Apparent accommodation in pseudophakic eyes with refractive against-the-rule, with-the-rule and minimum astigmatism

Toshiya Yamamoto,1 Takahiro Hiraoka,2 Tetsuro Oshika2

ABSTRACT

Aim To compare the magnitude of apparent accommodation in pseudophakic eyes with refractive against-the-rule (ATR), with-the-rule (WTR) and minimum astigmatism. Factors associated with apparent accommodation were also examined in each group.

Methods In total, 87 pseudophakic eyes (87 patients) that underwent monofocal intraocular lens (IOL) implantation after uneventful cataract surgery were included. There were 33, 24 and 30 eyes with refractive ATR, WTR and minimum (<0.5 dioptres) astigmatism, respectively. Age, time after surgery, pupil size, corneal and refractive astigmatism, axial length, IOL power, best-corrected visual acuity, corneal multifocality, ocular wavefront aberrations and apparent accommodation without cylindrical correction were compared among the three groups.

Results No significant difference was found in the amount of apparent accommodation between groups. In the ATR group, the amount of apparent accommodation was significantly correlated with pupil size (r = -0.470, p = 0.005) and refractive astigmatism (r = 0.529, p = 0.001). In the WTR group, the amount of apparent accommodation was significantly correlated with coma Zernike term (r = 0.409, p = 0.047). In the minimum astigmatism group, corneal multifocality was significantly associated with apparent accommodation (r = 0.464, p = 0.009).

Conclusion There was no significant difference in the average amount of apparent accommodation in pseudophakic eyes with refractive ATR, WTR and minimum astigmatism. However, the factors relevant to apparent accommodation varied depending on the status of postoperative refractive astigmatism.

INTRODUCTION

Patients with monofocal intraocular lens (IOL) implantation are widely reported to have good near and distance vision with only distance correction applied. This phenomenon has been termed as ‘apparent accommodation’. Apparent accommodation is thought to be attributable to several different optical properties of the eye, such as enhanced depth of focus associated with smaller pupil size. However, the mechanism by which apparent accommodation occurs is not completely understood. It was once thought that the IOL may move and broaden the range of clear vision, and several studies reported a significant relationship between myopic astigmatism and apparent accommodation in pseudophakic eyes. In contrast, other studies contradicted such a relationship. Thus, the role of astigmatism in apparent accommodation in pseudophakic eyes remains controversial.

Such discrepancy may partly result from the lack of studies evaluating the role of astigmatism in detail, including the influence of astigmatism axis orientation on apparent accommodation. Several studies have investigated the effects of against-the-rule (ATR) and with-the-rule (WTR) astigmatisms on visual performance in pseudophakic eyes. These findings suggest that the axis orientation and amount of astigmatism affect visual function in pseudophakic eyes, probably including apparent accommodation. There have been, however, no studies to compare the influence of different types of astigmatism on pseudophakic apparent accommodation and their relevant factors, especially after modern small-incision cataract surgery. Because surgically induced astigmatism and resultant postoperative cylinders have been decreasing with modern small-incision cataract surgery techniques, it seems that the discussion on apparent accommodation should be renewed from those based on conventional extracapsular cataract extraction and/or implantation of polymethyl methacrylate IOL.

The purpose of this study was to compare the amount of apparent accommodation in pseudophakic eyes with refractive ATR, WTR and minimum astigmatism (MA). Clinical factors affecting apparent accommodation were also examined.

PATIENTS AND METHODS

Patients

This was a retrospective, comparative study. In total, 87 eyes of 87 patients (44 men, 43 women) who had undergone uneventful phacoemulsification and implantation of a monofocal aspherical IOL (SN60WF, Alcon Laboratories, Fort Worth, Texas, USA) in the capsular bag through a 2.4 mm sclerocorneal incision were recruited. All patients were treated for uncomplicated age-related cataract at the University of Tsukuba Hospital. Inclusion criteria were postoperative best-corrected visual acuity (BCVA) of ≥20/30 (0.7) and postoperative negative cylindrical refractive error of ≤2.0 dioptres (D).

Refractive astigmatism between 0.5 and 2.0 D with cylindrical axes oriented at 90±30° and 180±30° was defined as ATR and WTR, respectively. Refractive astigmatism <0.5 D, regardless of cylindrical axis, was defined as MA. Eyes with...
postoperative oblique astigmatism were not included in this study. Eyes with corneal disease, glaucoma, retinal disease or other ocular pathologies potentially affecting visual acuity were also excluded. All study conducts adhered to the tenets of the Declaration of Helsinki, and the study protocol was approved by the Institutional Review Board of the University of Tsukuba Hospital. Informed consent was obtained from all study participants before any study examinations were performed.

Measurements

BCVA was measured at 5 m under standard room illumination using a high-contrast Landolt chart. On the basis of BCVA, refractive error was recorded and used for analyses. Pupil size was measured using a handheld, open-view type, digital pupillometer (FP-10000; TMI Co, Saitama, Japan) under photopic light conditions with a fixation distance of 40 cm. Corneal astigmatism and topography were obtained using a corneal topographer (TMS-4 Advance; TOMEY Co, Nagoya, Japan). Within the subjects’ pupillary area, the difference between the maximum and minimum corneal optical power was calculated and recorded as the refractive gradient of the cornea, which was used as an index of corneal multifocality.4 9 10 The near point of apparent accommodation was determined in each eye using an accommodometer (HS-9G; KOWA Co, Nagoya, Japan), while the fellow eye was occluded. A spherical lens of +2.0 or +3.0 D was added to the spherical equivalent refraction of the cornea to form the near point of accommodation. The chart was slowly moved closer until the patient reported image blurring. The Landolt target was then moved back until it became clear. Measurements were repeated 10 times, and the average distance (noted in dioptres) at which blurring and refocus occurred was recorded as the near point of accommodation. The amplitude of apparent accommodation was calculated from the far and near points. At baseline, ocular wavefront aberrations were assessed in a dark room with an undilated pupil using a Hartmann–Shack wavefront aberrometer (KR-1W; Topcon Co, Tokyo, Japan). The acquired datasets were expanded using normalised Zernike polynomials. By using Zernike coefficients, the root mean square (RMS) was calculated for total higher-order, third-order and fourth-order aberrations for the individual pupil size. The average of four measurements was used in data analyses. For each pair of standard Zernike terms (ie, trefoil, coma, tetrafoil and secondary astigmatism) a correlation test was used in data analyses. For each pair of standard Zernike terms (ie, trefoil, coma, tetrafoil and secondary astigmatism) a correlation test was used in data analyses. For each pair of standard Zernike terms (ie, trefoil, coma, tetrafoil and secondary astigmatism) a correlation test was used in data analyses. For each pair of standard Zernike terms (ie, trefoil, coma, tetrafoil and secondary astigmatism) a correlation test was used in data analyses.

Statistical analysis

All parameters examined were compared among the ATR, WTR and MA groups using Kruskal–Wallis test. If significant differences were observed, Steel–Dwass test for multiple comparisons was performed. Relationships between the amount of apparent accommodation and other parameters were also examined in whole patients and each group using Pearson’s correlation test. Moreover, stepwise multiple regression analysis was performed to simultaneously investigate the relationship between the amount of apparent accommodation and several variables. The dependent variable was the amount of apparent accommodation. Explanatory variables included pupil size, corneal and refractive astigmatism, corneal multifocality and ocular wavefront aberrations; all of which are known to possibly influence apparent accommodation. Furthermore, in whole patients, ATR, WTR and MA groups were converted to categorical variables to standardise other conditions and the pure effect of each group newly added as explanatory variables was analysed. Statistical significance was defined as p<0.05 for Pearson’s correlation test, Kruskal–Wallis test and Steel–Dwass test. All statistical analyses were performed using StatView V5.0 software (SAS Institute, Cary, North Carolina, USA). All data are presented as the mean±SD, where applicable.

RESULTS

There were 33 eyes (33 patients) in the ATR group, 24 eyes (24 patients) in the WTR group and 30 eyes (30 patients) in the MA group. The patients’ background data in whole patients and each study group are summarised and compared in table 1. Statistically significant differences were found between groups with regard to amount of corneal astigmatism (ATR vs WTR, p=0.003; WTR vs MA, p<0.001) and amount of refractive astigmatism (ATR vs MA, p<0.001; WTR vs MA, p<0.001). There was no significant difference in other parameters.

Table 2 summarises the relationships between apparent accommodation and various parameters. The amount of apparent accommodation was significantly correlated with pupil size (r=–0.227, p=0.034; figure 1), refractive astigmatism (r=0.228, p=0.034; figure 2) and coma RMS (r=0.032; figure 3) in the analysis of whole patients. In the ATR group, the amount of apparent accommodation was significantly correlated with pupil size (r=–0.470, p=0.005; figure 4) and refractive astigmatism (r=0.529, p=0.001; figure 5). In the WTR group, the amount of apparent accommodation was significantly correlated with coma RMS (r=0.409, p=0.047; figure 6). In the MA group, corneal multifocality was the only parameter significantly correlated with apparent accommodation (r=0.464, p=0.009; figure 7).

The results of stepwise multiple regression analysis are shown in table 3. Pupil size and coma RMS were significant contributors to the amount of apparent accommodation in the analysis of whole patients, refractive astigmatism, pupil size and trefoil RMS in the ATR group, coma RMS in the WTR group and corneal multifocality and trefoil RMS in the MA group.

DISCUSSION

When assessing apparent accommodation, it is very important to consider the target size used in the measurements of near points. Nawa et al4 compared the results of apparent accommodation measurements using 20/20 or 20/30 near vision optotypes, and demonstrated that apparent accommodation decreased when a smaller optotype was used. Kamiya et al5 measured mean apparent accommodation using a 20/20 near vision optotype, and reported values of 1.58±0.63 D. In contrast, Elder et al,1 Fukuyama et al7 and Oshika et al10 measured mean apparent accommodation with a 20/30 near vision optotype, and found values of 2.72±1.10, 2.00±0.92 and 2.03±0.93 D, respectively. In the present study, we used a 20/30 optotype, and obtained apparent accommodation of 2.53±1.38 D in whole patients, which is in good agreement with the results of previous studies.

There were no significant differences in the amount of apparent accommodation in the ATR, WTR and MA groups. However, clinical parameters relevant to apparent accommodation were different among the three groups. In eyes with ATR astigmatism, pupil size and refractive astigmatism were significantly correlated with the amount of apparent accommodation. In the stepwise multiple regression analysis, refractive astigmatism was the most relevant variable, followed by the pupil size.
<table>
<thead>
<tr>
<th></th>
<th>Whole patients</th>
<th>ATR group (range)</th>
<th>WTR group (range)</th>
<th>MA group (range)</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex (male:female)</td>
<td>44:43</td>
<td>17:16</td>
<td>12:12</td>
<td>15:15</td>
<td></td>
</tr>
<tr>
<td>Eyes (OD:OS)</td>
<td>48:39</td>
<td>20:13</td>
<td>12:12</td>
<td>16:14</td>
<td></td>
</tr>
<tr>
<td>Age (years)</td>
<td>67.3±14.0 (18–86)</td>
<td>72.0±8.7 (52–86)</td>
<td>62.3±17.8 (20–83)</td>
<td>66.3±14.1 (18–86)</td>
<td>0.064</td>
</tr>
<tr>
<td>Time after surgery (days)</td>
<td>231.0±337.4 (6–1434)</td>
<td>150.7±450.2 (7–1434)</td>
<td>289.6±7.1 (1.7–4.5)</td>
<td>3.01±0.68 (1.86–4.82)</td>
<td>0.070</td>
</tr>
<tr>
<td>Pupil size (mm)</td>
<td>2.8±0.62 (1.56–4.82)</td>
<td>0.87±0.50 (0.06–2.17)</td>
<td>1.29±0.58 (0.12–2.35)</td>
<td>0.80±0.45 (0.13–2.15)</td>
<td>0.002*</td>
</tr>
<tr>
<td>Corneal astigmatism (D)</td>
<td>0.96±0.54 (0.06–2.53)</td>
<td>0.96±0.57 (0.00–2.00)</td>
<td>0.96±0.57 (0.00–2.00)</td>
<td>0.96±0.57 (0.00–2.00)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Refractive astigmatism (D)</td>
<td>0.66±0.57 (0.00–2.00)</td>
<td>0.66±0.57 (0.00–2.00)</td>
<td>0.66±0.57 (0.00–2.00)</td>
<td>0.66±0.57 (0.00–2.00)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Axial length (mm)</td>
<td>24.0±3.79 (21.30–30.06)</td>
<td>23.68±1.59 (21.86–30.06)</td>
<td>24.11±2.08 (21.31–29.99)</td>
<td>24.26±1.75 (21.30–28.11)</td>
<td>0.319</td>
</tr>
<tr>
<td>BCVA (logMAR)</td>
<td>−0.04±0.08 (−0.30 to 0.22)</td>
<td>−0.03±0.08 (−0.18 to 0.22)</td>
<td>−0.05±0.09 (−0.30 to 0.15)</td>
<td>−0.04±0.07 (−0.18 to 0.15)</td>
<td>0.856</td>
</tr>
<tr>
<td>IOL power (D)</td>
<td>20.1±3.8 (6.0–26.0)</td>
<td>20.8±3.8 (8.0–26.0)</td>
<td>20.1±3.8 (6.0–25.5)</td>
<td>19.2±4.0 (6.0–24.0)</td>
<td>0.146</td>
</tr>
<tr>
<td>Corneal multifocality (D)</td>
<td>2.45±0.93 (1.00–5.74)</td>
<td>2.25±0.74 (1.00–4.28)</td>
<td>2.78±1.03 (1.00–5.74)</td>
<td>2.41±0.98 (1.31–5.42)</td>
<td>0.123</td>
</tr>
<tr>
<td>Total higher-order RMS (μm)</td>
<td>0.125±0.093 (0.020–0.532)</td>
<td>0.096±0.044 (0.022–0.177)</td>
<td>0.141±0.126 (0.020–0.532)</td>
<td>0.145±0.097 (0.041–0.442)</td>
<td>0.122</td>
</tr>
<tr>
<td>Third-order RMS (μm)</td>
<td>0.108±0.086 (0.016–0.526)</td>
<td>0.082±0.043 (0.016–0.190)</td>
<td>0.122±0.116 (0.017–0.526)</td>
<td>0.125±0.090 (0.032–0.408)</td>
<td>0.149</td>
</tr>
<tr>
<td>Fourth-order RMS (μm)</td>
<td>0.058±0.044 (0.010–0.302)</td>
<td>0.045±0.025 (0.014–0.110)</td>
<td>0.064±0.057 (0.010–0.302)</td>
<td>0.068±0.048 (0.025–0.259)</td>
<td>0.163</td>
</tr>
<tr>
<td>Trefoil RMS (μm)</td>
<td>0.071±0.062 (0.001–0.436)</td>
<td>0.055±0.036 (0.001–0.136)</td>
<td>0.083±0.083 (0.002–0.436)</td>
<td>0.078±0.063 (0.018–0.250)</td>
<td>0.263</td>
</tr>
<tr>
<td>Coma RMS (μm)</td>
<td>0.067±0.072 (0.003–0.393)</td>
<td>0.047±0.035 (0.003–0.141)</td>
<td>0.087±0.04 (0.004–0.393)</td>
<td>0.072±0.069 (0.007–0.347)</td>
<td>0.218</td>
</tr>
<tr>
<td>Tetrafoil RMS (μm)</td>
<td>0.030±0.021 (0.003–0.112)</td>
<td>0.022±0.015 (0.003–0.055)</td>
<td>0.037±0.025 (0.008–0.112)</td>
<td>0.032±0.023 (0.004–0.109)</td>
<td>0.059</td>
</tr>
<tr>
<td>Secondary astigmatism RMS (μm)</td>
<td>0.031±0.027 (0.003–0.136)</td>
<td>0.026±0.032 (0.003–0.099)</td>
<td>0.034±0.025 (0.003–0.110)</td>
<td>0.034±0.031 (0.005–0.136)</td>
<td>0.525</td>
</tr>
<tr>
<td>Spherical aberration (μm)</td>
<td>0.007±0.034 (–0.242 to 0.086)</td>
<td>0.008±0.014 (–0.014 to 0.038)</td>
<td>−0.002±0.056 (–0.242 to 0.057)</td>
<td>0.013±0.026 (–0.057 to 0.086)</td>
<td>0.457</td>
</tr>
<tr>
<td>Apparent accommodation (D)</td>
<td>2.53±1.38 (0.36–6.08)</td>
<td>2.40±1.38 (0.52–5.57)</td>
<td>2.86±1.49 (0.36–6.67)</td>
<td>2.40±1.30 (0.51–6.08)</td>
<td>0.331</td>
</tr>
</tbody>
</table>

Data are presented as the mean±SD.

*Indicates statistical significance (p<0.05) among the ATR, WTR and MA groups.

ATR, against-the-rule; BCVA, best-corrected visual acuity; D, dioptre; IOL, intraocular lens; MA, minimum astigmatism; OD, right eye; OS, left eye; RMS, root mean square; WTR, with-the-rule.
and trefoil RMS. Regarding the relationship between apparent accommodation and refractive astigmatism, Verzella and Calossi\(^8\) reported a multifocal effect of ATR astigmatism. Trindade \(et\ al\)^\(^1\) showed significantly better uncorrected near visual acuity in pseudophakic eyes with simple low myopic ATR astigmatism than in eyes with WTR astigmatism. The results of the current study agree with these reports, further strengthening the argument that refractive ATR astigmatism plays an important role in apparent accommodation in pseudophakic eyes.

Additionally, it is known that small pupils enhance depth of focus and thereby broaden the amplitude of apparent accommodation.\(^2\) In 1983, Nakazawa and Ohtsuki\(^2\) reported that pupil diameter was the most important factor in apparent accommodation; smaller pupils were associated with greater apparent accommodation in pseudophakic eyes. In a larger study with 62 pseudophakic eyes, Kamiya \(et\ al\)^\(^4\) also confirmed that pupil diameter was the most relevant variable to apparent accommodation using multivariate analysis. Although these previous studies did not investigate the influence of different astigmatism axis orientation, our results demonstrated similar tendency in eyes with ATR astigmatism.

Trefoil RMS was also selected as the relevant variable. Oshika \(et\ al\)^\(^1\) reported that some Zernike coefficients of third-order aberrations, such as trefoil, contribute to apparent accommodation. However, simple correction analysis did not show significant correlation with the amount of apparent accommodation. Further research investigating the reciprocal relationship of ocular wavefront aberrations in pseudophakic eyes with astigmatism is necessary to better understand the influences of higher-order aberrations on visual function.

In eyes with WTR astigmatism, both simple correction analysis and stepwise multiple regression analysis showed that coma RMS was significantly correlated with the amount of apparent accommodation. Nishi \(et\ al\)^\(^1\) reported that larger vertical coma

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**Table 2** Correlations between amount of apparent accommodation and clinical parameters

<table>
<thead>
<tr>
<th></th>
<th>Whole patients</th>
<th>ATR group</th>
<th>WTR group</th>
<th>MA group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CC</td>
<td>p Value</td>
<td>CC</td>
<td>p Value</td>
</tr>
<tr>
<td>Age (years)</td>
<td>0.086</td>
<td>0.427</td>
<td>0.313</td>
<td>0.076</td>
</tr>
<tr>
<td>Time after surgery (days)</td>
<td>−0.067</td>
<td>0.538</td>
<td>−0.091</td>
<td>0.616</td>
</tr>
<tr>
<td>Pupil size (mm)</td>
<td>−0.227</td>
<td>0.034*</td>
<td>−0.470</td>
<td>0.005*</td>
</tr>
<tr>
<td>Corneal astigmatism (D)</td>
<td>0.108</td>
<td>0.319</td>
<td>0.094</td>
<td>0.606</td>
</tr>
<tr>
<td>Refractive astigmatism (D)</td>
<td>0.228</td>
<td>0.034*</td>
<td>0.529</td>
<td>0.001*</td>
</tr>
<tr>
<td>Axial length (mm)</td>
<td>−0.016</td>
<td>0.887</td>
<td>0.024</td>
<td>0.894</td>
</tr>
<tr>
<td>IOL power (D)</td>
<td>0.035</td>
<td>0.748</td>
<td>0.017</td>
<td>0.926</td>
</tr>
<tr>
<td>BCVA (logMAR)</td>
<td>−0.174</td>
<td>0.107</td>
<td>−0.185</td>
<td>0.305</td>
</tr>
<tr>
<td>Corneal multifocality (D)</td>
<td>0.196</td>
<td>0.069</td>
<td>0.060</td>
<td>0.742</td>
</tr>
<tr>
<td>Total higher-order RMS (μm)</td>
<td>0.059</td>
<td>0.587</td>
<td>0.066</td>
<td>0.717</td>
</tr>
<tr>
<td>Third-order RMS (μm)</td>
<td>0.069</td>
<td>0.524</td>
<td>0.062</td>
<td>0.735</td>
</tr>
<tr>
<td>Fourth-order RMS (μm)</td>
<td>−0.005</td>
<td>0.961</td>
<td>0.062</td>
<td>0.735</td>
</tr>
<tr>
<td>Trefoil RMS (μm)</td>
<td>0.046</td>
<td>0.672</td>
<td>0.079</td>
<td>0.664</td>
</tr>
<tr>
<td>Coma RMS (μm)</td>
<td>0.229</td>
<td>0.032*</td>
<td>−0.049</td>
<td>0.790</td>
</tr>
<tr>
<td>Tetrafoil RMS (μm)</td>
<td>0.120</td>
<td>0.271</td>
<td>−0.115</td>
<td>0.526</td>
</tr>
<tr>
<td>Secondary astigmatism RMS (μm)</td>
<td>0.027</td>
<td>0.802</td>
<td>0.008</td>
<td>0.965</td>
</tr>
<tr>
<td>Spherical aberration (μm)</td>
<td>0.002</td>
<td>0.982</td>
<td>0.119</td>
<td>0.513</td>
</tr>
</tbody>
</table>

*Indicates statistical significance (p<0.05).

ATR, against-the-rule; BCVA, best-corrected visual acuity; CC, correlation coefficient; D, dioptres; IOL, intraocular lens; MA, minimum astigmatism; RMS, root mean square; WTR, with-the-rule.

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**Figure 1** Significant negative correlation between pupil size and apparent accommodation in pseudophakic eyes (Pearson’s correlation coefficient; \(r=−0.227, p=0.034\)). D, dioptre.

**Figure 2** Significant positive correlation between refractive astigmatism and apparent accommodation in pseudophakic eyes (Pearson’s correlation coefficient; \(r=0.228, p=0.034\)). D, dioptre.
aberration achieved a larger range of apparent accommodation. In addition, de Gracia et al.\textsuperscript{20} 21 showed that adding coma to astigmatism improved optical quality over astigmatism alone. Our results may suggest that some Zernike coefficients of coma aberrations contribute to apparent accommodation in concert with WTR astigmatism. Additionally, we have speculated that movements of the eyelids or the palpebral fissures\textsuperscript{7} 17 22 influence accommodation because narrowing palpebral fissures can reduce apparent pupil diameter in the vertical direction, enhancing depth of focus. However, another study with a large population is required to clarify the exact role of eyelid movement on apparent accommodation.

In eyes with MA, we found a significant correlation between corneal multifocality and apparent accommodation. There have been several other reports on the significant relationship between corneal multifocality and apparent accommodation in pseudophakic eyes.\textsuperscript{4} 9 10 Furthermore, in the stepwise multiple regression analysis, corneal multifocality was selected as the most relevant variable, followed by trefoil RMS. Oshika et al.\textsuperscript{10} demonstrated that third-order aberrations, especially vertical trefoil, of the cornea along with corneal multifocality contribute to apparent accommodation, which is in agreement with the clinical science group.bmj.com on November 4, 2016 - Published by group.bmj.com

Figure 3 Significant positive correlation between coma RMS and apparent accommodation in pseudophakic eyes (Pearson’s correlation coefficient; $r=0.229$, $p=0.032$). D, dioptre; RMS, root mean square.

Figure 4 Significant negative correlation between pupil size and apparent accommodation in pseudophakic eyes with against-the-rule astigmatism (Pearson’s correlation coefficient; $r=-0.470$, $p=0.005$). D, dioptre.

Figure 5 Significant positive correlation between refractive astigmatism and apparent accommodation in pseudophakic eyes with against-the-rule astigmatism (Pearson’s correlation coefficient; $r=0.529$, $p=0.001$). D, dioptre.

Figure 6 Significant positive correlation between coma RMS and apparent accommodation in pseudophakic eyes with minimum astigmatism (Pearson’s correlation coefficient; $r=0.409$, $p=0.047$). D, dioptre; RMS, root mean square.

Figure 7 Significant positive correlation between corneal multifocality and apparent accommodation in pseudophakic eyes with minimum astigmatism (Pearson’s correlation coefficient; $r=0.464$, $p=0.009$). D, dioptre.
results of the stepwise multiple regression analysis. In addition, a multifocal cornea has been hypothesised to represent the distribution of corneal refractive power similarly to trefoil. We are also interested in what type of shape induced corneal multifocality. In our results, a relatively larger difference was observed between corneal astigmatism and refractive astigmatism. We have speculated that internal astigmatism, including posterior corneal astigmatism, reduces corneal astigmatism. It may be possible to represent the shape of the multifocal cornea by analysing these factors, such as trefoil aberrations and corneal astigmatism. Therefore, further studies are needed in a larger group of patients to better understand this relationship.

In the analysis for whole patients, the results with similar ATR group were found. However, the factors associated with apparent accommodation in each group were different in the current study. Therefore, we consider it necessary to evaluate the role of astigmatism axis orientation on apparent accommodation.

Our study has some limitations. First, we did not include eyes with oblique astigmatism because our main goal was to compare the apparent accommodation mechanisms in eyes with ATR and WTR astigmatism, and few patients with oblique astigmatism were present in our study population. Several studies have shown that eyes with uncorrected oblique astigmatism have poorer visual performance than those with uncorrected ATR and WTR astigmatism. Understanding how apparent accommodation occurs in eyes with oblique astigmatism is interesting, and will be the subject of future studies. Second, some parameters, including age and pupil size, were not matched between groups at enrolment, which may have introduced some bias into our results. Such matching, however, is difficult because the type of astigmatism and pupil size are considerably age-dependent. Third, the number of eyes in each astigmatism group was small. We cannot completely deny the possibility that small sample size may contribute to these results. Hence, another well-designed study with a larger group of subjects should be conducted to confirm our findings. Fourth, we recruited only eyes with astigmatism <2.0 D because we judged that this is a clinically feasible condition after modern small-incision cataract surgery, and eyes with astigmatism ≥2.0 D are likely affected by a pathological condition. Therefore, the results of the current study may not be directly compared with those of the previous studies involving conventional extracapsular cataract extraction techniques and/or implantation of polymethyl-methacrylate IOL.

In conclusion, we found that smaller pupil size and greater refractive astigmatism contributed to apparent accommodation in eyes with <2.0 D of refractive ATR astigmatism. In eyes with WTR astigmatism, coma Zernike term associated with apparent accommodation was shown. In eyes with refractive MA, corneal multifocality contributed to apparent accommodation. These findings imply that the mechanism of apparent accommodation varies depending on the presence and direction of astigmatism in eyes with monofocal IOLs after cataract surgery. The current report represents the first study to investigate the influence of the status of refractive astigmatism on apparent accommodation after small-incision cataract surgery.

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