Purpose. The pathophysiology and pathogenesis of myopia are still a matter of controversy. Exaggerated longitudinal eye growth is assumed to play an important role in the development of myopia. A significant correlation between refraction and amount of near-work has been reported. However, current knowledge of changes of axial eye length with accommodation is limited because clinical ultrasound biometry does not provide the precision and resolution required to thoroughly investigate these phenomena.

Methods. Partial coherence interferometry (PCI), a noninvasive biometric technique, uses laser light with short coherence length in combination with interferometry to achieve precision in the micrometer to submicrometer range and resolution of 10 μm. In the present study this technique was used to investigate axial eye length changes in 11 emmetropic and 12 myopic eyes during monocular fixation at the far and near point. In 7 subjects, the contralateral eye has also been measured to investigate interocular differences in eye elongation.

Results. All investigated eyes elongated during accommodation. This elongation was more pronounced in emmetropes than in myopes (P < 0.001). Mean accommodation-induced eye elongations of 12.7 μm (range, 8.6–19.2 μm) and 5.2 μm (range, 2.1–9.5 μm), corresponding to a dioptric change of approximately −0.036 D and −0.015 D, were obtained for emmetropes and myopes. No significant difference in accommodative amplitudes between groups (5.1 ± 1.2 D [range, 3.8–7.1 D] versus 4.1 ± 2.0 D [range, 1.0–7.1 D]; P = 0.14) was detected. No significant interocular difference in accommodation-induced eye elongation was revealed (P = 0.86). Also, a mean backward movement of the posterior lens pole of 38 μm (range, 9–107 μm) was observed in both study groups.

Conclusions. The detected eye elongation can be explained by the accommodation-induced contraction of the ciliary muscle, which results in forward and inward pulling of the choroid, thus decreasing the circumference of the sclera, and leads to an elongation of the axial eye length. Finally, it was demonstrated that PCI, in contrast to clinical ultrasound, is capable of characterizing eye length changes during accommodation in humans. (Invest Ophthalmol Vis Sci 1998;39: 2140–2147)
have found that axial eye elongation produced by negative defocus requires an intact optic nerve, whereas deprivation-induced axial elongation still occurs if the optic nerve is cut. Nevertheless, some caution should be exercised when extrapolating these animal findings to naturally occurring myopia in humans, because several longitudinal and cross-sectional studies have demonstrated a moderate but significant correlation between refraction and amount of accommodation and near-work. For example, a study conducted on ophthalmologists revealed that 66% were myopic, with 50% of them having developed myopia after beginning the job, indicating that near-work acts as a trigger mechanism for the development of myopia. It may—in certain subgroups—be related to the onset of myopic progression.

Until now, only inconclusive studies on accommodation-induced eye length changes have been reported, demonstrating mean changes ranging from an 80-μm decrease to a 100-μm increase. These controversial results may be due to the limited resolution and precision (120–200 μm) of clinical ultrasound biometry for axial eye length measurements. An additional limitation of these studies arises from the fact that the fixation target has to be presented to the contralateral eye when conducting accommodation studies with ultrasound. Furthermore, biometric findings performed with applanation techniques of ultrasound may vary by ~140 μm because of different application depths of the cornea caused by the ultrasound probe. Partial coherence interferometry (PCI), a novel noninvasive optical ranging technique, has been developed. This technique has been successfully used for accurate biometry of intraocular distances with a precision of 0.3 μm to 10 μm, depending on the ocular structure being measured, and for high resolution (10 μm) topographic and tomographic in vivo imaging of the retina in humans. Analysis and quantification of the changes of the anterior eye segment during accommodation have been reported recently. In the present study this technique was used to assess axial eye length changes induced by accommodation in emmetropes and myopes.

**Methods**

**Dual Beam PCI**

The basic principle of dual beam PCI has been described in detail previously. Briefly, an external Michelson interferometer splits a light beam (λ = 855 nm) of high spatial coherence but very short coherence length into two parts, forming a dual beam. This dual light beam, which contains two beam components with a mutual time delay introduced by the interferometer, illuminates the eye, and both components are reflected at several intraocular interfaces, which separate media of different refractive indexes, for the measurement of the axial eye length, for example, at the anterior surface of the cornea and the inner surface of the retinal pigment epithelium. If the delay of these two light beam components, produced by the interferometer, equals a distance within the eye, an interference PCI-signal is detected. The obtained PCI signals are similar to those of ultrasound A-scans but have a very high resolution and precision, the latter being more than one order of magnitude better than that of clinical ultrasound biometry. Furthermore, this technique is a noncontact method with no need for local anesthesia, no risk of corneal infection, and no need for pupil dilation for in vivo measurements.

**Subjects and Study Design**

All research and measurements performed in this study followed the tenets of the Declaration of Helsinki; informed consent was obtained from all subjects in this study after the nature and possible consequences of the study had been explained. The study was approved by the ethics committee of the Vienna University School of Medicine.

Axial eye elongation during accommodation was investigated in 23 eyes of 23 normal female and male subjects (21–30 years of age), 11 of whom were emmetropic with a spherical equivalent (SE) ranging from +0.38 D to −0.75 D, and 12 myopic with a SE ranging from −1.0 D to −9.5 D. Refractive error was measured with an autorefractometer (KR 3500 Auto Kerato-Refraktometer; Topcon, Paramus, NJ). After performing 10 measurements of each eye, the mean value of the SE was calculated. These two groups were age-matched. The mean age of the emmetropes and myopes was 25.8 ± 2.7 years (mean ± SD; range, 21 to 29 years) and 25.0 ± 2.4 years (range, 22 to 30 years), respectively. Corneal thickness, anterior chamber depth, lens thickness, and vitreous length were measured during monocular fixation of the eye and the near point, by offering a moveable fixation target, a black crosshair (diameter, 5 mm; thickness, 0.5 mm) in front of a green light-emitting diode (λ = 565 nm; ~35 mcd), to the examined eye. A fixation distance ranging from 5 to 50 cm, and fixation at infinity could be offered. Intraocular distances and their changes were measured at the nearest and most distant, individually determined, point of fixation. The near point was determined by moving the target from the far point to the nearest individually determined distance, where the target could still be fixated and did not blur. Focusing distances could be measured with a ruler that was mounted on a rail and were used to determine accommodative amplitudes. None of the subjects wore glasses during measurements. By adding the measured intraocular distances, it was possible to calculate the total axial eye length (defined as the distance from the anterior corneal surface to the retinal pigment epithelium).

Also, measurements were performed in emmetropes during fixation at a distance of ~30 cm. Furthermore, the contralateral eye of seven subjects (mean age, 26.1 ± 1.8 years; range, 24 to 30 years) was measured to investigate interpupillary differences in eye elongation.

Because PCI yields optical distances, they need to be divided by the group refractive index of the respective ocular medium to obtain geometrical distances. These group refractive indexes were derived from the phase refractive indexes reported for each ocular medium in the literature, with medium dispersion assumed to be equal to that of water.

**Data Analysis**

Data are presented as mean values and ranges of geometrical distances. For the conversion of optical to geometrical dimensions, group refractive indexes were assumed to be equal for all accommodative states. Paired and unpaired
Near point

Focusing distance 30 cm

Far point

FIGURE 1. Partial coherence interferometry (PCI) measurements of the anterior eye segment of an emmetropic subject during fixation at the near point, at a focusing distance of 30 cm, and at the far point. Four PCI-signal peaks, arising from light reflected at the anterior and posterior corneal and lens surfaces, can be distinguished. During accommodation from the far to the near point, a decrease in anterior chamber depth and an increase in lens thickness are detected. In addition to the forward movement of the anterior lens pole, an approximately three to four times less pronounced backward movement of the posterior lens pole can be observed during accommodation from the far to the near point.

\[\text{Optical distance to anterior corneal surface (mm)}\]

FIGURE 2. Change of axial eye length during accommodation. The three different peaks are caused by reflection of the light at three retinal interfaces (probably the photoreceptor/retinal pigment epithelium interface, retinal pigment epithelium/choriocapillary interface, and choriocapillary/choroidal interface). Scans are shown during fixation at the near point, at a focusing distance of \(\sim 30\) cm, and at the far point. The plots have been enlarged to elucidate the displacement of the first of these peaks, which originates at the retinal pigment epithelium. This signal peak together with the peak reflected at the posterior lens surface (cf. Fig. 1) is used to determine the vitreous length, with a precision of \(5\ \mu\text{m}\). The axial eye length

\(t\)-tests were used to assess the change in eye length during accommodation. \(P < 0.05\) was considered to be significant. The precision of PCI was defined as the SD of multiple recorded consecutive measurements of the ocular medium under investigation.

RESULTS

Figure 1 shows three typical measurements of the anterior eye segment of an emmetropic subject during fixation at the near point, at a focusing distance of \(\sim 30\) cm, and at the far point. The PCI-signal intensity is plotted versus the optical distance to the anterior corneal surface. Four main peaks, arising from light reflected at the anterior and posterior corneal and lens surfaces, can be distinguished, indicating the corneal thickness, the anterior chamber depth, and the lens thickness, respectively. During fixation change from the far point to the near point, a significant decrease of the anterior chamber depth from 2.720 mm (fixation of the far point) to 2.650 mm (fixation distance of 30 cm) and 2.557 mm (fixation of the near point) was observed, and an increase of lens thickness from 4.092 mm (fixation of the far point) to 4.163 mm (fixation distance of 30 cm) and 4.314 mm (fixation of the near point) was observed. During maximum accommodation, the forward movement of the anterior lens pole is approximately three times that of the backward movement of the posterior lens pole. The geometrical corneal thickness in this case was \(\sim 534\ \mu\text{m}\) for all three accommodative states. The precision for the measurements of the anterior chamber depth and lens thickness was \(5\ \mu\text{m}\) in all subjects, and \(0.4\ \mu\text{m}\) for corneal thickness.

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Figure 2. Partial coherence interferometry (PCI) measurements of axial eye length during accommodation. The optical distances from the anterior corneal surface to peaks arising from three retinal interfaces, probably the photoreceptor/retinal pigment epithelium interface (1), retinal pigment epithelium/choriocapillary interface (2), and choriocapillary/choroidal interface (3), are indicated. The plots have been enlarged to elucidate the displacement of the first, highly reflective peak, which originates at the retinal pigment epithelium. Therefore, the peak, caused by light reflected at the internal limiting membrane, indicating the retinal thickness, is not illustrated.

was determined by the addition of corneal thickness, anterior chamber depth, lens thickness, and vitreous length, with a resulting precision of 8 \( \mu \)m. In the case shown in Figures 1 and 2, the eye length increased by 10 \( \mu \)m during accommodation.

Table 1 lists all measured intraocular distances and their absolute changes during fixation at the near point in relation to the far point. The mean axial eye length of emmetropes and myopes during fixation of the far point were 23.838 mm (range, 22.565-24.843 mm) and 25.174 mm (range: 22.905-27.481 mm), respectively. In all eyes tested in this study, a significant accommodation-induced increase of the axial eye length was detected. Figure 3 shows the absolute eye length changes of all emmetropic (left side) and myopic (right side) eyes as a function of accommodative amplitude relative to the far point. A highly significant difference in eye elongation during accommodation was detected \((P < 0.001)\). Mean accommodation-induced eye elongations of 12.7 \( \mu \)m (range, 8.6-19.2 \( \mu \)m) and 5.2 \( \mu \)m (range, 2.1-9.5 \( \mu \)m) were detected for the emmetropes and myopes, respectively. Although the mean accommodative amplitude in emmetropes was slightly greater but not significantly different from that of myopes \((5.1 \pm 1.2 \text{ D}; \text{range, 3.8-7.1 D}; 4.1 \pm 2.0 \text{ D}; \text{range, 1.0-7.1 D}; P = 0.14)\), a significant correlation between accommodation-induced eye elongation and accommodative amplitude was detected \((r = 0.47, P < 0.05)\). It has been shown, that a reduction in axial eye length of approximately 120 \( \mu \)m corresponds to a refractive error of approximately +0.34 D\(^{41,42}\). Therefore, the accommodation-induced eye elongations that were detected correspond to a dioptic change of approximately \(-0.036 \text{ D}\) and \(-0.015 \text{ D}\) for emmetropes and myopes, respectively.

In addition, a fixation target was offered at a fixation distance between the far and near points (30 cm) to all emmetropic eyes. As indicated in Figure 4, the measured axial eye lengths of all investigated eyes in this accommodative state were within the range measured during fixation at the far and near points. The mean axial eye elongation at this fixation distance was 5.4 \( \mu \)m (range, 3.5-7.6 \( \mu \)m). Axial eye lengths measured during fixation of the far point \((23.824 \pm 0.743 \text{ mm}; \text{range, 22.565-24.843 mm}); \text{fixation of a distance of 30 cm (23.830 \pm 0.744 mm; \text{range, 22.571-24.851 mm}); \text{fixation of the near point (23.837 \pm 0.745 mm; \text{range, 22.575-24.858 mm}) were significantly different (P < 0.0001).}

Maximum accommodation caused a decrease in anterior chamber depth of 131 \( \mu \)m (mean; range, 30-271 \( \mu \)m), an increase in lens thickness of 175 \( \mu \)m (mean; range: 45-340

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TABLE 1. Main Results of the Measurements of Intraocular Structures during Accommodation (mean ± standard deviation)

<table>
<thead>
<tr>
<th></th>
<th>Emmetropes</th>
<th>Myopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>25.8 ± 2.7</td>
<td>25.0 ± 2.4</td>
</tr>
<tr>
<td>Refraction (SE; D)</td>
<td>-0.34 ± 0.30</td>
<td>-3.50 ± 2.80*</td>
</tr>
<tr>
<td>Cylinder (D)</td>
<td>0.40 ± 0.34</td>
<td>0.54 ± 0.39</td>
</tr>
<tr>
<td>Accommodative amplitude (D)</td>
<td>5.1 ± 1.2</td>
<td>4.1 ± 2.0</td>
</tr>
<tr>
<td>Axial eye length (mm)</td>
<td>23.838 ± 0.737</td>
<td>25.174 ± 1.276*</td>
</tr>
<tr>
<td>Eye elongation (µm)</td>
<td>+12.7 ± 3.4</td>
<td>+5.2 ± 2.0*</td>
</tr>
<tr>
<td>Lens thickness (mm)</td>
<td>3.875 ± 0.243</td>
<td>3.672 ± 0.250</td>
</tr>
<tr>
<td>Lens thickness change (µm)</td>
<td>+170 ± 76</td>
<td>+180 ± 108</td>
</tr>
<tr>
<td>Anterior chamber depth (mm)</td>
<td>3.044 ± 0.246</td>
<td>3.322 ± 0.270*</td>
</tr>
<tr>
<td>Anterior chamber depth change (µm)</td>
<td>-126 ± 64</td>
<td>-135 ± 87</td>
</tr>
<tr>
<td>Vitreous length (mm)</td>
<td>16.401 ± 0.709</td>
<td>17.672 ± 1.239*</td>
</tr>
<tr>
<td>Vitreous length change, i.e., posterior lens pole movement† (µm)</td>
<td>-32 ± 20</td>
<td>-39 ± 24</td>
</tr>
<tr>
<td>Corneal thickness (µm)</td>
<td>518.0 ± 24.6</td>
<td>508.5 ± 44.0</td>
</tr>
</tbody>
</table>

Values are mean ± SD (range).
* Significantly different (P < 0.05).
† Negative values indicate a backward movement.
Intraocular distances during focusing the far point and their changes during fixating the near point are indicated for emmetropes and myopes.

and a backward movement of the posterior lens pole of 38 µm (mean; range, 9–107 µm; including all measured eyes of emmetropes and myopes). No significant difference between emmetropes and myopes was detected for the changes in the anterior eye segment during accommodation (P = 0.78 for the decrease in anterior chamber depth; P = 0.80 for the thickening of the lens; P = 0.58 for the movement of the posterior lens pole). Furthermore, there was no correlation between changes in lens thickness and eye elongation induced by accommodation (r = -0.02, P = 0.90).

A significant negative correlation of accommodation induced eye elongation with axial eye length (r = 0.36, P < 0.05) was detected, confirming that there is a reduced eye elongation in myopes. No significant interocular difference in accommodation induced eye elongation was revealed for the 7 bilaterally investigated subjects (P = 0.86). Mean eye elongations of 5.4 ± 2.0 µm and 5.6 ± 2.4 µm were detected for the right and the left eyes, respectively. There was no significant interocular difference in accommodative amplitude (4.3 ± 2.4 D, 4.4 ± 1.8 D, P = 0.76), axial eye length (25.310 ± 1.287 mm, 25.288 ± 1.273 mm, P = 0.81), or refraction (-3.4 ± 2.9 D, -3.1 ± 2.2 D, P = 0.43).

DISCUSSION

In our study partial coherence interferometry—in contrast to ultrasound—was demonstrated to be capable of accurately detecting accommodation-induced axial eye length changes due to its unprecedented high precision and resolution. All eyes investigated became elongated during accommodation, with no significant interocular difference.

EMMETROPES

![Figure 3](https://example.com/image3.png)

MYOPEs

![Figure 3](https://example.com/image4.png)

**Figure 3.** Absolute eye length changes as a function of accommodative amplitudes relative to the far point of all the emmetropic and myopic eyes investigated in this study.
Eye Elongation during Accommodation in Humans

This increase in eye length was more pronounced in emmetropes than in myopes. Although no significant difference in accommodative amplitudes was detected in either group, a significant correlation was detected between accommodation-induced eye elongation and accommodative amplitude. Also, a backward movement of the posterior lens pole was detected in emmetropes and in myopes. The amplitude of the posterior movement was approximately three times less than the anterior movement of the anterior lens pole. This is in contrast to the common view that the posterior lens pole remains virtually fixed during accommodation.43

Based on our results we cannot determine whether the detected accommodation-induced eye elongation is caused by a choroidal or a scleral effect—or a combination of both. One possible mechanism of eye elongation during accommodation could arise from the contraction of the ciliary muscle directly. This muscle consists of a ring of smooth muscles adjacent to the inner surface of the anterior sclera,43 it is effectively continuous with the choroid,44 and its fibers originate at the corneoscleral spur and insert at Bruch's membrane.45 Contraction of the ciliary muscle results in a maximal force of 5 mN46 and an axipetal displacement (i.e., forward and inward) of the zonular attachment, with a forward pulling of the choroid,45 thus possibly decreasing the circumference of the sclera, and thereby leading to an elongation of the posterior segment and consequently the axial length. In support of this hypothesis, a significant increase of the eye length was observed during accommodation in emmetropes and in myopes, and a significant correlation between axial elongation and accommodative amplitude.

Although no significant difference in accommodative demand was detected between groups, the mean accommodative amplitude of the myopic group was slightly lower. Therefore, a possible explanation for the detected difference in eye elongation during accommodation between emmetropes and myopes could be poorer accommodation of the latter group, because the far and near points were determined subjectively. Because of the high level of myopia in some subjects, the target distance was extremely close during accommodation at the near point. A slight error in measuring this distance would have a great effect on the dioptric amplitude after conversion. Furthermore, it has been shown that myopes have poor accommodation47 compared with emmetropes and that they are furthermore relatively insensitive to blur.48 The detected correlation between axial elongation and accommodative amplitude would be consistent with this interpretation.

Because the axial eye length was determined by measuring the distance between the anterior corneal surface and the retinal pigment epithelium, a change of choroidal thickness during accommodation cannot be excluded. Future investigations with increased sensitivity of PCI, and therefore the possibility of measuring choroidal thickness, may possibly help to discriminate between scleral and choroidal contributions to eye elongation during accommodation.

A potential limitation of the present study arises from the conversion of optical distances to geometrical distances. We cannot entirely exclude the possibility that the group refractive index of the lens changes during accommodation. An increase in refractive index of the lens of 0.3% could account for the measured results without a change of the eye length in emmetropes and myopes during accommodation. This seems unlikely because eye elongation is two times larger in emmetropes than in myopes. Hence, the refractive index would have to increase twice as much in emmetropes as in myopes. However, we did not observe a difference in lens thickening during accommodation between the two groups, and there was no correla-
tion between changes in lens thickness and accommodation-induced eye elongation. Therefore, an artifact seems unlikely.

The results of the current study prove that PCI is a new tool for the investigation of eye length changes during accommodation and, consequently, for studying the pathophysiology of myopia in humans. Based on our results one could hypothesize that prolonged excessive near-work causes slight eye elongation, possibly contributing to excessive axial eye growth. This hypothesis would be compatible with the association of near-work and myopia.

Acknowledgments

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References