

Subjects: Ninety-one patients aged 20 to 67 years (70 healthy, phakic eyes and 21 myopic eyes after phakic intraocular lens implantation) were enrolled at a tertiary eye hospital.

Methods: All patients underwent DSA measurements; the accommodative amplitude of 13 patients chosen at random was additionally examined using the subjective push-up method introduced by Duane. DSA measurements were also compared with Duane's historical results.

Main Outcome Measures: Accommodative amplitude, dynamic parameters of accommodation, and near pupil motility.

Results: Dynamic stimulation aberrometry allowed objective measurement of binocular accommodation, which decreased with age (e.g., 30–39 years vs. $>$ 50 years; 3.8 $\pm$ 0.9 diopters [D] and 0.1 $\pm$ 0.4 D, respectively). Dynamic parameters, such as time delay of the commencement of accommodation after near target presentation, increased with age (0.26 $\pm$ 0.14 seconds for 20–30 years vs. 0.43 $\pm$ 0.15 seconds for 40–50 years, $P = 0.0002$). The objective accommodative amplitude was significantly smaller than Duane's historic results ($P = 0.001$) as well as the subjective push-up method. Dynamic stimulation aberrometry records pupil motility dynamically in parallel to wavefront measurements. Maximum pupil motility during accommodation significantly decreased with age ($P = 0.0002$). Maximum pupillary speed did not correlate significantly with age.

Conclusions: Dynamic stimulation aberrometry allows objective, dynamic, binocular measurement of accommodation and pupil motility with high time resolution in subjects with accommodative amplitudes up to 7 D. This article introduces the method in a large study population and may serve as a control for further studies.

Financial Disclosure(s): Proprietary or commercial disclosure may be found after the references. *Ophthalmology Science 2023;3:100309 © 2023 by the American Academy of Ophthalmology. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).*

Supplemental material available at www.ophthalmologyscience.org.

Accommodation is the process during which the human eye changes its refractive status when focusing on nearby objects. During accommodation, the anterior radial muscle fibers of the ciliary muscle contract toward the sclera, thus increasing the tension on the equatorial zonules, which are the active component in determining the optical power change of the lens.[1] Alexander Duane was one of the first ophthalmologists to systematically assess accommodation. Starting in 1908, he measured the accommodative ability of 4200 eyes using subjective techniques he developed himself.[2] His graphs of declining accommodative ability and patient age are still renowned today. One of the methods Duane used was the subjective push-up method. After the optimal refractive correction is ensured, the patient moves a target closer to the eye until the black line of the target becomes blurry. The distance between the cornea and the target is measured, and the maximum accommodative amplitude is calculated.[2] Subjective measurements of accommodation have serious downsides and are influenced by many factors.[3–5] Although Duane had to rely solely on subjective measures, recent developments such as accommodating intraocular lenses (IOLs) with a shifting focal point brought up the need for objective measures of accommodation.[6]

https://doi.org/10.1016/j.xops.2023.100309
ISSN 2666-9145/23

Before this study, several approaches to objectively measure accommodation with inherent advantages and disadvantages have been proposed. An overview is presented in Table 1.

Ramasubramanian and Glasser[7–9] in 2015 established ultrasound biomicroscopy to objectively measure accommodation. While one eye is presented the variable stimulus of 1 to 6 diopters (D), the other eye is examined using ultrasound biomicroscopy. Based on morphological changes, the authors found that, using linear regressions, they could predict optical response in prepresbyopic eyes. The method holds inherent disadvantages; objective accommodation cannot be dynamically evaluated during the process of accommodation, the stimulus is not presented to the eye examined, and the technique is not applicable in pseudophakic eyes, which might be of interest for real and pseudoaccommodating IOLs in the future. Similarly, Neri et al[10] used swept-source anterior segment OCT to visualize changes in the anterior segment morphology dynamically at 8 frames per second. As such, the accommodative process can be objectively recorded, and the stimulus can be presented to the eye of interest. However, the accommodative amplitude is again based on regression analyses and is therefore only applicable in phakic patients thus far.

Although the previously introduced methods indirectly correlate morphological changes to a refractive change, autorefractors are an objective method to quantify accommodation. Using static autorefractors, refractive error can be calculated while the eye of interest is focusing either on a far or near target. Dynamic autorefractors also allow measurements throughout the process of accommodation.[11–14] However, the near and far target is only presented to the eye measured, creating an unnatural accommodation setting that patients are not used to, which might influence results. Objective accommodation can also be measured by infrared photorefraction, as used in the Power Ref 3 (Plusoptix Inc.), even allowing binocular measurement simultaneously. The device itself does not project any targets, so the measurement of dynamic accommodation by presenting a near target after distant focus requires a customized setup.[15]

Another approach to objectively measure accommodation is by observing ocular aberrations and their changes during the process of accommodation. Dynamic stimulation aberrometry (DSA) makes use of this approach.[16] Studies confirmed the potential of DSA as an alternative to OCT and A-scan ultrasound, possibly leading to more accurate results and allowing the dynamic assessment of the process of accommodation.[16,17] During the measurement, the device can switch between a real distant and near target. The process of accommodation can be calculated based on the dynamic aberration measurements performed by a connected aberrometer. The binocular projection of Landolt-rings allows both eyes to be involved, and the accommodation stimulus can be varied between 3 D and 7 D by moving the near target closer to the eye in steps of 0.25 D. A total of 300 measurements are taken over 12 seconds and immediately evaluated after corrections based on the smallest pupil size during near accommodation. Figure 1 depicts the main elements of the DSA unit. To make use of the great potential of objective accommodation measurements, it is important to not only compare these results to subjective measurement methods that are applied more frequently in current clinical practice but to also generate data to function as a control in further studies.

In this study, we had the following objectives: we sought to first introduce dynamic stimulation aberrometry in a substantial number of patients with varying age and then compare this objective measure of accommodation with the historical data of Duane as well as the subjective push-up method in a subset of patients chosen at random.

Methods

Study Design

In this study, we included adult patients with a spherical equivalent refractive error between 3 and −3 D and astigmatism of < 2.5 D. We excluded patients with ocular diseases, especially retinal disease or optical nerve disease. Patients with good vision but other systemic diseases, such as cancer or diabetes, were also excluded.

Ninety-one eyes of 91 patients were included in this study. The examined eye was chosen at random. Twenty-one eyes previously underwent phakic anterior iris-fixated IOL implantation to correct myopia to test the ability of the device to handle more complex circumstances. The patients' mean age was 38 ± 11 years. All patients gave written informed consent to participate in this study. This study was conducted in accordance with internationally recognized guidelines, including Good Clinical Practice and the Declaration of Helsinki. The local Institutional Review Board of the Medical Faculty of Heidelberg approved this study.

Dynamic Stimulation Aberrometry

A setup previously described by our group was used.[16] The DSA device (Optana GmbH) was connected to a WASCA aberrometer (Carl Zeiss Meditec AG) or the Schwind Ocular Wavefront Analyzer (Schwind GmbH & Co. KG).

The basic principle of DSA measurements combines dynamic assessment of the ocular wavefront with high time resolution with an external target that can be moved into the beam path of the wavefront measurement. The subject focuses on different targets of varying distance, inducing binocular accommodation. A periscope mirror optic allows presentation of the target while still ensuring alignment for ocular wavefront measurements (Fig 1C)

Binocular accommodation is required to create an environment that allows realistic stimulation of the accommodation. Thus, targets must be presented to both eyes simultaneously, which remains a challenge in commonly used aberrometer setups. Often, internal targets are used to create a fixation point for the subject to be tested. However, a realistic accommodative response cannot be ensured with internal targets due to various reasons, such as instrument myopia or unrealistic targets. The DSA concept solves this challenge through its periscope system. Figure 1D presents the arial view of the study setup during measurement of the right eye. The right eye is aligned with the optical axis of the aberrometer. The left partner eye therefore is exposed to a doubled stereopsis angle due to the asymmetry of the target presentation. However, this allows the realistic binocular stimulation with simultaneous real target presentation that allows the subject to experience a normal visual impression. The delay until the commencement of accommodation was graded manually. The accommodative amplitude as well as dynamic parameters, such as maximum

Table 1. Overview of Objective Measurements of Accommodation

	Dynamic Stimulation Aberrometry	Dynamic Refractometer	Static Refractometer	Ultrasound	OCT	Infrared Photorefraction (Power Ref 3, Plusoptix Inc.)
Objective accommodation	Yes	Yes	Yes	Yes	Yes	Yes
Target presented to the eye measured	Yes	Yes	Yes	No	Yes	Yes
Stimuli presented to both eyes	Yes	No	Yes	No	No	Yes
Dynamic measurement	Yes	Yes	No	Yes	Yes	Yes
Applicable in pseudophakic eyes	Yes	Yes	Yes	No	No	Yes
Real target	Yes	No	No	No	No	No (only after individual customization)
Measures of high accommodative amplitudes	Up to 7 D	Up to 30 D	Up to 30 D	Established up to 6 D	Established up to 9 D	Up to 7 D

Dynamic stimulation aberrometry allows dynamic measurement of objective accommodation with the stimulus presented to both eyes throughout measurements. Only 1 eye is measured at a time. As is it based on wavefront measurements, it is also applicable in pseudophakic eyes and could therefore be utilized to research accommodating intraocular lenses. D = diopters.

pupillary speed, were based on a sigmoidal curve fitting conducted in PRISM 8 (GraphPad Inc.).

Study Procedures

Measurements were taken in a room with standardized dimmed light conditions. After autorefraction measurements (Humphrey Instruments, Automatic Refractor, Model 597, Carl Zeiss Inc., see Ehmer et al[16] for more details). Three hundred measurements of the ocular wavefront were performed in 3 × 4 seconds. Measurements were conducted without refractive correction to prevent interference of spectacle correction with the dynamic ocular wavefront measurements. First, the patient focused on the distant stimulus for 4 seconds (100 measurements); subsequently, the pivotable near the target was presented for 4 seconds (100 measurements). Finally, the distant stimulus was presented for another 4 seconds (100 measurements). Every patient completed a test run with a near target of 3 D. Measurements were examined immediately after being performed. If the subject achieved the expected accommodation, the near stimulus was increased by 0.5 D in the following measurement. When maximum accommodation was reached, measurements were repeated 3 times to assure consistency of results. If results were not consistent, patients were allowed breaks in between measurements to prevent further issues with the tear film, which was the most common cause of irreproducibility. If measurements were still not reproducible, the accommodation stimulus was adjusted; this was only necessary in very few cases. Measurement values were recalculated for the smallest pupil size to compare aberrations for each of the 300 points of measurement. A central 2-mm area was used throughout analysis of all patients. During the entire procedure, both eyes are engaged in the accommodation process, but only 1 eye undergoes measurements. Once the measurements for 1 eye were completed, the process was then repeated for the other eye. The eye included in analysis was chosen at random to minimize potential bias due to eye dominance. An optional distance target was used for a subset of subjects with moderate myopia that can be attached to the device in variable distance to allow the subject to fixate on a *distant* target without blurring. If not previously conducted, an examination in cycloplegia was waived as study subjects underwent DSA measurements without refractive correction.

The Subjective Push-up Method by Duane

Next, for a comparison with historical data, 13 patients chosen at random additionally underwent accommodation measurements using the subjective push-up method. Optimal correction was ensured before commencement of the measurements using subjective refraction. Duane's testing figure (Online Supplement 1, available at www.ophthalmologyscience.org) was used as first introduced.[18] The subject slowly moved the test figure toward the eye, until the black, vertical line got blurry. Monocular followed by binocular measures were taken and repeated 3 times. The distance between the near stimulus and the cornea of the examined eye was measured. To allow better comparison, we used the level of the corneal apex as the beginning point of the scale.

Historical Data of Duane

We compared the decline of accommodation with increasing age measured by DSA with historical data from Duane from his publication from 1922.[2] The Prince's ruler's scale used in all of Duane's measurements started 14 mm in front of the cornea, where correction glasses were placed. We recalculated all measurements of Duane based on the different scale starting points (14 mm in front of the cornea vs. corneal apex) to allow for better comparison. The added distance (14 mm) therefore decreases the accommodative amplitude of the historical results.

A Priori Sample Size Calculation

An a priori sample size estimation was conducted. G*Power 3[19,20] was used for all sample size estimations. Considering a difference of 2 D in accommodative amplitude with a standard deviation of 2 D between age groups as a clinically relevant change in accommodative function, an effect size (Cohen's *d*) of 1 can be assumed. To detect a significant difference between the mean of 2 independent groups, in this case subjects of different age categories, a sample size of 23 subjects per group is needed to achieve a power of 90%. Given that patients aged 50 years or older have near to no accommodative function and therefore a smaller standard deviation (assumably 1 D) to achieve a power of 90%, only 15 subjects were needed. Recruitment was continued until the last age category (40–49-year-olds) reached

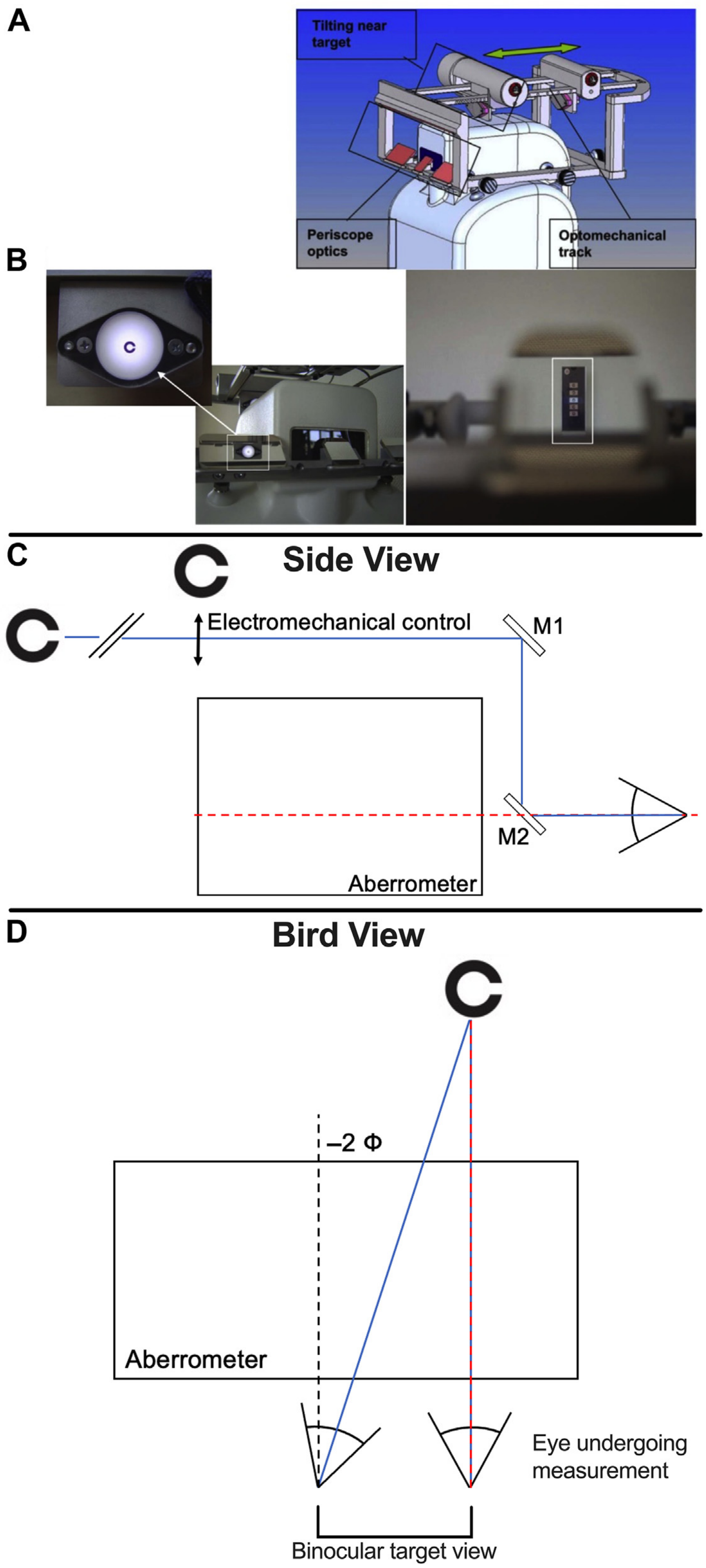

Figure 1. **A**, The dynamic stimulation aberrometry setup consists of an optomechanical track, a tilting near target, as well as periscope optics to project a distance target. A dynamic stimulation aberrometry device is attached to an aberrometer. Figure modified from Ehmer et al.[16] **B,** Subject view during measurement of the near target (left) and the distant target (right). **C,** A periscope optic system allows fixation of the target. Two mirrors (M1/M2) redirect the target image to align the line of sight with the optical axis of the aberrometer. **D,** The bird view on the study setup. Again, the periscope optic allows binocular stimulation with a real target. In this example, the right eye undergoes measurement, and therefore, the line of sight has to be aligned with the optical axis of the aberrometer. Because of the unavoidable asymmetry, the left eye therefore must converge.

the target of 23 subjects. In total, 91 subjects were included: 28 subjects aged 20 to 29 years, 24 subjects aged 30 to 39 years, 23 subjects aged 40 to 49 years, and 16 subjects aged > 50 years.

Statistical Analysis

Normal distribution was examined using the Kolmogorov−Smirnov test. Correlations, paired *t*-tests, or Wilcoxon tests were conducted, as appropriate. *P*-values of < 0.05 were considered statistically significant. The decline in the accommodative amplitude within age categories was analyzed using logistic regression models. PRISM 8 (GraphPad Inc) and Stata 17 (StataCorp) were used for analysis. The maximum accommodation was determined using a sigmoidal curve fit on the dynamic assessment of the spherical refraction throughout the measurement, as presented in Figure 3. More details are presented in Online Supplement 2 (available at www.ophthalmologyscience.org). Pupil correlation analyses were conducted only for patients < 50 years of age to allow calculation of pupil constriction to accommodation ratios.

Results

Effect of Age on the Objectively Measured Accommodative Amplitude

A nearly linear decline of the objective accommodative amplitude with age was observed. Figure 2 shows the maximum accommodative amplitude for all individual patients included in the study. Figure 3 depicts the individual results of 2 patients at the end of the age spectrum. Dynamic stimulation aberrometry allows the examiner to observe accommodation dynamically at a high time resolution. Pupil motility, another component of the near triad, is also dynamically recorded in parallel.

Once divided into age categories of 20 to 29, 30 to 39, 40 to 49, and > 50 years, significant differences in the accommodative amplitude can be observed between the age groups. Although patients aged 20 to 29 years showed a mean maximum accommodative of 4.1 D, patients aged 50 years or older showed only negligible accommodative function (Fig 4). Within the age categories, linear regression models show a decrease in the accommodative amplitude of 0.24 D, 0.25 D, and 0.21 D within the age categories 20 to 29 years, 30 to 39 years, and 40 to 49 years, respectively. Patients older than 50 years showed nearly no accommodative amplitude (0.003 D decrease per year of age; Online Supplement 3, available at www.ophthalmologyscience.org). In the category of patients aged 50 years or older, singular subjects showed a negative accommodative amplitude most likely attributed to the natural fluctuation of refraction in patients with a minimal accommodation function.

Delay in Commencement of Accommodation after Stimulus Presentation

The near target was presented to the subject after 4 seconds automatically. The delay in accommodation was defined as the subject's reaction time to initiate accommodation after this stimulus presentation. The delay of accommodation positively correlated with increasing age (mean of subjects aged 20−39 and 40−49 years: 0.26 ± 0.14 seconds and 0.43 s ± 0.15 seconds, respectively, $P = 0.0002$). Individual results and correlations are presented in Figure 5.

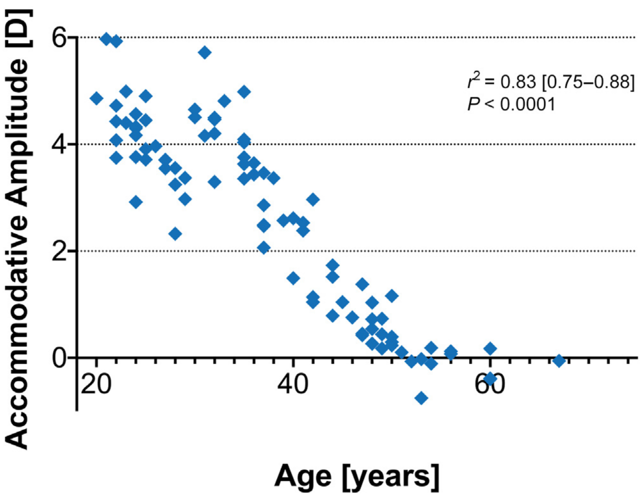

Figure 2. Declining accommodative amplitude with increasing age measured using dynamic stimulation aberrometry. The 91 eyes of varying age measured in this study revealed a near linear decline of the accommodative amplitude with age. D = diopters.

Comparison of Objectively Measured Accommodation with Historical Results of Duane

Next, we compared the results of objective binocular dynamic measurements of accommodation with historic results of Duane, as presented in the Duane plots. The mean accommodative amplitude measured by Duane after recalculation (see Methods) was used for comparison. We used the maximum achieved accommodative amplitude per patient measured by the DSA device. The mean of the maximum accommodative amplitude was calculated for all patients with the same age. Figure 6 presents the results. If both curves are assessed without separation into age groups, the mean difference in the accommodative amplitude between the objective measures and Duane's result is 1.6 D (unpaired *t*-test; $P = 0.0001$). The greatest mean difference occurred for patients aged 20 to 29 years, with 4.1 ± 0.5 D, and the smallest was seen for patients aged > 50 years. Although DSA measurements showed nearly no remaining accommodative amplitude in this age group, the subjective results of Duane showed a remaining amplitude of 1 D. (1.1 ± 0.1 D) For the near linear decline of accommodative amplitude from age 20 to 50 years, Duane's curve results in a decrease of 0.26 D per year, whereas the DSA measurements show a decrease of 0.16 D per year based on linear regression models.

Comparison of Subjective and Objective Methods to Measure Accommodation

Thirteen patients chosen at random also underwent accommodation measurements using the subjective push-up

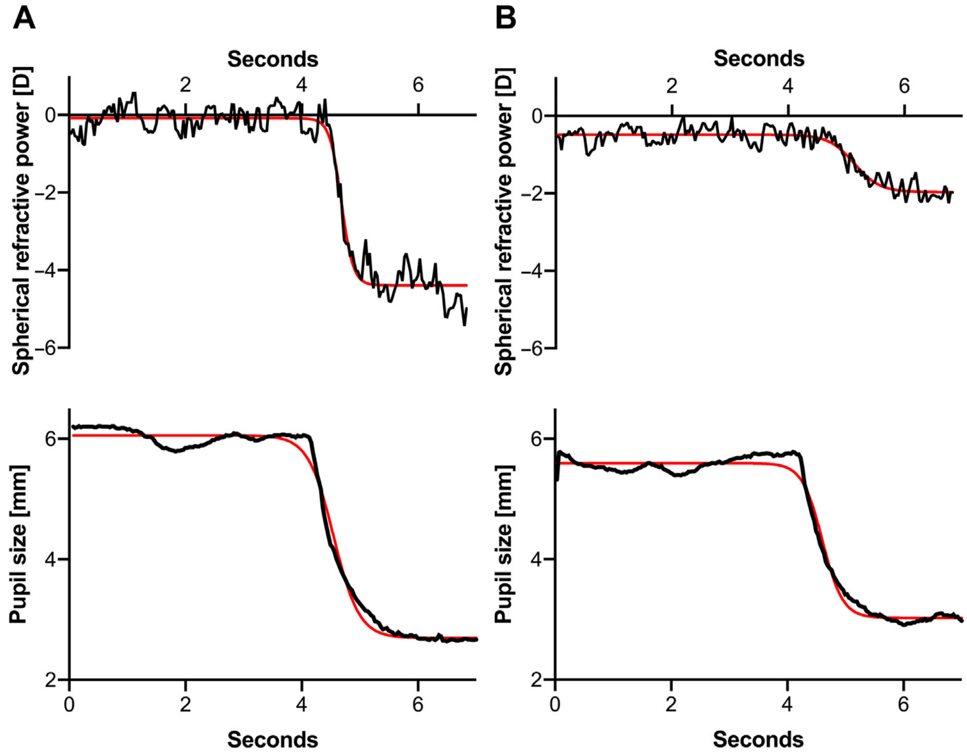

Figure 3. XY-Plots of one young and one older patient generated by dynamic stimulation aberrometry (DSA). Figure 3 depicts the XY-plots of the accommodative amplitude (black) of a 21-year-old patient (left) and a 45-year-old patient (right). The dynamic approach of the DSA method opens the possibility to see changes during the process of accommodation in parallel with pupil motility. The red line depicts sigmoidal fitting used to quantify dynamic parameters in both, accommodative and pupillary response. Maximum accommodation was defined as the span between the top and bottom part of the curve. D = diopters.

method. Figure 7 compares the accommodative amplitude for all individuals. Again, the results diverged significantly from each other ($P < 0.001$, paired t-test). No significant correlation between the 2 methods was apparent ($P = 0.51$). There was a mean difference in the accommodative amplitude of 4.2 ± 2.1 D. The greatest differences could be seen for 2 young, myopic patients (sph −3.00 D).

Comparison of Subjective Push-up Method and Historical Data of Duane

Finally, we compared the results of the subjective push-up method with the results of Duane from 1922. Figure 7 compares the accommodative amplitude for all individuals. The results were comparable; no significant differences between the historic results and the conducted subjective push-up method could be seen. There was a mean difference of 0.8 ± 1.4 D and a strong correlation (see Fig 7; $r^2 = 0.58$; $P = 0.003$).

Changes in Pupil Size

Only patients aged < 50 were included, as patients 50 and older had near to no accommodative function and therefore did not allow correlations of changes in pupil size and accommodation. Figure 8 depicts changes in maximum pupil size (during distant target view) and minimum pupil size (during near target view) with age. A weak but significant correlation with age was found with maximum pupil size ($r^2 = 0.06$; $P = 0.04$); this was not the case for minimum pupil size ($r^2 = 0.01$; $P = 0.45$). Maximum pupil motility (maximum pupil size − minimum pupil size) again showed a weak but significant correlation with age ($r^2 = 0.12$; $P < 0.02$). Finally, the ratio of pupil constriction and accommodative amplitude positively correlated weakly with increasing patient age ($r^2 = 0.39$; $P < 0.0001$). There was no significant correlation of peak velocity of pupil constriction with age ($P = 0.16$).

Discussion

In this study, we compared subjective measurements of accommodation with an objective technique to dynamically assess accommodation. The DSA technique has many advantages over other objective measurement methods. It is based on continuous wavefront measurements and is therefore not relying on correlation with morphological parameters, in contrast to ultrasound biomicroscopy and OCT. The continuous dynamic measurements allow the researcher to capture the process of accommodation as a whole; pupil size, another parameter of the near triad, is measured and analyzed simultaneously. These parameters, enabled by the dynamic approach of the measurement, might be of great interest in future studies.[21] Furthermore,

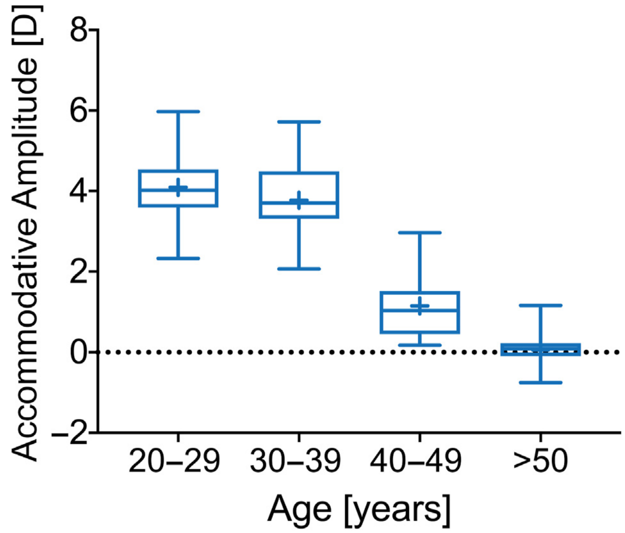

Figure 4. Boxplot of the maximum objective accommodative amplitude in different age categories. Although the accommodative amplitude shows only minimal changes for patients aged 20 to 39 years, a great decline is noted in patients aged 40 to 49 years. Subjects aged 50 years and above did not show accommodative amplitude. D = diopters.

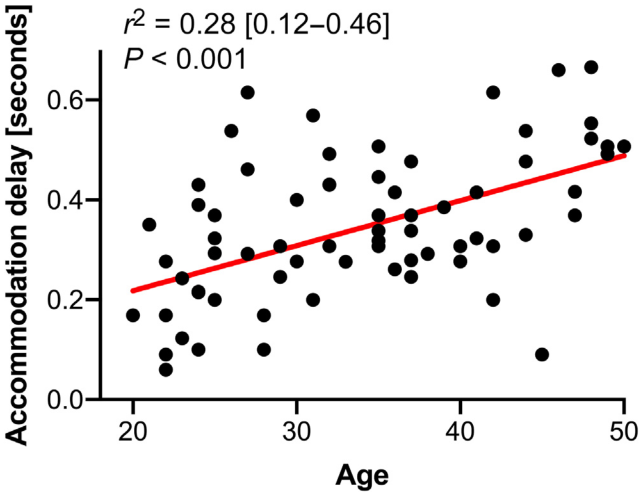

Figure 5. Delay of commencement of accommodation after near stimulus presentation.The time delay until the subject reacts to the newly presented near stimuli significantly increased with age ($P < 0.001$).

the near target is a real target that is presented to both eyes at the same time via a periscope mirror setup being visible during the entire duration of the accommodation process, thus preventing instrument myopia to occur.

This combination of benefits grants the DSA method great potential when researching accommodation, especially presbyopia and its possible corrections. The data we present also include patients with phakic anterior iris-fixated lenses showcasing that the DSA device performs well even in cases with possible alteration of higher-order aberrations. In this study, we assessed the objective accommodation using dynamic stimulation aberrometry in a large number of patients with varying age.

Effect of Age on Objective Accommodation

In line with previous literature, objective accommodative amplitude showed a strong correlation with age (r = -0.9; $P < 0.001$). Although this dynamic approach holds the great potential of the device, it also limits the range of assessable accommodation changes with the Hartmann−Shack aberrometer to 7 D, which itself limits the assessment of patients' accommodative ability within the younger age categories. Accordingly, we did not see a great difference in the accommodative amplitude between the age categories 20- to 29-year-olds and 30- to 39-year-olds. Anderson et al showed a similar change of accommodative amplitude with age using different objective, static autorefractor measurements in 230 subjects from preschool to subjects aged > 60 years. Interestingly, the near linear decline of accommodation with age can also be noted in Anderson et al. These results were further confirmed by data from Wold et al[5] and are in line with the data we gathered using the method of dynamic stimulation aberrometry. However, all studies mentioned used objective measurements that require the stimulation of the contralateral eye, whereas the eye undergoing the measurements cannot be involved in the accommodation process. This difference may play a big role in patients aged around 38 to 49 years, the patient population most prone to notice worsening of presbyopia. Win-Hall et al[22] used an autorefractor and an aberrometer in this patient population to objectively measure monocular accommodation. Indeed, the DSA measurements of our study indicate a smaller accommodative amplitude when compared with the results of Win-Hall et al. Further studies need to elucidate possible differences in accommodative amplitude between monocular and binocular stimulation. A pioneer study conducted by Otake et al[23] that used a preliminary but similar setup to the DSA device allowed target representation for an autorefractor. They reported a mean increase in the accommodative amplitude of 0.7 D when both eyes were involved in the accommodation process. In this study, we only evaluated dynamic data. There might be a difference in static and dynamic objective accommodation measurements, and no conclusion can be drawn based on the existing evidence. Win-Hall et al[24] in 2010 showed, in 15 patients, that only small differences between dynamic and static measurements occur; however, subjects were 20 to 28 years old and therefore did not struggle during dynamic measurements.

Delay in Accommodation

In this study, next to accommodative amplitude, we evaluated the delay in the initiation of accommodation after near-stimulus presentation. We saw a significant increase in this parameter with increasing age, from 0.26 ± 0.14 seconds and 0.43 ± 0.15 seconds for 20- to 29-year-old patients and 40- to 49-year-old patients, respectively. This is again in line with previous evidence; Mordi et al[25] also noticed an increase of this delay in accommodative response with age.

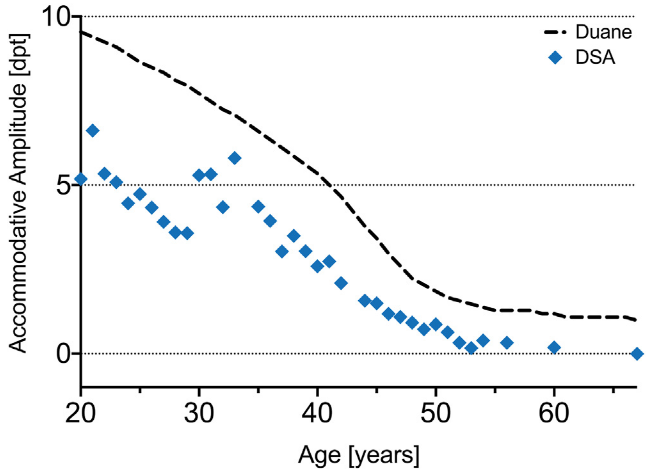

Figure 6. Comparison of dynamic stimulation aberrometry (DSA) results with historical Duane data.Subjective measures show a greater accommodative amplitude over the entire age spectrum.

Differences between Subjective and Objective Measures of Accommodation

In this study, we also compared objectively measured accommodative amplitude with subjective measures first introduced by Alexander Duane.[2] Ostrin and Glasser[4] showed a difference of 2.2 D between the push-up method, Duane's preferred method, and refractor measurements with a near stimulation of the partner eye with monocular stimulus presentation. Again, Anderson et al showed great differences in monocular subjective and objective accommodation based on autorefractor measurements and the subjective push-up test. In addition, for 13 patients chosen at random, we assessed the accommodation not only using DSA but also with the subjective push-up method. A great discrepancy between both methods must be noted. Once again, the subjective measurements far exceeded the results of the objective measurements. This difference was magnified the younger and the more myopic the patients were. The greatest difference between objective and subjective measurement was thus observed for 2 myopic (-3 D) patients aged < 30 years. The vast majority of the greater accommodative amplitude of subjective methods compared with results of the DSA measurements may originate from the subjective interpretation of the task. The subject does not differentiate between learning effects, the depth of vision through constriction of the pupil, the subjective feeling of blur, target size, target illumination, and the actual objective refractive changes of the eye.

Pupil Motility during Accommodation and Age

Next to refractive changes of the lens, we evaluated another parameter of the near triad in this study: pupil size and motility during the accommodation process. Only weak correlations between maximum pupil size and pupil motility and age were found, whereas no significant correlation was apparent for minimum pupil size and age. In contrast, the ratio of pupil constriction and the achieved accommodative amplitude increased with age. This indicates that pupil function during accommodation is preserved. This is supported by previous evidence by Kasthurirangan et al.[11]

Limitations

This study also has inherent limitations. Subjects underwent DSA measurements without correction to prevent spectacles from influencing the dynamic measurements of the wavefront. Also, other objective measurements of accommodation, such as the PowerRef 3, were established without patients wearing refractive correction. Myopic patients must accommodate less when presented with the near target at the same distance than an emmetropic patient. As such, a greater disparity between the accommodation stimulus and the actual

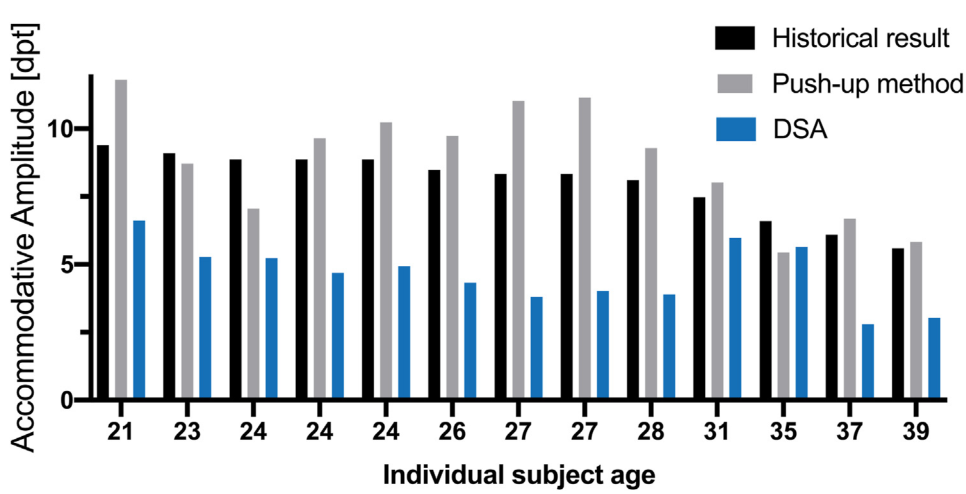

Figure 7. Comparison of the subjective push-up method to DSA and historical results from Duane. Although no statistically significant difference between the subjective push-up method and historical results from Duane were apparent, the great interindividual variability of the accommodative amplitude within 1 age category was observed. Again, the subjective push-up test showed significantly greater accommodative amplitudes when compared with the binocular objective accommodation measured by DSA. DSA = dynamic stimulation aberrometry; D = diopters.

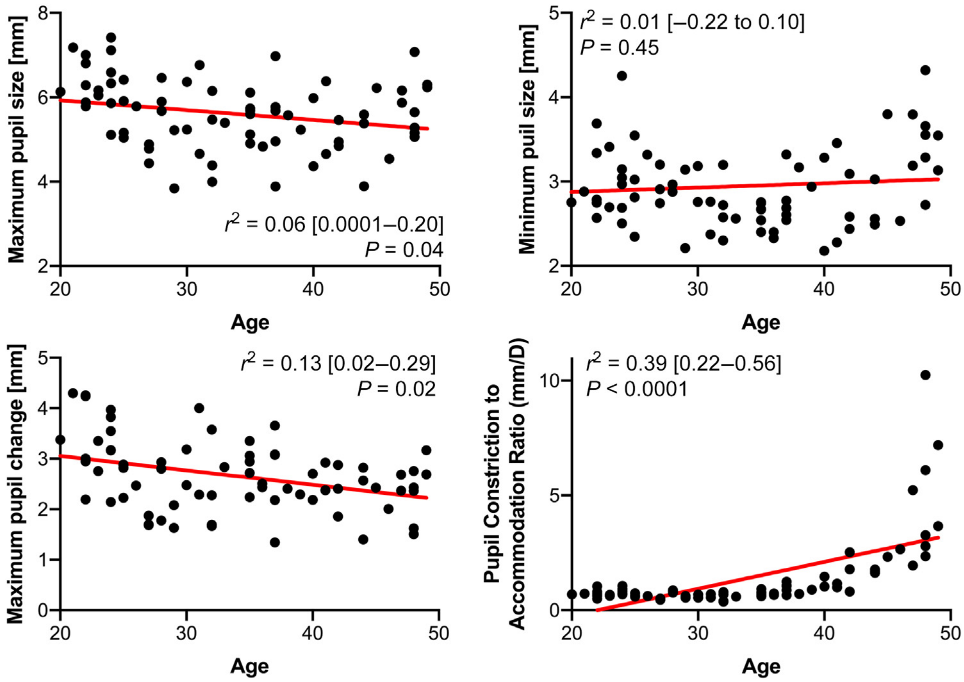

Figure 8. Changes in pupil size and motility with age measured by the dynamic stimulation aberrometry device in parallel to wavefront aberration measurements. Although no clear difference was seen in minimum pupil size, significant changes were observed for the maximum pupil size, pupil motility (maximum pupil size during far target fixation − minimum pupil size during near target fixation) and the ratio of pupil constriction to accommodative amplitude.

needed accommodative change can be seen with increasing degrees of myopia. Given the limited sensor range of 7 D of accommodation, for high-myopic subjects, no reliable data can be produced. Many of the dynamic, objective approaches to measuring accommodation, including DSA and infrared photorefraction, share this limitation. Furthermore, the error in myopic subjects may increase due to smaller margins of error in placement of the near target. In addition, it is unclear how uncorrected astigmatism might influence the accommodative stimulus induced by the near target. In future studies, dynamic, objective measures of accommodation should be evaluated with refractive correction in place, although other challenges such as overcorrection in the subjects' spectacles may play a role in this setting.

Another possible limitation could be the occurrence of accommodation fatigue due to the increasing accommodation stimulus. Accommodation fatigue is defined as the reduced performance of the accommodative system due to prolonged and/or repeated effort.[26] It is known that repeated accommodation can fatigue vergence in humans.[27] However, Vilupuru et al tested a repeated accommodation protocol without noticing a decline in the objectively measured accommodative amplitude in humans after 30 minutes of continuous accommodation and disaccommodation.[28] The study protocol of the present study with an increasing accommodative stimulus is less challenging; between measurements, subjects were able to take breaks when needed. However, accommodation fatigue still poses as a possible limitation of this study.

Conclusion

In conclusion, DSA is a method that allows dynamic measurement of accommodation. In line with other monocular objective measurements, it shows smaller accommodative amplitude than subjective measurement methods. Possible areas of application include diagnostics of presbyopia and its corrections. It can also be applied to study the effect of retinal and optic nerve disease on the accommodative function.

Footnotes and Disclosures

Originally received: November 29, 2022.
Final revision: March 24, 2023.
Accepted: April 6, 2023.
Available online: April 13, 2023. Manuscript no. XOPS-D-22-00254R2.

[1] David J. Apple International Laboratory for Ocular Pathology, Heidelberg, Germany.

[2] Department of Ophthalmology, University Hospital Heidelberg, Heidelberg, Germany.

Disclosures:

All authors have completed and submitted the ICMJE disclosures form.

G.U.A.: Grants to conduct independent research − Alcon, AMO/Johnson & Johnson, Biotech, Carl Zeiss Meditec, Contamac, Cristalens, Croma, EyeYon, Hanita, Hoya, Kowa, Teleon, Oculus; Consulting fees − Alcon,

AMO/Johnson & Johnson, Carl Zeiss Meditec, Cristalens, EyeYon, Presbia, Rayner, SIFI, VSY; Travel expenses − Alcon, AMO/Johnson & Johnson, Carl Zeiss Meditec, EyeYon, Hoya, Kowa, Teleon, Rayner, SIFI, Ursapharmc.

G.U.A.: Supported by the Klaus-Tschira-Foundation. The funding organization had no role in the design or conduct of this research.

HUMAN SUBJECTS: Human subjects were included in this study. This study was conducted in accordance with internationally recognized guidelines, including Good Clinical Practice and the Declaration of Helsinki. The local Institutional Review Board of the Medical Faculty of Heidelberg approved this study. Written consent was obtained from all patients.

No animal subjects were used in this study.

Author Contributions:

Conception and design: Hammer, Heggemann, Auffarth

Data collection: Hammer, Heggemann, Auffarth

Analysis and interpretation: Hammer, Auffarth

Obtained funding: Auffarth

Overall responsibility: Hammer, Heggemann, Auffarth

Abbreviations and Acronyms:
D = diopters; **DSA** = dynamic stimulation aberrometry; **IOLs** = intraocular lenses.

Keywords:
Dynamic wavefront measurement, Accommodation, Aberrations, Pupil motility, Objective accommodation.

Correspondence:
Gerd U. Auffarth, MD, PhD, David J. Apple International Laboratory for Ocular Pathology, International Vision Correction Research Centre, Department of Ophthalmology, Ruprecht-Karls University of Heidelberg, Im Neuenheimer Feld 400, 69120 Heidelberg, Germany. E-mail: gerd.auffarth@med.uni-heidelberg.de.

References

1. Schachar RA. The mechanism of accommodation and presbyopia. *Int Ophthalmol Clin*. 2006;46:39−61.
2. Duane A. Studies in monocular and binocular accommodation, with their clinical application. *Trans Am Ophthalmol Soc*. 1922;20:132−157.
3. Anderson HA, Stuebing KK. Subjective versus objective accommodative amplitude: preschool to presbyopia. *Optom Vis Sci*. 2014;91:1290−1301.
4. Ostrin LA, Glasser A. Accommodation measurements in a prepresbyopic and presbyopic population. *J Cataract Refract Surg*. 2004;30:1435−1444.
5. Wold JE, Hu A, Chen S, Glasser A. Subjective and objective measurement of human accommodative amplitude. *J Cataract Refract Surg*. 2003;29:1878−1888.
6. Alio JL, Simonov A, Plaza-Puche AB, et al. Visual outcomes and accommodative response of the lumina accommodative intraocular lens. *Am J Ophthalmol*. 2016;164:37−48.
7. Ramasubramanian V, Glasser A. Can ultrasound biomicroscopy be used to predict accommodation accurately? *J Refract Surg*. 2015;31:266−273.
8. Ramasubramanian V, Glasser A. Prediction of accommodative optical response in prepresbyopic subjects using ultrasound biomicroscopy. *J Cataract Refract Surg*. 2015;41:964−980.
9. Ramasubramanian V, Glasser A. Objective measurement of accommodative biometric changes using ultrasound biomicroscopy. *J Cataract Refract Surg*. 2015;41:511−526.
10. Neri A, Ruggeri M, Protti A, et al. Dynamic imaging of accommodation by swept-source anterior segment optical coherence tomography. *J Cataract Refract Surg*. 2015;41:501−510.
11. Kasthurirangan S, Glasser A. Age related changes in the characteristics of the near pupil response. *Vision Res*. 2006;46:1393−1403.
12. Kasthurirangan S, Glasser A. Age related changes in accommodative dynamics in humans. *Vision Res*. 2006;46:1507−1519.
13. Kasthurirangan S, Glasser A. Influence of amplitude and starting point on accommodative dynamics in humans. *Invest Ophthalmol Vis Sci*. 2005;46:3463.
14. Labhishetty V, Bobier WR, Lakshminarayanan V. Is 25 Hz enough to accurately measure a dynamic change in the ocular accommodation? *J Optom*. 2019;12:22−29.
15. Ghahghaei S, Reed O, Candy TR, Chandna A. Calibration of the PlusOptix PowerRef 3 with change in viewing distance, adult age and refractive error. *Ophthalmic Physiologic Optic*. 2019;39:253−259.
16. Ehmer A, Mannsfeld A, Auffarth GU, Holzer MP. Dynamic stimulation of accommodation. *J Cataract Refract Surg*. 2008;34:2024−2029.
17. Nennstiel M, Kunert K, Dick M, et al. Dynamische Aberrometrie der Akkommodation mit binokularer Stimulation. *Klin Monatsbl Augenheilkd*. 2007;224:s-2007-984626. 10.1055/s-2007-984626.
18. Duane A. A modified accommodation line and Prince's Rule. *Trans Am Ophthalmol Soc*. 1921;19:178−179.
19. Faul F, Erdfelder E, Buchner A, Lang AG. Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses. *Behav Res Methods*. 2009;41:1149−1160.
20. Faul F, Erdfelder E, Lang A-G, Buchner AG. *Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods*. 2007;39:175−191.
21. Pourreza ghoushchi V, Prieto P, Artal P. Speed of accommodation responses in myopes. *Invest Opthalmol Vis Sci*. 2019;60:1791−1791.
22. Win-Hall DM, Glasser A. Objective accommodation measurements in pseudophakic subjects using an autorefractor and an aberrometer. *J Cataract Refract Surg*. 2009;35:282−290.
23. Otake Y, Miyao M, Ishihara S, et al. An experimental study on the objective measurement of accommodative amplitude under binocular and natural viewing conditions. *Tohoku J Exp Med*. 1993;170:93−102.
24. Win-Hall DM, Houser J, Glasser A. Static and dynamic accommodation measured using the WAM-5500 autorefractor. *Optom Vis Sci*. 2010;87:873−882.
25. Mordi JA, Ciuffreda KJ. Dynamic aspects of accommodation: age and presbyopia. *Vision Res*. 2004;44:591−601.
26. Hasebe S, Graf EW, Schor CM. Fatigue reduces tonic accommodation. *Ophthalmic Physiol Opt*. 2001;21:151−160.
27. Yuan W, Semmlow JL. The influence of repetitive eye movements on vergence performance. *Vision Res*. 2000;40:3089−3098.
28. Vilupuru AS, Kasthurirangan S, Glasser A. Dynamics of accommodative fatigue in rhesus monkeys and humans. *Vision Res*. 2005;45:181−191.