Peripheral Design of Progressive Addition Lenses and the Lag of Accommodation in Myopes

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With its increasing prevalence, myopia is one of the major refractive errors that can affect eye health. Especially in East Asian countries, reports find prevalences reaching and exceeding 80% to 90%.1

It was observed that myopic children show an insufficient accommodation (lag of accommodation [LA]), which would result in a reduced power of the eye during reading.2 Further research also found that the amount of the LA depends on the reading distance, the device used to measure accommodation, the time of the onset of myopia (early onset [EOM] or late onset [LOM]), and many more (for review, see Ref. 3). Since it is known from animal research that a hyperopic defocus (when the image is behind the retina) leads to the development of myopia,4 the LA might be a risk factor for the development and/or progression of myopia.5–7 On the other hand, there are studies that do not support this theory for the onset8 or progression9 of myopia.5–11 There are also investigations that have found the LA to be present in emmetropes but not in myopes12 or that argued that the LA does not necessarily reflect a reliable loss of image quality on the retina due to the failure to include the effects of higher order aberrations or an increased depth of focus due to pupil constriction during accommodation.13

Assuming that the LA does play a role in stimulating excessive elongation of the eyeball resulting in progressing myopia, it is of interest to find the means of reducing the LA in myopes. It has been known that accommodative responses (ARs) can be elicited by stimuli imaged not just on the fovea but also on the peripheral retina (for review see Ref. 14). This opens up a possibility of modulating ARs with aspherized lens designs that change the peripheral focal properties of the visual field. It has already been shown to be possible with bifocal contact lenses15 and contact lenses with varying amounts of spherical aberration16 worn by young myopic subjects. Recently this topic was also investigated with multifocal contact lenses.17 In this study, we are investigating the feasibility of this approach with progressive spectacle lenses, which offer the possibility of aspherizing the area adjacent to the near vision zone without affecting the wearer's distance vision quality.

Progressive addition spectacle lenses (PAL) have been investigated in order to assess their influence on the progression of myopia. Most studies using progressive addition lens (PAL) spectacles10,18–22 found a reduction in myopia progression due to the treatment with PALs of around 30% in the first year when compared to wearers of single vision lenses, with the effect often waning or saturating in the following years. One study23 did not find any statistically significant effect of a +1.50 D addition PAL on the progression of myopia even in the first year, while another testing the same lens a few years later24 recorded a 21% retardation of myopia progression (adjusted for confounding variables) after 2 years with no

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evidence of effect saturation after 12 months. In earlier days, standard progressive lenses with long corridor lengths developed for presbyopes have been used. Later on, new PAL designs adapted for juvenile use with shorter corridors, making it easier for children to access the addition power, have been developed and tested. Hasebe et al. investigated the influence of the addition power and the positive asherization of the distance zone of the PAL on their efficacy to provide retardation of myopia progression. The positive asherization of the distance zone did not retard myopia and a minimum of +1.50 D addition was required to get an initial efficacy of 30% in the first year.

The purpose of the study was to establish the influence of the design of a PAL on the reduction of the LA by using different widths of the near zone and varying the horizontal power gradients in the immediate vicinity of the near zone of a lens. Assuming the accommodative stimulus is spatially averaged in some way, the expectation was to have greater lens. Assuming the accommodative stimulus is spatially averaged in some way, the expectation was to have greater efficacy of 30% in the first year.

**Methods**

**Subjects**

Thirty-one participants aged 18 to 25 years with a mean spherical equivalent refractive error of the dominant eye of $-2.8 \pm 1.5$ D (range, $-5.6$ to $-0.8$ D) participated in the study. Inclusion criteria for participation were as follows: central refractive errors $\geq -6$ D sphere, $\geq -1.5$ D of cylinder, and best-corrected visual acuity of 0.0 logMAR or better. Subjects with known ocular diseases were not allowed to participate. Permission was obtained from the Ethics Commission of the Medical Faculty of the University of Tuebingen. The research followed the tenets of the Declaration of Helsinki and, in addition, informed consent was obtained from all subjects after explanation of the nature and possible consequences of the study.

**Measurement of Refractive Errors**

Objective as well as subjective refraction was measured prior to the course of the study. Autorefraction was measured for a pupil diameter of 3 mm using a wavefront aberrometer (i.profiler Plus, Carl Zeiss Vision GmbH, Aalen, Germany). Subjective refraction was measured under natural pupil conditions, using a Subjective Refraction Unit (SRU; Carl Zeiss Vision GmbH).

After the subjective measurement of the sphero-cylindrical refractive errors, the dominant eye of each participant was determined using the pinhole test. We fitted the progressive lenses into a custom developed frame, where the height and the pupillary distance were adjustable (Engelhardt Eyewear Pty Ltd., Richmond, SA, Australia).

**Correction of Refractive Errors and Lens Design**

The trial included a single vision spherical lens (SVL) and 4 PAL designs. One of the PAL designs was used as a benchmark with a known myopia control efficacy. This was a +1.50 D addition positively asherized (PA) PAL trialed for 2 years on the Asian 6-12-year-old myopes, having a corridor of 14 mm in length measured from the fitting cross (FC) to the near reference point (NRP). The ability of this lens to reduce the LA was not known prior to the study. This lens was called PAL 2 in the trial and was used as a benchmark against which the ability of other lenses to reduce the LA was judged. It has a progressive surface on the front of the lens and a prescription surface on the back side. The first of the new designs tested, labelled PAL 1, was derived from PAL 2 and also had the +1.50 D addition. The positive asherization of the distance zone of PAL 2 was removed. Then its corridor length was shortened and the distance–near zone size balance transformed. The aim of the design modifications was to provide a much wider zone for clear distance vision and a higher and narrower near zone. The corridor length was changed to 12 mm, and the new zone size balance adjustment was achieved by rotating the distance zone boundaries down by $24^\circ$ with the corresponding rotation in the inward direction for the near zone boundaries. The design was implemented on the back surface of the lens configured to provide both the prescription and addition power, with the front surface being spherical.

The second new design, labelled PAL 3, has a +1.50 D addition with a 13-mm corridor length, and a moderately wide distance and near zones. Its unique feature is the design of the periphery, which has a reversed sign (positive) horizontal mean power gradient adjacent to the near zone compared to the conventional PALs (see the optical mean addition power contour plots of PAL 3 in Figs. 1, 2). The design has a relatively high astigmatism in the periphery due to this unusual power distribution. This design was implemented with a progressive back surface and a spherical front surface.

The third new test design, labelled PAL 4, has a 13-mm corridor length with a wide distance zone and a relatively narrow near zone surrounded by areas having the mean optical power close to the power of the distance zone. Consequently, the design has relatively large negative horizontal gradients of mean power around the near zone. It also has relatively large values of peripheral astigmatism in some peripheral areas due to the presence of high power gradients. The progressive surface providing the optical power progression was implemented on the back side of the lens.

All lenses were ordered and produced at Carl Zeiss Vision to correct the sphero-cylindrical errors of the dominant eye for each subject. The contour plots of ray-traced optical astigmatism and optical mean addition power distributions for all PAL designs used in this study are displayed in Figure 1.

To visualize the optical power distribution in the object space provided by the PALs when looking through the near zone of the lens at the target stimulus, we have computed static eye ray traces for each of the tested PALs at three target object distances used during the experiments. The ray tracing has been done for a wearer having a distance prescription of $-2.50$ D looking through the NRP of each of the PALs at the center of the target stimulus. It has been assumed that the wearer’s eye is responding to the accommodative stimulus perfectly with the mean power error being zero at the fixation point marked by the intersection of gray lines. The contour plots of the mean power error distribution on the reference plane in the object space for each of the 4 PALs and three near target distances tested are shown in Figure 2. Under each of the contour plots, the mean horizontal gradient of ray-traced mean power calculated over the nasal (to the right hand side from the center) extent of 92 mm from the center of the target stimulus is printed in units of D/m in object space.

**Accommodation Measurement Protocol**

While the subjects were wearing a customized spectacle lens correction with one of the five different lenses, the refractive error of the nondominant eye covered with an infrared-transparent filter (Kodak IR 87C, Kodak Corp., Rochester, NY, USA) was measured using the Grand Seiko WAM-5500 autorefractor (Grand Seiko Co., Ltd., Fukuyama Hiroshima, Japan).
Japan). The filter was also fitted into the test frame. Refractive errors were measured for distances of 25 cm (4 D dioptric object distance), 33 cm (3 D dioptric object distance), and 40 cm (2.5 D dioptric object distance), as well as for distance vision (400 cm). For each combination of spectacle lens and distance, five individual readings of sphere, cylinder, and axis were obtained. The sequence of testing (# spectacle lens and distance) was randomized between the subjects. During near vision, the subjects were asked to look at an acuity chart and to fixate the lowest line of optotypes. Prior to the measurement and while accommodation for the different distances was measured, the examiner controlled subjectively the alignment of the near point of the spectacle lens and the subject’s eye in order to ensure that the subjects looked through the NRP. This inspection was done by checking if the NRP of the spectacle lens was in one line with the eye of the subject and that the acuity chart was on the same height as the NRP and the eye, for every target distance. All far distance measurements of the spherical error were corrected by 0.25 D since the measurements were done at 400 cm distance. The individual readings were transformed into the power vector components of refraction (M, J0, and J45) and averaged.

Calculation of the LA

The different object distances were defined relative to the corneal plane, while the setup of the autorefractor was configured to calculate the measured refractions with the lens 12 mm in front of the corneal plane (equal to the vertex distance [VD]). The following formulae were used to calculate the AR, accommodative demand (AD), and LA at the corneal plane:

$$\text{Calculation of the LA}$$
Lag of Accommodation in Myopes Wearing PALs

TABLE. AR, LA and the Standard Error of the Mean of the LA for All Tested Lenses (SVL, PAL 1, PAL 2, PAL 3, PAL 4) and for the Three Object Distances From the Eye

<table>
<thead>
<tr>
<th>Object Distance, 40 cm</th>
<th>Object Distance, 33 cm</th>
<th>Object Distance, 25 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR</td>
<td>LA</td>
<td>SEM</td>
</tr>
<tr>
<td>SVL</td>
<td>1.75</td>
<td>0.60</td>
</tr>
<tr>
<td>PAL 1</td>
<td>0.85</td>
<td>0.15</td>
</tr>
<tr>
<td>PAL 2</td>
<td>0.85</td>
<td>0.15</td>
</tr>
<tr>
<td>PAL 3</td>
<td>0.72</td>
<td>0.27</td>
</tr>
<tr>
<td>PAL 4</td>
<td>0.91</td>
<td>0.09</td>
</tr>
</tbody>
</table>

\[
AR = \frac{GS(SV) + 0.25}{1 - VD[GS(SV) + 0.25]} - \frac{GS(PAL-Near)}{1 - VD \cdot GS(PAL-Near)} \tag{1}
\]

\[
AD = \frac{Rx}{1 - VD \cdot Rx} - \frac{1 + (DX + DT)(Rx + ADD)}{DT - VD(1 + VD)(Rx + ADD)} \tag{2}
\]

\[
LA = AD - AR \tag{3}
\]

The following formulae from Atchison and Varnas\(^2^7\) were used: formula 8b = formula 1, AR; formula 5d = formula 2, AD. For AR (Equation 1), GS(SV) is the Grand Seiko measured sphere equivalent refraction of the occluded nondominant eye when the dominant eye is wearing a SVL equal to the distance Rx and viewing a target at a distance of 400 cm. GS(PAL-Near) is the measured Grand Seiko sphere equivalent refraction of the nondonnant eye when the other eye is looking through the NRP of a PAL, viewing a target at one of the closer object distances. In formula (2), Rx is the sphere equivalent of the subjective refraction for distance objects, DT is the object distance from the cornea (with a negative sign). ADD is the addition power of the lens—it is zero for the SVL and +1.50 D for each of the PALs. In case the LA is calculated for the SVL, GS(PAL-Near) in Equation 1 is replaced by “GS(SV-Near)—the Grand Seiko measured sphere equivalent refraction of the nondominant eye when the dominant eye is wearing SVL and viewing a near target. Using this formula for the LA, the lags come out positive and the accommodative leads are negative.

Statistics

Two main hypotheses were formulated before the trial: (1) Narrower near zones lead to lower lags of accommodation, and (2) the high negative horizontal power gradients adjacent to the near zone will provide the maximum reduction of accommodative lag.

Statistical analyses were performed in R (The R Foundation for Statistical Computing). Exploratory data analysis had revealed significant deviations from the normal distribution, as well as the presence of outliers in a range of data sets. Since each subject has been measured with five different lenses at four target object distances, these data sets cannot be regarded as independent. Violation of data independence makes the use of ANOVA analysis inappropriate. Therefore, we applied a robust or nonparametric hypothesis testing method for paired data. A 1-tailed Mann-Whitney U test with an appropriately formulated alternative hypothesis was employed.

Results

Baseline AR With Single Vision Correction and Progressive Addition Lenses

Subjects were wearing SVL or PALs correcting their spherocylindrical refractive error of the dominant eye, which was fixating on three different near viewing targets at distances of 40, 33, and 25 cm, while the consensual AR was measured in the nondonnant eye occluded by the infrared-transparent filter. The LA in the spectacle plane was calculated using formulae 1 to 3, and the Table shows the ARs, LAs, and standard errors of the LA.

Statistical analysis using the Mann-Whitney U test revealed significant differences for the LA between 25 and 40 cm (\(P < 0.001\)), as well as between 25 and 33 cm (\(P < 0.001\)), but not for the comparison of 40 versus 33 cm (\(P = 0.06\)), in case the SVL were used.

The Lag of Accommodation for the Benchmark PAL and Comparison to SVL

In order to test if the benchmark PAL (PAL 2) reduces the LA during near work when compared to the SVL, a statistical analysis was run to compare the LA. The null hypothesis was that the mean LA for each of the near object distances tested with PAL 2 was the same as that with the SVL. When making these analyses, it was ensured that the alternative hypothesis matched the assumptions. In this case, the alternative hypothesis was that the SVL showed a greater LA than the PAL 2. To test this, a “greater-than” alternative hypothesis [i.e., \(LA(SVL) > LA(PAL\;2)\)] was needed instead of a “two-sided” alternative hypothesis. Using the Mann-Whitney U test, it was found that SVL causes greater LA than PAL 2 at all object distances (\(P < 0.001\) in all cases).

Testing the Hypotheses

In order to test the hypotheses, the lags of accommodation with the different PALs were tested against the defined benchmark. The Mann-Whitney U test with properly formulated one-sided alternative hypothesis for each of the comparisons was used to test the statistical significance of the differences between the lags. The alternate hypotheses in comparisons between the PALs followed the rationale of the formulated primary and secondary hypotheses: the PALs with narrower near zones are expected to give smaller lags of accommodation and PALs with lesser positive gradients or more negative gradients are expected to ensure smaller lags of accommodation.

Statistical analysis revealed the following: PAL 1 did not have less LA than PAL 2 for any object distance at the 5% confidence level but has shown a trend for the 25-cm object distance (\(P = 0.07\)). PAL 3 had a higher LA than PAL 2 for all object distances (\(P < 0.05\)). PAL 4 had a lower LA than PAL 2 for the 25-cm object distance (\(P = 0.03\)), but the effect lost significance for larger object distances (\(P = 0.08\) and \(P = 0.17\) for the 33-cm and 40-cm object distances, respectively). For details, see Figure 3.
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**FIGURE 3.** Mean LA for the spherical equivalent refractive error, separated for the three target distances, for the five lenses (SVL and PALs). SVL, red; PAL 1, blue; PAL 2, green; PAL 3, violet; PAL 4, turquoise. Error bars: ±1 SEM.

**DISCUSSION**

The current study investigated the efficiency of a progressive addition lens design on the reduction of the LA, a known risk factor for the development as well as progression of myopia. The results suggest that negative horizontal mean power gradients adjacent to the near vision zone of a PAL enhance a reduction in the LA due to addition power in a young myopic study group.

**Baseline LA Using Single Vision Spectacle Lenses**

Using SVLs to correct the individual spherocylindrical refractive errors, the LA (mean ± SD) increased with an increasing AD (2.5 D: 0.6 D ± 0.5 D; 3.0 D: 0.6 D ± 0.5 D; 4.0 D: 0.9 D ± 0.5 D). Variable amounts of the LA have been found among different studies. Mean lags of accommodation in myopic children and young adults, corrected for their distance vision, for the 33-cm target object distance include 0.6 D,28 1 D to 1.3 D,29 and up to 1.5 D.31 Our mean value at this distance with the SVL of 0.6 D is on the low side of the range but matches Tarrant,28 which is the only study among those listed above that was measuring young adults.

**LA With SVL Distance and Near Correction**

Berntsen et al.29 investigated the influence of the type of correction (SVL or SVL with 2.0 D add power) on the LA in 85 myopic children that had high lags of accommodation for a 4-D Badal stimulus (mean age ± SD: 9.9 ± 1.3 years). The correction of myopia with SVL resulted in a LA of 1.7 ± 0.4 D, while the SVL with +2.00 D add power reduced the lag by 0.5 ± 0.3 D. Measuring the LA with SVL in 29 Chinese myopic children,29 a reduction of the LA with a 1.5-D add on the SVL to 0.7 (SD: ±0.5 D) was found, while the lag with the SVL was 1.0 D (SD: ±0.7 D). Investigating the influence of 2.0 D add power on the accuracy of accommodation in myopic and emmetropic children, Sreenivasan et al.32 observed that the ÷2.0 D addition lenses eliminated the lags of accommodation in myopic children during natural viewing conditions.

**Benchmark PAL and SVL**

PAL 2 has been used already in a clinical trial to investigate its efficacy in reducing progression of myopia in children.21 There was a statistically significant (P = 0.02) retardation of myopia progression (0.27 ± 0.11 D, equivalent to a reduction ratio of 20%) during the 24-month period of the trial (0.24 D of which has occurred in the first 12 months) for the positively aspherized PAL with the 1.5 D of add power, when compared with a SVL control group.21 The reduction of myopia progression using the PA-PAL and 1.50 D add power was within the range of reported retardations of myopia from earlier trials that used standard PALs. Standard single vision spherical lenses lead to higher lags of accommodation than the benchmark lens, indicating that the progressive addition lens is effective in the reduction of the LA.

**Test of the Two Hypotheses**

The ray tracing of test designs for the static eye viewing near targets at the studied range of object distances has revealed that the current study did not succeed in separating the test lens designs into pairs that differ in the width of the near zone only. Lens design PAL 1 has not only a narrower near zone than PAL 2 but also has higher negative horizontal mean power gradients than PAL 2, especially for the 25-cm object distance. Since PAL 1 did not show a statistically significantly different LA from PAL 2 at any object distance, despite some differences in power gradients on top of the near zone width differences, it is most likely that hypothesis #1 is incorrect—narrower near zones in PALs are unlikely to lead to lower LA.

Our results suggest that accommodation responses, when looking at near objects through the center of the near zone of PALs, depend not just on the addition power of the lens but also on the distribution of the peripheral power in the lower viewing zone of the lens, and that the designs with the more negative horizontal mean power gradient lead to a lower LA, especially compared to those with the positive horizontal mean power gradient (the LA with PAL 4 was significantly [P < 0.005] smaller for all three object distances when compared to PAL 3). The conventional progressive lens (PAL 2) reduced the LA by approximately 40% to 75% when compared to the SVL, depending on the object distance. PAL 4 appears to further reduce the LA 30% more than conventional PAL.

**LA and Depth of Focus**

When selecting the optimal PAL design for the retardation of myopia progression, one can hypothesize that the LA should be reduced below the depth of focus, which has been reported to be approximately ±0.3 D.33 In the set of PALs in the current study, this is satisfied by PAL 4 for the near distances down to 35 cm, but none of the tested PALs was able to do this for the closest object distance tested (25 cm) that some children may also use, especially when working with small electronic devices like hand-held video game devices.

**CONCLUSIONS**

The current study suggests that accommodation responses using PALs are dependent on the addition power and on the distribution of the peripheral power in the lower viewing zone of the lens. Whether this may have an impact on the rate of myopia retardation needs to be tested in a clinical trial. Measuring the children’s ARs when viewing near targets through the lower viewing zone of those lenses would also test the longer term adaptation of the accommodation system to addition power and will hopefully shed some light on the saturation of efficacy of PALs in the reduction of the progression of myopia.
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References