OPO OPHTHALMIC & PHYSIOLOGICAL OPTICS
THE JOURNAL OF THE COLLEGE OF OPTOMETRISTS

Ophthalmic & Physiological Optics ISSN 0275-5408

Age-related changes in accommodation measured with a double-pass system

Mikel Aldaba, Meritxell Vilaseca, Montserrat Arjona and Jaume Pujol

Centre for Sensors, Instruments, and Systems Development (CD6), Universitat Politecnica de Catalunya (UPC), Barcelona, Spain

Citation information: Aldaba M, Vilaseca M, Arjona M & Pujol J. Age-related changes in accommodation measured with a double-pass system. *Ophthalmic Physiol Opt* 2013, **33**, 508–515. doi: 10.1111/opo.12038

Keywords: accommodation, accommodative response, ageing, double pass technique, retinal image quality

Correspondence: Mikel Aldaba
E-mail address: aldaba@cd6.upc.edu

Received: 7 November 2012; Accepted: 7 January 2013

Abstract

Purpose: To measure the accommodative response in a wide age range population using the retinal image quality assessments provided by a double-pass system.
Methods: The accommodative response was measured using a custom-built double-pass setup in 84 patients from 15 to 55 years of age. Patients were classified in four groups (A: 15–25 year old; B: 26–35; C: 36–45; D: 46–55). Accommodation was stimulated from 0 to 5 dioptres (D) with the push up method using an open field fixation test. The total accommodative response in the stimulated range, the accommodative stimulus-response curve, the slope and the progression of optical quality with accommodation were measured.
Results: The total accommodation obtained in groups A and B was high, with a mean value of 4 D or higher, whereas values in older individuals were significantly lower. The accommodative stimulus-response curve and the slope were also high with a sudden decrease in patients over 35 years of age. The optical quality of the eye during accommodation did not change significantly.
Conclusions: Participants aged 15–35 years showed a good accommodative response. Thereafter, a significant decrease of the response in the total accommodation, stimulus response curve and slope was observed. The younger groups showed a larger accommodative response than previously published.

Introduction

The mechanism of accommodation is affected by age-related changes,[1] that have been studied for many years.[2] Several studies have focused on the loss of amplitude of accommodation with age.[3–6] These studies report a continuous decrease in the amplitude of accommodation of around 0.3 D per year, with the onset of presbyopia occurring between 35 and 40 years of age. Another development of the ageing eye in relation to accommodation is the change in the accommodative stimulus-response curve (ASRC). Some authors[6–8] have highlighted that the slope of the ASRC decreases slightly until the age of 40–45, with a sudden reduction of the slope thereafter. The importance of the study of the ASRC with age relates to the theories that explain the accommodative mechanism. According to the Duane–Fincham theory, the amount of ciliary muscle contraction required for a given change in accommodation increases throughout life[1]; consequently, the slope of the ASRC decreases with age. On the other hand, the Hess–Gullstrand theory states that this required contraction is constant during life[1]; accordingly, the slope of the accommodative response curve should not change with age.

Accommodation is usually measured with simple subjective techniques based on increasing the accommodative demand of a fixation test until it begins to blur.[9] These techniques, in comparison with objective methods, provide an overestimation of the accommodation due to depth of focus.[10] Moreover, the method for stimulating accommodation can also influence the result due to the magnification of the test. In the push up method, accommodation is stimulated by moving the test chart towards the patient's eyes and as a consequence there is an increase of the angular size at higher accommodative demands. On the other hand, if accommodation is stimulated by means of negative lenses the angular size of the test decreases. Some authors[4] have reported a difference in the amplitude of accommodation of 1.72 D when comparing both methods.

Several objective techniques can measure the accommodative response: dynamic retinoscopy,[11] autorefractors,[12] photorefraction[13] and aberrometers.[14,15] Recently, aberrometric measurements have shown that spherical aberration could be responsible for a false lag of accommodation since a certain amount of defocus could be necessary to enhance retinal image quality.[16,17] Consequently, global image quality-based measurements seem more appropriate than techniques based just on defocus measurements. The suitability of a double-pass system for measuring accommodative response based on image quality has been shown in a recent study.[18]

The double-pass technique, based on recording images of a point-source object after reflection on the retina and a double-pass through the ocular media,[19] has been widely used in laboratory and daily clinical practice to assess the retinal image quality in different conditions like the ageing eye[20,21] or the effects of refractive surgery and intraocular lenses.[22] A single report has shown the applicability of this method to the study of accommodation.[23] However, this study reports a comparison of the retinal image quality of the accommodated and unaccommodated eye rather than the actual accommodative response. López–Gil and collaborators found no differences in the optical quality of the accommodated and unaccommodated eye, unlike other authors that used a Hartmann–Shack aberrometer.[24] Other studies have found a similar optical quality up to 3 D of accommodation and a worsening in higher accommodative responses.[25,26] Finally, a study that used a Hartmann–Shack aberrometer and which included patients with a broad age range[27] found a small but constant decrease of the optical quality with accommodation.

The main goal of this study was to measure the accommodative response in a population with a wide age range using the double-pass technique. Firstly, we measured the total accommodative response that occurred when stimulating from 0 to 5 D. Secondly, we assessed the ASRC and its slope for the accommodative stimulation range. Finally, we analysed optical quality progression during accommodation. To our knowledge, no study assessing the accommodative response in a broad age range population using a technique based on recording the retinal image quality and therefore taking into account all aberrations has previously been published.

Methods

Subjects

This prospective study was conducted on healthy adults. All subjects or legal representatives gave their written informed consent after a written and verbal explanation of the nature and aims of the study. The research followed the tenets of the Declaration of Helsinki and was approved by the Ethics Committee. The criteria for inclusion were as follows: best spectacle-corrected visual acuity of 0.00 logMAR (Snellen 6/6 or 20/20) or better, and no history of any ocular condition, eye surgery and/or pharmacological treatment. Eighty-four subjects, forty-five male and thirty-nine female, were eventually enrolled in the study. Measurements were carried out in only one eye: due to the configuration setup, the left eye was chosen in all cases. The mean age ($\pm$ standard deviation) was 34.9 $\pm$ 12.3 years (range: 15–55 years). The mean uncorrected visual acuity was 0.17 $\pm$ 0.31 logMAR (Snellen 6/9 or 20/30; range: 1.30 ––0.08), and the mean best spectacle-corrected visual acuity was -0.05 ± 1.00 (Snellen 6/5 or 20/15; range: 0.00–-0.08). The mean spherical refractive error was -1.01 ± 1.72 dioptres (D) (range: +3.00––8.00 D), and the mean cylindrical refraction was -0.46 ± 0.45 D (range: 0.00––1.75 D). Patients were divided in four groups according to their age: group A (range: 15–25 years), group B (range: 26–35 years), group C (range: 36–45 years) and group D (range: 46–55 years). Mean age $\pm$ S.D., uncorrected visual acuity, best spectacle-corrected visual acuity and refraction for the different groups are shown in *Table 1*.

Setup

Accommodative response measurements were carried out using an experimental double-pass setup[19] developed in our laboratory, as shown in *Figure 1*. The setup and measurement procedures were similar to those described by Aldaba and collaborators.[18] In the first pass, a point source is projected on the retina of the subject. An infrared laser diode (LD, λ = 780 nm) coupled to an optical fibre is collimated and passes through a 2 mm diameter diaphragm, which acts as the entrance pupil (EP) of the system and is conjugated to the subject's pupil plane. After retinal reflection and a double-pass through the ocular media, double-pass images are recorded with a digital CCD (charge-coupled device) camera. Since no diaphragm is placed in the second pass, the pupil of the patient acts as the exit pupil of the system.

The vergence of the laser beam is changed by means of a Badal system (L_2, L_3, M_2, M_3). A black and white Maltese cross containing a wide range of frequencies, presented on a monitor screen with a luminance of 20 cd m^{-2} and viewed through open field is used as fixation test (FT). Although there is a magnification effect when moving the test toward, even for the closest positions of the test the Maltese cross presents high enough frequencies to properly stimulate accommodation. A CCD camera is used for pupil monitoring and centring.

Table 1. Study groups. Number of patients (*n*), mean age in years (±S.D.), uncorrected visual acuity (UCVA), best spectacle-corrected visual acuity (BSCVA) and sphere and cylinder in dioptres (D).

					Refraction	
Group	***n***	**Age (years)**	**UCVA (logMAR)**	**BCVA (logMAR)**	**Sphere (D)**	**Cylinder (D)**
A	24	20.5 ± 3.8	0.19 ± 0.29	−0.06 ± 1.05	−1.30 ± 1.93	−0.47 ± 0.51
B	20	29.8 ± 2.6	0.12 ± 0.29	−0.06 ± 1.05	−1.13 ± 2.05	−0.40 ± 0.36
C	20	41.2 ± 3.6	0.10 ± 0.31	−0.05 ± 1.00	−0.92 ± 1.47	−0.31 ± 0.53
D	20	51.3 ± 4.6	0.23 ± 0.38	−0.05 ± 1.00	−0.44 ± 1.22	−0.42 ± 0.54

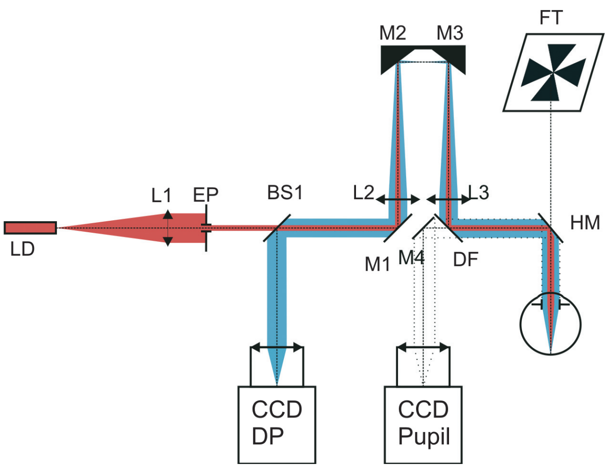

Figure 1. Diagram of the double-pass setup. LD: Laser diode; L1, L2, L3: lenses; BS1: Beamsplitter; M1, M2, M3, M4: Mirrors; DF: Dichroic filter; HM: Hot mirror; EP: Entrance pupil; FT: Fixation Test; CCD-DP, CCD-Pupil: CCD cameras used for the double-pass and pupil monitoring, respectively.

Measurement procedures

All subjects underwent an optometric examination performed by the same qualified examiner to analyse their left eye. Refractive state was assessed by means of the Grand Seiko Auto Ref/Keratometer WAM-5500,[28] streak retinoscopy and subjective refraction. Uncorrected visual acuity, stenopeic visual acuity and best spectacle-corrected visual acuity were also evaluated.

Subjects were placed in front of the setup with their head on a chinrest, wearing their subjective refraction on the left eye and with the right eye occluded. They were instructed to fix and try to see clearly the fixation test. Accommodation was stimulated by means of the push up method in the range from 0 to 5 D with a 1 D step. The accommodative response was calculated aiming at the best double-pass image of a through focus scanning performed with the Badal system. The vergence of the best double-pass image was then associated with the accommodative response value, as shown in *Figure 2*. To determine the best double-pass image and assess the corresponding optical quality, the metric used was the volume under the Modulation Transfer Function, which has been shown to be a good predictor of the refractive state of the eye.[29]

Similarly to previous studies,[18] the accommodative response cross over point was set at 1 D to offset the system, i.e. there was no accommodative error at 1 D of stimulation.

Since participants were corrected with spectacles during measurements, lens effectivity formulae were applied both for accommodation stimulations and response calculations as shown in equations (1) and (2). Specifically, we applied Mutti's effectivity formulae,[17,30]

$$AS = \frac{1}{\frac{1}{\frac{1}{D_{vertex} - D_{Test}} + P_{lens}} - D_{vertex}} - Rx \qquad (1)$$

$$AR = \frac{1}{\frac{1}{\frac{1}{RawAR} + D_{vertex}} + P_{lens}} - D_{vertex}} - Rx \qquad (2)$$

where AS is the accommodative stimulation, AR is the accommodative response, Rx is the subjective refraction of

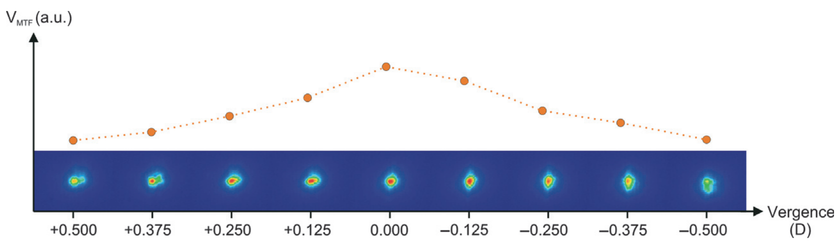

Figure 2. Example of double-pass images acquired along the through focus scanning (bottom) and the volume under the Modulation Transfer Function (V_{MTF}) in arbitrary units (a.u.) for each image (top). The vergence (in dioptres) that maximizes the retinal image quality, and thus the accommodative response, is 0.0 D in this case.

the subject, P_{lens} is the power of the trial lens and *RawAR* is the raw measured accommodative response (in dioptres). D_{vertex} is the vertex distance and D_{Test} is the test distance (in metres).

The total accommodative response was calculated as the difference between the maximum and minimum accommodative response in the stimulated range, i.e. from 0 to 5 D. Note that this could differ from the amplitude of accommodation in some cases, particularly in the younger groups, where some patients did not reach their accommodative limit.

The slope of the ASRC was calculated according to published studies.[6,8] Regression lines were fitted to accommodative stimulus response data in the range where the response was linear. The slope was thereafter calculated as the gradient of the fitting line.

Statistics

Statistical analysis was performed using commercial SPSS software for Windows (www.ibm.com/software/uk/analytics/spss). A *p* value of 0.05 was considered significant. The Kolmogorov–Smirnov test was used to evaluate the normal distribution of all variables analysed. In order to compare results from different groups, one-way ANOVA was carried out with a *post hoc* Tukey analysis.

Results

Total accommodation

The total accommodative response was calculated as the difference between the maximum and minimum accommodative response in the stimulated range, i.e. from 0 to 5 D. *Figure 3* shows the total accommodative response that occurs when stimulating up to 5 D for all patients. When dividing by age groups, the total accommodative responses were 4.51 ± 0.38 D (group A), 4.05 ± 0.67 D (group B), 2.79 ± 1.15 D (group C) and 0.73 ± 0.33 D (group D). The results showed a normal distribution according to the Kolmogorov–Smirnov test ($p > 0.05$) and significant differences between groups when applying the ANOVA analysis were found ($p < 0.001$). The *post hoc* Tukey test showed no differences between the youngest groups A and B ($p = 0.19$). However, differences in all the other comparisons among groups were found ($p < 0.001$).

Accommodative stimulus-response curve

The ASRC was measured in the different age groups as shown in *Figure 4*. The accommodative response results for every stimulation had a normal distribution according to the Kolmogorov–Smirnov test ($p > 0.05$) and significant differences between groups when applying the ANOVA analysis ($p < 0.001$) for stimulations higher than 1 D were found. *Table 2* shows the ANOVA values for each comparison and the *post hoc* Tukey values comparing different groups.

Slope

The slope of the ASRC for all patients is shown in *Figure 5*. When dividing by age groups, the slope was as follows: 0.93 ± 0.05 (group A), 0.85 ± 0.11 (group B), 0.66 ± 0.23 (group C) and 0.18 ± 0.08 (group D). The results had a normal distribution according to the Kolmogorov–Smirnov test ($p > 0.05$) and significant differences between groups when applying the ANOVA analysis ($p < 0.001$) were found. The *post hoc* Tukey shows no

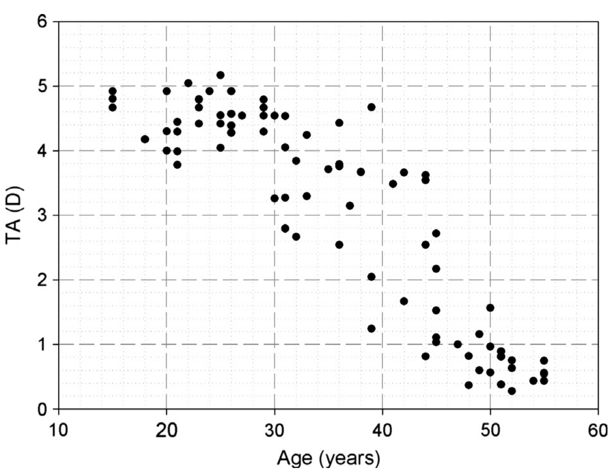

Figure 3. Scatter plot of age and total accommodative response (TA) when stimulating accommodation up to 5 D for all patients.

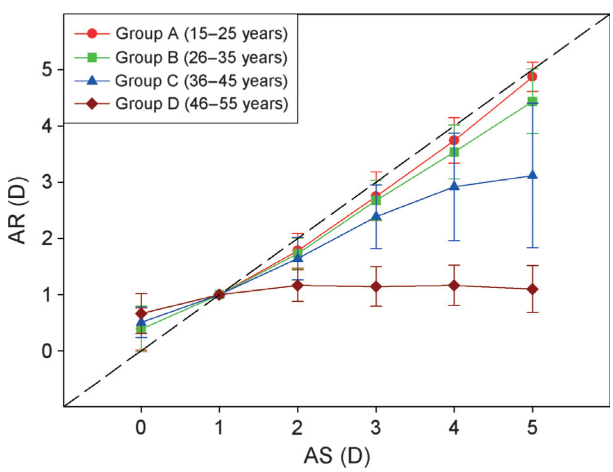

Figure 4. Comparison of the ASRC in the different age groups. The mean accommodative response (AR) with (±S.D.) is plotted against the accommodative stimulation (AS) for each case (D: dioptres).

Table 2. ANOVA and *post hoc* Tukey *p* values for the accommodative response at the different accommodative stimulations (AS) and groups. (D: dioptres).

	AS 0 D	AS 1 D	AS 2 D	AS 3 D	AS 4 D	AS 5 D
ANOVA						
A-B-C-D	0.064**	1**	<0.001	<0.001	<0.001	<0.001
Post hoc (Tukey)						
A-B	1**	1**	0.95**	0.95**	0.66**	0.25**
A-C	0.70**	1**	0.45**	0.036	<0.001	<0.001
A-D	0.08**	1**	<0.001	<0.001	<0.001	<0.001
B-C	0.73**	1**	0.79**	0.16**	0.007	<0.001
B-D	0.10**	1**	<0.001	<0.001	<0.001	<0.001
C-D	0.58**	1**	<0.001	<0.001	<0.001	<0.001

**Non-significant differences.

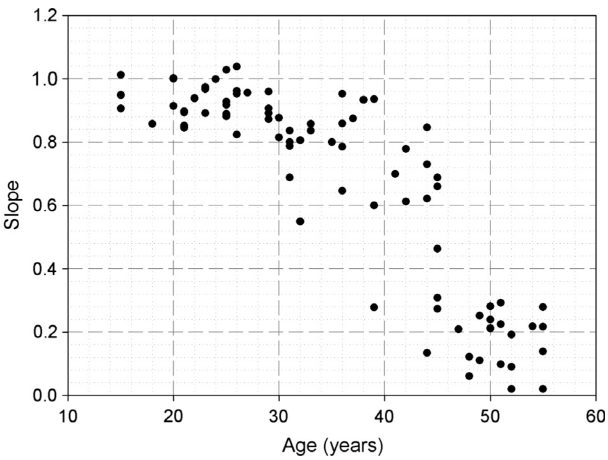

Figure 5. Scatter plot of ASRC and age for all patients.

difference between the younger groups A and B ($p = 0.24$), and differences in all the other comparisons among groups ($p < 0.001$).

Optical quality

Finally, changes in the optical quality with accommodation were studied for the different age groups. *Figure 6* shows the evolution of the double-pass image quality, measured as the volume under the Modulation Transfer Function, with accommodation. When performing a regression on the measured data, no significant correlations were found due to the high inter-subject variability: group A (all $r^2 < 0.01$, $p > 0.34$).

The mean baseline optical quality for the different groups was as follows: 6.50 ± 1.18 (group A), 5.76 ± 1.33 (group B), 5.62 ± 1.39 (group C) and 5.37 ± 1.29 (group D). The results had a normal distribution according to the Kolmogorov–Smirnov test ($p > 0.05$) and significant differences among groups when applying the ANOVA analysis were found ($p = 0.041$). The *post hoc* Tukey showed differences between groups A and D ($p = 0.038$), and no differences in any of the other comparisons between groups ($p > 0.05$). The mean baseline pupil diameter for the different groups was 6.01 ± 0.82 mm (group A), 5.70 ± 0.92 mm (group B), 5.58 ± 1.00 mm (group C) and 4.84 ± 0.92 mm (group D).

Discussion

In this study we have measured the accommodative response in a wide age range population when stimulating from 0 to 5 D using a method based on measuring the best image quality provided by a double-pass system. We measured the total accommodation that occurs when stimulating from 0 to 5 D as the difference between the maximum and minimum accommodative responses. We found a large total accommodation in the two younger groups (A and B) with no significant differences between them, whereas a noticeable decrease was detected in patients over 35 years of age. Other authors who used photorefraction[31] have already published similar data, although only the accommodative response at 5 D stimulation rather than the total accommodation was included. The most remarkable difference between our study and that reported by Kasthurirangan and colleagues is a larger accommodative response found in our younger population groups. This discrepancy can be attributed to the use of different measuring techniques. In a previous study, Aldaba and collaborators[18] measured higher accommodative responses than formerly published, probably as a result of the use of a technique based on optical quality metrics. It has already been suggested that a certain amount of accommodative error could be used to enhance the retinal image quality[16,17]; therefore defocus-based measurements could underestimate the accommodative response in comparison with retinal quality measurements. In the older population, we can assume that our total accommodation data equals the amplitude of accommodation measurements. In comparison with previous subjective amplitude of accommodation measurements,[3–5] we have found a significantly lower amplitude of accommodation in the older participants. While these studies reported an amplitude of accommodation for groups C and D of circa 5 and 2 D, our analysis showed a total accommodative response for the same groups of 2.79 ± 1.15 and 0.73 ± 0.33 D, respectively. This discrepancy could be attributed to the differences between subjective and objective measuring methods. Other authors[14] have already mentioned significant differences between subjective and objective measurements, with subjective measurements overestimating the amplitude of accommodation by almost 2 D. On the other hand, objective amplitude of accommodation measurements made by other authors are

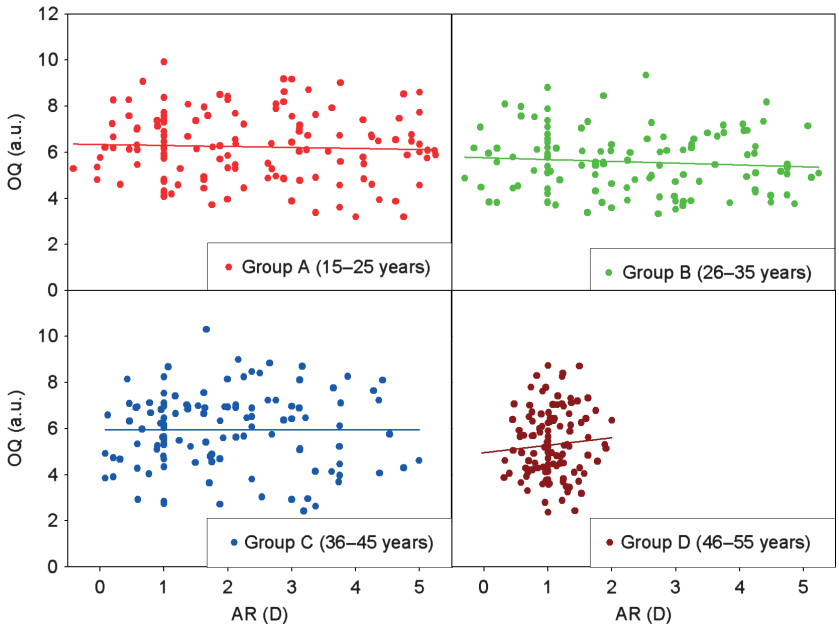

Figure 6. Change in optical quality (OQ) in arbitrary units (a.u.) as a function of accommodative response (AR) in the different age groups.

more in line with our results than the subjective measurements; Ostrin and collaborators[32] measured an amplitude of 2.5 D and 0.95 D for the C and D age groups, and Win–Hall[14] an amplitude of 2.9 D for the age range from 38 to 49 years.

The analysis of the ASRC showed a highly accurate response in the two younger groups (A and B), whereas a significantly decreased response was found in the older groups (C and D). Similar to the assessment of total accommodation, the mean ASRC was more accurate in group A, although no significant differences with group B were found. The ASRC in the younger groups was slightly more accurate than that previously published by Kalsi and colleagues,[8] and noticeably more accurate than the ASRC measured by Iida.[24] This could be explained by the measuring technique used: larger accommodative responses are obtained when optical quality metrics instead of defocus-based techniques are used. Moreover, another source of differences when comparing Iida's work with ours could be the accommodative stimulation as Iida used a Badal system while we stimulated with a push-up method. Group D was significantly different from all the others, and group C was similar to group A for up to 2 D of stimulation and for up to 3 D when compared with group B, which underlines the noticeable changes in the accommodative response in patients over 35 years of age.

The evolution of the ASRC slope with age agrees with the findings from several authors[6–8,33]: the slope decreases slightly until middle age, falling sharply thereafter. There are some differences in the literature regarding the age in which the slope starts to fall more abruptly: while some authors[6,7] did not find significant changes in the response slope until 45 years of age or over, others[8,33] brought forward this age to 40. Our data match the two last studies mentioned, with a more pronounced change in the slope decrease beginning at the age of 40. The discrepancies between similar studies could be explained by the differences in determining the linear region of the accommodative stimulus response or by the smaller number of patients in the first two reports (Ramsdale *et al.* one patient; Mordi *et al.* 30 patients) in comparison with the other studies (Kalsi *et al.* 49 patients; Radhakrishnan *et al.* 47; and 84 patients in the current study). The evolution of the slope of the ASRC with age could be used in order to support the two main theories explaining the mechanism of presbyopia. The results in our study do not agree with the expectations from both theories, as we can assume constant slope until middle age and a decreasing slope thereafter. In this sense, we agree with the interpretation made by other authors,[8] Duane–Fincham and Hess–Gullstrand theories can be oversimplifications of the complex mechanism of presbyopia.

With regard to optical quality, other authors have already reported a decrease with age[20,21,33–35] of the baseline or far vision optical quality. In our study, we only found a significant differences among groups when comparing the youngest versus the oldest groups. The reason for this difference with other studies could be the use of the natural pupil of the patient in our measurements. As pointed by other authors[21] age-related optical quality differences are reduced when using natural pupils as the age-related miosis compensates for increases in aberrations and light scattering.

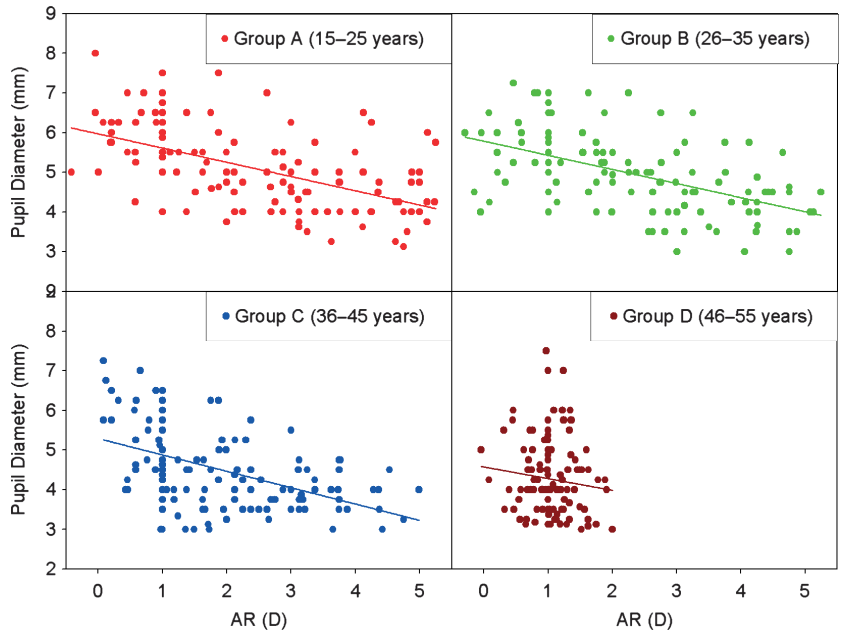

Figure 7. Change in pupil diameter in millimetres (mm) as a function of accommodative response (AR) in the different age groups.

We found also a slight worsening of optical quality with accommodation, although this change was small and not significant. In the case of group D, the fitted line shows an increase (positive slope) of the optical quality with accommodation. Possible explanations of these results are the narrow width in the accommodative response axis, inter-subject variability and the possibility of having a pupillary miosis due to proximity of the fixation test, by which the patient is unable to accommodate. Some authors[24] found no differences when comparing the root mean square of the aberrations (RMS) measured with a Hartmann–Shack device with accommodation. In addition, when using the double-pass technique, similar Modulation Transfer Functions were obtained in the accommodated and unaccommodated eye.[23] Other authors[25,26] found similar RMS in the range 0–3 D, and increasing differences in higher accommodative stimulations. On the other hand, Li and colleagues[36] found significant differences between the accommodated and unaccommodated eye (accommodative stimulation=2.5 D) for 5 mm pupils, while no differences for 3 mm pupils were reported. López–Gil and collaborators[27] registered a progressive RMS worsening for different age groups. Although several studies report a slight worsening in the optical quality with accommodation, consensus has not been reached on this topic. Our study detected a slightly worse optical quality in the accommodated eye but a conclusion cannot be reached due to the great inter-subject variability. Some authors[27] have found a more noticeable change of the optical quality with the accommodative response when using fixed pupils instead of natural pupils. In our measurements natural pupils were used and the evolution of pupil diameter with accommodative response is shown in *Figure 7*, where the well known accommodative miosis can be appreciated. Thus, in our measurements under real viewing conditions with natural pupils, the increase of aberrations with accommodation is partially compensated by the accommodative miosis. Consequently there is just a slight optical quality worsening with accommodation.

In conclusion, our study includes a large number of participants and shows that the accommodation measured using the double-pass technique is generally in agreement with previously published research. However, we found some differences attributable to the measuring technique based on optical quality metrics. In this context larger accommodative responses were found in younger patients.

Acknowledgments

This study was partially funded by the Spanish Ministry of Science and Innovation with the project grant DPI2008-06455-C02-01, and the European Union. Mikel Aldaba would like to thank the Spanish Ministry of Science and Innovation for his awarded Ph.D. studentship.

Disclosure

The authors report no conflicts of interest and have no proprietary interest in any of the materials mentioned in the article.

References

1. Atchison DA. Accommodation and presbyopia. *Ophthalmic Physiol Opt* 1995; 15: 255–272.
2. Donders FC. *On the anomalies of accommodation and refraction of the eye*. The New Sydenham Society: London, 1864; pp. 204–232.
3. Duane A. Studies in monocular and binocular accommodation, with their clinical application. *Trans Am Ophthalmol Soc* 1922; 20: 132–157.
4. Kragha IK. Amplitude of accommodation: population and methodological differences. *Ophthalmic Physiol Opt* 1986; 6: 75–80.
5. Brückner R, Batschelet E & Hugenschmidt F. The Basel longitudinal study on aging (1955-1978). Ophthalmo-gerontological research results. *Doc Ophthalmol* 1987; 64: 235–310.
6. Mordi JA & Ciuffreda KJ. Static aspects of accommodation: age and presbyopia. *Vision Res* 1998; 38: 1643–1653.
7. Ramsdale C & Charman WN. A longitudinal study of the changes in the static accommodation response. *Ophthalmic Physiol Opt* 1989; 9: 255–263.
8. Kalsi M, Heron G & Charman WN. Changes in the static accommodation response with age. *Ophthalmic Physiol Opt* 2001; 21: 77–84.
9. Rabbetts RB. *Clinical visual optics*. 4th Edition. Elsevier-Butterworth Heinemann: London, 2007.
10. Wold JE, Hu A, Chen S & Glasser A. Subjective and objective measurement of human accommodative amplitude. *J Cataract Refract Surg* 2003; 29: 1878–1888.
11. Campbell E, Benjamin WJ & Howland HC. Objective refraction: retinoscopy, autorefraction and photorefraction. *Borish's Clinical refraction*. W.B. Saunder: Philadelphia, 1998.
12. McBrien NA & Millodot M. The effect of refractive error on the accommodative response gradient. *Ophthalmic Physiol Opt* 1986; 6: 145–149.
13. Seidemann A & Schaeffel F. An evaluation of the lag of accommodation using photorefraction. *Vision Res* 2003; 43: 419–430.
14. Win-Hall DM & Glasser A. Objective accommodation measurements in prepresbyopic eyes using an autorefractor and an aberrometer. *J Cataract Refract Surg* 2008; 34: 774–784.
15. Tarrant J, Roorda A & Wildsoet CF. Determining the accommodative response from wavefront aberrations. *J Vis* 2010; 10: 1–16.
16. Plainis S, Ginis HS & Pallikaris A. The effect of ocular aberrations on steady-state errors of accommodative response. *J Vis* 2005; 5: 466–477.
17. Buehren T & Collins MJ. Accommodation stimulus-response function and retinal image quality. *Vision Res* 2006; 46: 1633–1645.
18. Aldaba M, Vilaseca M, Díaz-Doutón F, Arjona M & Pujol J. Measuring the accommodative response with a double-pass system: comparison with the Hartmann-Shack technique. *Vision Res* 2012; 62: 26–34.
19. Santamaría J, Artal P & Bescos J. Determination of the point-spread function of human eyes using a hybrid optical-digital method. *J Opt Soc Am A* 1987; 4: 1109–1114.
20. Artal P, Ferro M, Miranda I & Navarro R. Effects of aging in retinal image quality. *J Opt Soc Am A* 1993; 10: 1656–1662.
21. Guirao A, Gonzalez C, Redondo M, Geraghty E, Norrby S & Artal P. Average optical performance of the human eye as a function of age in a normal population. *Invest Ophthalmol Vis Sci* 1999; 40: 203–213.
22. Vilaseca M, Padilla A, Pujol J, Ondategui JC, Artal P & Güell JL. Optical quality one month after Verisyse and Veriflex phakic IOL implantation and Zeiss MEL 80 LASIK for myopia from 5.00 to 16.50 diopters. *J Refract Surg* 2009; 25: 689–698.
23. López-Gil N, Iglesias I & Artal P. Retinal image quality in the human eye as a function of the accommodation. *Vision Res* 1998; 38: 2897–2907.
24. Iida Y, Shimizu K, Ito M & Suzuki M. Influence of age on ocular wavefront aberration changes with accommodation. *J Refract Surg* 2008; 24: 696–701.
25. Cheng H, Barnett JK, Vilupuru AS *et al.* A population study on changes in wave aberrations with accommodation. *J Vis* 2004; 4: 272–280.
26. He JC, Gwiazda J, Thorn F, Held R & Vera-Diaz FA. The association of wavefront aberration and accommodative lag in myopes. *Vision Res* 2005; 45: 285–290.
27. López-Gil N, Fernández-Sánchez V, Legras R, Montés-Micó R, Lara F & Nguyen-Khoa JL. Accommodation-related changes in monochromatic aberrations of the human eye as a function of age. *Invest Ophthalmol Vis Sci* 2008; 49: 1736–1743.
28. Sheppard AL & Davies LN. Clinical evaluation of the Grand Seiko Auto Ref/Keratometer WAM-5500. *Ophthalmic Physiol Opt* 2010; 30: 143–151.
29. Guirao A & Williams DR. A method to predict refractive errors from wave aberration data. *Optom Vis Sci* 2003; 80: 36–42.
30. Mutti DO, Jones LA, Moeschberger ML & Zadnik K. AC/A Ratio, Age, and Refractive Error in Children. *Invest Ophthalmol Vis Sci* 2000; 41: 2469–2478.
31. Kasthurirangan S & Glasser A. Age related changes in the characteristics of the near pupil response. *Vision Res* 2006; 9: 1393–1403.
32. Ostrin LA & Glasser A. Accommodation measurements in a pre-presbyopic and presbyopic population. *J Cataract Refract Surg* 2004; 30: 1435–1444.
33. Radhakrishnan H & Charman WN. Age-related changes in ocular aberrations with accommodation. *J Vis* 2007; 7: 11.
34. McLellan JS, Marcos S & Burns SA. Age-related changes in monochromatic wave aberrations of the human eye. *Invest Ophthalmol Vis Sci* 2001; 42: 1390–1395.
35. Artal P, Berrio E, Guirao A & Piers P. Contribution of the cornea and internal surfaces to the change of ocular aberrations with age. *J Opt Soc Am A* 2002; 19: 137–143.
36. Li YJ, Choi JA, Kim H, Yu SY & Joo CK. Changes in ocular wavefront aberrations and retinal image quality with objective accommodation. *J Cataract Refract Surg* 2011; 37: 835–841.