Theoretical and Measured Pseudophakic Accommodation After Implantation of a New Accommodative Posterior Chamber Intraocular Lens

Achim Langenbacher, PhD; Berthold Seitz, MD, FEBO; Stefan Huber, MD; Nhungh X. Nguyen, MD; Michael Küchle, MD

Objective: To analyze different techniques of measuring accommodation after implantation of a new accommodative posterior chamber intraocular lens (PCIOL).

Methods: In this comparative, nonrandomized interventional study, we analyzed 15 eyes of 15 patients (aged 44-84 years) at 6 months after cataract surgery and PCIOL implantation (Akkommodative 1CU; HumanOptics AG, Erlangen, Germany) and compared these results with those of an age-matched control group (n=15). We used the following methods to measure accommodation: dynamic measurement with objective (videorefractometry [PowerRefractor; PlusOptix, Erlangen] and streak retinoscopy) and subjective (subjective near point [push-up test and accommodometer] and defocusing) techniques, as well as static measurement of the change in anterior chamber depth (ACD) using the IOLMaster (Zeiss, Jena, Germany) after pharmacological stimulation using 2% pilocarpine eye drops.

Main Outcome Measures: Theoretical accommodation calculated from the forward shift of the lens optics (decrease of ACD) using paraxial geometrical optics and measured accommodation amplitude.

Results: Accommodation amplitude (mean±SD; range; median) results after 6 months in the study and control groups were as follows: 1.00±0.44; 0.75-2.13; 1 diopter (D); and 0.35±0.26; 0.10-0.65; 0.25 D, respectively, using the PowerRefractor; 0.99±0.48; 0.13-2.00; 0.88 D; and 0.24±0.21; -0.13-0.75; 0.25 D, respectively, using retinoscopy; 1.6±0.55; 0.50-2.56; 1.7 D; and 0.42±0.25; 0.00-0.75; 0.50 D, respectively, using subjective near point; and 1.46±0.53; 1.00-2.50; 1.75 D; and 0.55±0.33; 0.25-0.87; 0.50 D, respectively, using defocusing. Anterior chamber depth decreased in the study and control groups as follows: 0.78±0.12; 0.49-1.91; 0.65 mm; and 0.16±0.09; 0.00-0.34; 0.18 mm, respectively, after applying 2% pilocarpine eyedrops, indicating an accommodation of 1.16±0.22; 0.72-1.88; 1.05 D vs 0.22±0.13; 0.00-0.47; 0.23 D (P=.001).

Conclusions: Accommodation after implantation of a presumably accommodative PCIOL can be measured with clinical methods or derived from the biometric data of the eye and the measured ACD decrease using geometrical optics. For clinical purposes, pseudophakic accommodation should be assessed with a variety of different techniques, including subjective and objective measurements. The theoretical approach using geometrical optics may be an additional indicator for the accommodative response in patients with pseudophakic eyes and may allow a subdivision of the measured accommodation into true pseudophakic accommodation and pseudoaccommodation.

Arch Ophthalmol. 2003;121:1722-1727

In patients with phakic eyes, several different measurement techniques and devices are available to assess accommodation.1,3 Some of these techniques are subjectively based on the patient’s capability of reading optotypes on a far or near target,1,4 whereas other techniques measure the refraction of the eye objectively.

In patients with pseudophakic eyes, objective measurement techniques of refraction or accommodation are more difficult to apply owing to a significant optical reflex from the anterior and the posterior surfaces of the artificial lens. Because the refractive index of the artificial lens material is significantly higher compared with the refractive index of the crystalline lens and because the surfaces of the artificial lens are mostly spherical in contrast with the aspherical crystalline lens, which has many (higher-order) optical aberrations, Purkinje images III and IV may interfere with the measurements of autorefractometers and videorefractometers. Thus, some of the measurement methods do not yield proper results in patients with pseudophakic eyes and should be used only with great care, whereas other methods have to be modified to provide correct results after cataract surgery. Furthermore, pupillary constriction induced by accommodation or pilocarpine eyedrops may interfere with correct measurements. If the concept of accommodation in pseudophakic eyes is based on a forward movement of the lens optic...
due to ciliary muscle contraction (focus-shift principle), accommodation amplitude can be determined from the change in anterior chamber depth (ACD) using ray-tracing techniques or calculating the refraction with intraocular lens prediction formulas using the biometric data in the accommodated and nonaccommodated state of the eye. The primary (object-side) focal point can easily be deduced using linear geometrical optics with simple matrix operations. Defining power matrices for each refractive surface and translation matrices for each space between the surfaces, the total optical system can be described with 1 resulting \(2 \times 2\) matrix. Thus, a translation of the lens optics can be transformed into an accommodation amplitude by calculating the primary focal point in both the nonaccommodated and accommodated states of the lens optics.

A series of subjective and objective direct and indirect measurement techniques of accommodation were used to validate pseudophakic accommodation. Some of these measurement techniques were performed dynamically with a variable-fixation target distance; other techniques were based on pharmacological stimulation (contraction or relaxation of the ciliary muscle) for measurement in static conditions. The purpose of this study was to compare different measurement techniques for accommodation in patients following implantation of the Akkommodative 1CU posterior chamber intraocular lens (PCIOL) (HumanOptics AG, Erlangen, Germany) and to compare these results with the theoretical pseudophakic accommodation calculated from the translation of the lens optics due to ciliary muscle contraction during accommodation using linear geometrical optics.

## METHODS

### STUDY DESIGN AND POPULATION

A prospective nonrandomized comparative study was undertaken following the tenets of the Declaration of Helsinki to investigate the results of implanting a new PCIOL. Before the study was started, inclusion criteria, exclusion criteria, intervals of follow-up, and examination methods were defined and documented in a study protocol.

Of 72 consecutive patients with senile or presenile cataracts who underwent phacoemulsification and implantation of the new PCIOL between June 2000 and October 2002, 15 patients (9 men and 6 women) with a postoperative follow-up of at least 6 months were included in the study. A complete set of measurements was performed for all patients at all follow-up examinations.

The study protocol of postoperative examinations included slitlamp evaluation, laser flare-cell photometry, appplanation tonometry, keratometry, corneal videokeratography with a topography analysis system (TMS-1, Tomey Corp, Nagoya, Japan), corneal specular microscopy (EM 1100; Tomey Corp.), subjective refraction, refraction, retinoscopy, autorefraction (RE; Canon Inc, Tokyo, Japan), videorefraction (PowerRefractor; PlusOptix, Erlangen, Germany) with a variable-fixation target distance and measurement of ACD (IOLMaster; Zeiss, Jena, Germany) as well as ultrasonic biometry (A-Scan AL-2000; Tomey GmbH, Erlangen, Germany) before and after application of pilocarpine eyedrops, and photodocumentation. Surgical intervention was standardized and has been described in detail in previous articles.

### CONTROL GROUP

A control group of 15 age-matched patients (aged 47-85 years; 7 men and 8 women) were analyzed for comparison. Patients were randomly selected from the routine cataract population undergoing phacoemulsification in our hospital. Patients underwent phacoemulsification and PCIOL implantation by the same surgeon (M.K.) with a comparable surgical technique and received either a 1-piece polymethyl methacrylate PCIOL through a 6-mm sclerocorneal tunnel (Pharmacia 811 B; Pharmacia & Upjohn, Erlangen) (n=9) or a 1-piece hydrophilic acrylic nonaccommodative PCIOL through a 3.2-mm sclerocorneal tunnel (K3; HumanOptics AG) (n=6). The preoperative and postoperative treatments were identical to those of the study group. Accommodation measurements and measurements of the change in ACD due to pharmacological stimulation of the ciliary muscle were performed at the 6-month follow-up examination.

### ASSESSMENT OF ACCOMMODATION AND MAIN OUTCOME MEASURES

Postoperative examinations were performed 4 weeks and 3 and 6 months following surgery. Patients underwent refraction for distance. Distance visual acuity was determined with best-distance correction. Subsequently, near-reading vision was determined using the same distance correction and Birkhauser reading charts (Scalae Typographicae Birkhaeuseri; Birkhauser Verlag, Basel, Switzerland) as well as Jaeger charts (Light-house, New York, NY) at a distance of 35 cm with an illumination of 70 candelas per square meter. The reading charts were held by the patients at a normal reading position (ie, angled slightly inferior by 20°).

With the videorefractor (PowerRefractor), the patient was asked to fixate alternately on a far target at a distance of 5 m and a near target at a distance of about 35 cm. Refraction and pupil diameter were measured and recorded continuously by the device. To prevent off-axis refraction errors due to eye movements, the near and far targets were positioned in a fixation line to the patient with a minimal tilt to the detection path of the infrared camera.

Near and distance refraction were determined by streak retinoscopy. All retinoscopy was performed by an experienced examiner who was not informed whether the individual patient had received the new PCIOL or a traditional PCIOL. For distance retinoscopy, the patient was asked to fixate on a visual chart projected at a distance of 5 m. For near retinoscopy, the patient was asked to fixate on a visual chart positioned at a distance of 35 cm.

Accommodation was determined subjectively using the same distance correction. With an accommodometer (Clement Clarke RAE; Frohnhaeuser, Unterhaching, Germany), a small reading chart was slowly moved toward the eye from a distance of 1 m (with a spherical reading glass of +2 diopters (D) added to the distance correction) until the patient noted blurring of the optotypes. Reading distance was converted to diopters and corrected for the 2-D near addition to get the subjective accommodation or reconverted to distance to get the subjective near point.

Defocusing was performed with a far-distance correction for the patient and reading charts at a distance of 5 m. Visual acuity was measured with defocusing of the patient in steps of 0.5 D, starting with +0.5 and ending with −3.0-D spherical glasses. For accommodation amplitude, we defined the minus lens with which the patient retained a visual acuity of 0.4 (20/50) in the affected eye.

The ACD was measured with the IOLMaster and by noncontact (immersion with balanced salt solution) ultrasonic biometry (A-Scan AL-2000). First, measurements were ob-
The focus-shift principle. The Akkommodative 1CU lens (HumanOptics AG, Erlangen, Germany) does not change its form or power but rather moves forward in near vision when the ciliary body changes in form and the pupil contracts. On the left side, the lens is shown in a nonaccommodated state, whereas on the right side, it is in the accommodated state. \( t \) indicates distances from the lens to the retina. \( R \) is the refractive power of the lens or through an interspace between lenses. This type of optical axis, which arises during the passage of the ray through the interspaces. This is done by specifying this formalism to a system with more than 1 lens (Figure). From the left, the spectacle correction (equivalent-power \( R_s \)) is followed by the single-surface cornea (equivalent-power \( R_c \) at a distance \( t_c \) behind the spectacle plane). The lens implant is predicted to lie at a distance \( t_l \) behind the corneal plane, which shortens during pseudophakic accommodation based on the focus-shift principle (dashed lines in the Figure). The total axial length of the eye is assumed to be \( t_a \) and the residual distance from the lens to the retina (vitreous) is \( t_r = t_a - t_l \).

Determination of the Primary Focal Point

Any optical system can be subdivided into refracting surfaces and their interspaces. An incident ray of light intersects a refractive surface with a certain angular direction and exits the surface in a different angular direction. Refraction can therefore be interpreted as a coordinate transformation specified as a matrix problem using a refraction matrix. A second type of matrix is called a translation matrix. Both the refraction and translation matrices are \( 2 \times 2 \). To determine the effect of an optical system on an incident ray of light, it is necessary to calculate the refractive effect of each interface and the translation of the ray through the interspaces. This is done by specifying the refraction and translation matrices of all refracting surfaces and interspaces and then multiplying them together to get the specification of the total optical system.

The refraction matrix \( P \) has the following form:

\[
P = \begin{bmatrix} 1 & -R \\ 0 & 1 \end{bmatrix}
\]

where \( R \) describes the refractive power of the surface. The translation matrix \( T \) has this characteristic format:

\[
T = \begin{bmatrix} 1 & 0 \\ t/n' & 1 \end{bmatrix}
\]

where \( t \) represents the interval between 2 refractive surfaces and \( n' \) represents the refractive index of the optical medium \( (t/n') \) represents the reduced distance between sequential surfaces. Distances are described in meters and refractive powers in diopters.

The system matrix \( P_{\text{system}} \) of an optical system consisting of the refractive elements \( R_1, R_2, \ldots, R_n \) from left to right and interspaces \( t_1, t_2, \ldots, t_n \) is defined as

\[
P_{\text{system}} = P_n \times T_{n-1} \times \ldots \times P_2 \times T_1 \times P_1
\]

with the definition of the refraction matrix \( P \) and the translation matrix \( T \) as shown earlier.\(^{11}\)

The primary (object side) \( (F_1) \) and secondary (image side) \( (F_2) \) focal points can be extracted from the elements of the system matrix \( P \) as follows:

\[
F_1 = \frac{a}{b} \quad F_2 = \frac{n'' - d}{b}
\]

where \( n \) is the refractive index of the medium before the lens and \( n'' \) is the refractive index behind it. Following the common convention in geometrical optics, light is considered to enter from the left, passing through the optical system and exiting to the right, and the focal points are referenced from the respective vertices of the lens surface. Distances with a negative value mean that the respective focal point is located to the left of the reference, whereas positive values indicate that the focal point is located to the right of the reference.

The optical system of the eye can be assessed by generalizing this formalism to a system with more than 1 lens (Figure). From the left, the spectacle correction (equivalent-power \( R_s \)) is followed by the single-surface cornea (equivalent-power \( R_c \) at a distance \( t_c \) behind the spectacle plane). The lens implant is predicted to lie at a distance \( t_l \) behind the corneal plane, which shortens during pseudophakic accommodation based on the focus-shift principle (dashed lines in the Figure). The total axial length of the eye is assumed to be \( t_a \) and the residual distance from the lens to the retina (vitreous) is \( t_r = t_a - t_l \).

Statistical Analysis

All data were collected with specifically designed data sheets and stored in a relational database (Access 2003; Microsoft, Redmond, Wash). Results were indicated descriptively with statistical analysis software (SPSS 10.0; SPSS Inc, Chicago, Ill) in a cross-sectional fashion. Comparisons between groups or variables were performed using nonparametric tests (Mann-Whitney U test for unpaired samples). For bivariate correlation analysis, Spearman rank correlation coefficient \( r \) was used. A \( P < .05 \) was considered statistically significant.

Results

Visual Acuity and Accommodation Without Pharmacological Stimulation

After 6 months, the distance visual acuity with distance correction ranged from 20/28 to 20/16 in the affected eye (median 20/20) in the study group and from 20/30 to 20/16 in the affected eye in the control group (Table 1). The subjective near point determined with best-distance correction ranged from 39 to 100 cm (mean ± SD, 75 ± 42 cm; median, 64 cm) in the study group and from 133 to 400 cm (mean ± SD, 210 ± 95 cm; median, 140 cm) in the control group. Near visual acuity with distance correction at 35 cm ranged from Birkhäuser 0.20 (Jaeger 7.00) to Birkhäuser 0.60 (Jaeger 1.00) (mean ± SD, 0.32 ± 0.11;
After 6 months, accommodative amplitude as determined by the PowerRefractor using a variable target distance (difference between near and distance refraction) ranged from 0.75 to 2.13 D (mean±SD, 1.00±0.44 D; median, 1.00 D) in the study group and from 0.10 to 0.65 D (mean±SD, 0.35±0.26 D; median, 0.30 D) in the control group (Table 2). Accommodative amplitude determined by streak retinoscopy (difference between near and distance refraction) ranged from 0.13 to 2.00 D (mean±SD, 0.99±0.48 D; median, 0.88 D) in the study group and from −0.13 to 0.75 D (mean±SD, 0.24±0.21 D; median, 0.25 D) in the control group. Accommodative amplitude calculated from subjective near point ranged from 0.50 to 2.56 D (mean±SD, 1.60±0.55 D; median, 1.70 D) in the study group and from 0.00 to 0.75 D (mean±SD, 1.42±0.25 D; median, 0.50 D) in the control group. Evaluated with defocusing, the accommodative amplitude ranged from 1.00 to 2.50 D (mean±SD, 1.46±0.53 D; median, 1.75 D) in the study group and from 0.25 to 0.87 D (mean±SD, 0.55±0.33 D; median, 0.50 D) in the control group.

**MEASURES WITH PHARMACOLOGICAL STIMULATION**

Six months after surgery, ACD decreased after use of 2% pilocarpine eyedrops by 0.49 to 1.26 mm (mean±SD, 0.78±0.12 mm; median, 0.65 mm) in the study group and by 0.00 to 0.34 mm (mean±SD, 0.16±0.09 mm; median, 0.18 mm) in the control group. Accommodative amplitude evaluated with streak retinoscopy (difference between near and distance refraction) ranged from 0.75 to 2.13 D (mean±SD, 1.00±0.44 D; median, 1.00 D) in the study group and from 0.10 to 0.65 D (mean±SD, 0.35±0.26 D; median, 0.30 D) in the control group (Table 2). Accommodative amplitude determined by streak retinoscopy (difference between near and distance refraction) ranged from 0.13 to 2.00 D (mean±SD, 0.99±0.48 D; median, 0.88 D) in the study group and from −0.13 to 0.75 D (mean±SD, 0.24±0.21 D; median, 0.25 D) in the control group. Accommodative amplitude calculated from subjective near point ranged from 0.50 to 2.56 D (mean±SD, 1.60±0.55 D; median, 1.70 D) in the study group and from 0.00 to 0.75 D (mean±SD, 1.42±0.25 D; median, 0.50 D) in the control group. Evaluated with defocusing, the accommodative amplitude ranged from 1.00 to 2.50 D (mean±SD, 1.46±0.53 D; median, 1.75 D) in the study group and from 0.25 to 0.87 D (mean±SD, 0.55±0.33 D; median, 0.50 D) in the control group.

**Table 1. Distance and Near Visual Acuity With Far-Distance Correction of 15 Eyes Following Implantation of an Accommodative Posterior Chamber Intraocular Lens**

<table>
<thead>
<tr>
<th>Follow-up Examination</th>
<th>Best-Corrected Distance Visual Acuity</th>
<th>Near Visual Acuity (35 cm) With Far-Distance Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Study Group</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Week 4</td>
<td>0.92 ± 0.18 (0.80 to 1.25)</td>
<td>1.00 ± 0.37 (0.30 to 0.60) ; 0.35</td>
</tr>
<tr>
<td>Month 3</td>
<td>1.06 ± 0.18 (0.80 to 1.25)</td>
<td>1.00 ± 0.38 (0.20 to 0.70) ; 0.35</td>
</tr>
<tr>
<td>Month 6</td>
<td>1.02 ± 0.20 (0.70 to 1.25)</td>
<td>1.00 ± 0.32 (0.11 to 0.60) ; 0.30</td>
</tr>
<tr>
<td>Control Group†</td>
<td>0.93 ± 0.22 (0.60 to 1.25)</td>
<td>1.00 ± 0.14 (0.05 to 0.3) ; 0.15</td>
</tr>
</tbody>
</table>

*Values are expressed as mean ± SD (range); median. The accommodative lens used was Akkommodative 1 GU (HumanOptics AG, Erlangen, Germany). †Control group (n = 15) had conventional intraocular lens.

The calculated accommodation amplitude in our patients did not differ significantly from the corresponding value measured with the defocusing technique (P = .15), the accommodometer (P = .08), or videorefractometry (P = .05), but it was significantly larger than the corresponding value as assessed by streak retinoscopy (P = .02). It correlated significantly with the accommodation amplitude evaluated with the defocusing technique (r = .52; P = .01) and to a borderline extent with the accommodometer (subjective near point) (r = .41; P = .05), but it did not correlate with the accommodation amplitude evaluated with streak retinoscopy (r = .42; P = .08) or the respective value from the videorefractometry (r = .41; P = .12).

In the control group, there was no significant statistical difference between the calculated accommodation amplitude based on the forward shift measured with the IOLMaster (P ≥ .10) or ultrasound (P ≥ .08) 6 months after surgery. It did not correlate with any of the measurement techniques for accommodation response derived from the forward shift of the PCIOL optics measured with the IOLMaster (P ≥ .06) or ultrasound (P ≥ .08).

Presbyopia is one of the great unsolved challenges in ophthalmology today. Ever since von Helmholtz,14 many investigators analyzed mechanisms of accommodation, presbyopia, and potential solutions.1,14-18

We believe that 2 points are important with regard to research on accommodative intraocular lenses: terms and methods. First, in the literature, various terms such as accommodation, pseudaccommodation, and apparent accommodation are being used interchangeably with regard to pseudophakic eyes.4,19-21 We define pseudophagic accommodation as the dynamic change of the refractive state of the pseudophakic eye caused by interactions between the contracting ciliary muscle and the zonules (capsular bag) of the intraocular lens, resulting in a change of refraction at near fixation.3 Furthermore, we define pseudophagic pseudocommodation (apparent accommodation) as static optical properties of the pseudophakic eye independent of the ciliary muscle, resulting in improved, uncorrected near vision.7

In the last 20 years, several measuring devices for the accommodative response have been developed. One
Accommodation amplitude is based on the forward translation of the lens optics during ciliary muscle contraction using linear geometrical optics. The accommodative lens used was Akkommodative 1 CU (HumanOptics AG, Erlangen, Germany).

The ACD static measures were determined with pharmacological stimulation before and 30 minutes after application of 2% pilocarpine eyedrops.

One of the unsolved problems in measuring the accommodation amplitude of a patient is the lack of repeatability. Accommodation is dependent on the general condition of the patient as well as external measuring conditions. Small variations of parameters may effect completely different accommodative results.

Another problem is the cognitive demand on accommodation. Optotypes on a reading chart have to be a compromise. If the optotype size is too small, the patient cannot read it and no accommodation can be measured. In contrast, if the optotype is too large, we observe underaccommodation of the patient and get an artificially small accommodation amplitude. Furthermore, the distance of the optotype should be chosen carefully. If the distance is too small, the patient cannot focus on the reading chart for the total period of the measurement and fluctuations in the accommodation amplitude are measured.

The Akkommodative 1CU PCIOL that our data were based on was developed to allow transmission of the contracting forces of the ciliary body into anterior movement of the lens optics to achieve pseudophakic accommodation. The lens positions in the nonaccommodated and the accommodated states were used in our study to derive the amplitude of pseudophakic accommodation through linear geometrical optics. This value was independent of any pseudoaccommodation, which may also be observed in patients with pseudophakic eyes with a nonaccommodative lens implant. Thus, the indirect method of measuring the change in ACD for the prediction of the accommodative response may be the first step toward objectively evaluating the true pseudophakic accommodation in cases in which the PCIOL is working according to the focus-shift principle.

In patients with pseudophakic eyes, the effects of accommodation and pseudoaccommodation are superimposed and make the separation of both effects difficult. With dynamic conditions, this separation is not possible and the subjective near point assessed with the push-up test and the defocusing or fogging technique yields the most stable results to determine accommodation amplitude, whereas videorefractometry with the PowerRefractor lacks accuracy owing to determination of the true Purkinje image I from the anterior corneal surface and elimination of the Purkinje images III and IV for calculation of the illumination gradient of the cornea. If we want to separate the effect of pseudophakic pseudoaccommodation in patients with a PCIOL working with the

### Table 2. Postoperative Accommodation Amplitude Calculations of 15 Eyes Following Implantation of an Accommodative Posterior Chamber Intraocular Lens

<table>
<thead>
<tr>
<th>Follow-up Examination</th>
<th>Videorefractometry</th>
<th>Streak Retinoscopy</th>
<th>Subjective Near Point, m</th>
<th>Defocusing With Minus Glasses (Fogging)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Study Group</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Week 4</td>
<td>1.19 ± 0.71 (0.63 to 2.00); 1.50</td>
<td>1.10 ± 0.49 (0.13 to 1.88); 1.00</td>
<td>1.97 ± 0.45 (1.33 to 2.70); 2.00</td>
<td>1.43 ± 0.60 (1.00 to 2.00); 1.50</td>
</tr>
<tr>
<td>Month 3</td>
<td>0.96 ± 0.72 (0.75 to 2.38); 1.00</td>
<td>1.10 ± 0.56 (0.38 to 1.88); 1.12</td>
<td>1.87 ± 0.42 (1.00 to 2.78); 1.85</td>
<td>1.66 ± 0.48 (1.50 to 2.50); 1.75</td>
</tr>
<tr>
<td>Month 6</td>
<td>1.00 ± 0.44 (0.75 to 2.13); 1.00</td>
<td>0.99 ± 0.48 (0.13 to 2.00); 0.88</td>
<td>1.60 ± 0.55 (0.50 to 2.56); 1.70</td>
<td>1.46 ± 0.53 (1.00 to 2.50); 1.75</td>
</tr>
<tr>
<td>Control Group‡</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Month 6</td>
<td>0.35 ± 0.26 (0.10 to 0.65); 0.30</td>
<td>0.24 ± 0.21 (−0.13 to 0.75); 0.25</td>
<td>0.42 ± 0.25 (0.00 to 0.75); 0.50</td>
<td>0.55 ± 0.33 (0.25 to 0.87); 0.50</td>
</tr>
</tbody>
</table>

*Values are expressed in diopters as mean ± SD (range), median. The accommodative lens used was Akkommodative 1 CU (HumanOptics AG, Erlangen, Germany).
†Control group (n = 15) had conventional intraocular lens.

### Table 3. Postoperative Decrease of the Anterior Chamber Depth and Calculated Accommodation Amplitude in 15 Eyes Following Implantation of an Accommodative Posterior Chamber Intraocular Lens

<table>
<thead>
<tr>
<th>Follow-up Examination</th>
<th>IOLMaster Measurement</th>
<th>Ultrasonic Biometry Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Decrease in ACD, mm</td>
<td>Accommodation Amplitude, D</td>
</tr>
<tr>
<td>Study Group</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Week 4</td>
<td>0.38 ± 0.14 (0.12 to 0.46); 0.36</td>
<td>0.57 ± 0.21 (0.19 to 0.71); 0.51</td>
</tr>
<tr>
<td>Month 3</td>
<td>0.88 ± 0.48 (0.51 to 1.91); 0.66</td>
<td>1.27 ± 0.48 (0.71 to 2.43); 1.03</td>
</tr>
<tr>
<td>Month 4</td>
<td>0.78 ± 0.12 (0.49 to 1.26); 0.65</td>
<td>1.16 ± 0.22 (0.72 to 1.88); 1.05</td>
</tr>
<tr>
<td>Control Group‡</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Month 6</td>
<td>0.16 ± 0.09 (0.00 to 0.34); 0.18</td>
<td>0.22 ± 0.13 (0.00 to 0.47); 0.23</td>
</tr>
</tbody>
</table>

Abbreviations: ACD, anterior chamber depth; D, diopter.

*The ACD static measures were determined with pharmacological stimulation before and 30 minutes after application of 2% pilocarpine eyedrops.
†Control group (n = 15) had conventional intraocular lens.
‡Control group (n = 15) had conventional intraocular lens.

of the classic devices for assessment of accommodation is a modified version of the refractometer (Canon AutoRef R-1; Tokyo) with widespread and extensive use in clinical practice. Most of these devices show valid, reliable results in patients with phakic eyes but fail in measuring pseudophakic eyes. Limitations of such instruments are encountered with pupil sizes of less than 2.5 to 3.0 mm.

One of the unsolved problems in measuring the accommodation amplitude of a patient is the lack of repeatability. Accommodation is dependent on the general condition of the patient as well as external measuring conditions. Small variations of parameters may effect completely different accommodative results.

Another problem is the cognitive demand on accommodation. Optotypes on a reading chart have to be a compromise. If the optotype size is too small, the patient cannot read it and no accommodation can be measured. In contrast, if the optotype is too large, we observe underaccommodation of the patient and get an artificially small accommodation amplitude. Furthermore, the distance of the optotype should be chosen carefully. If the distance is too small, the patient cannot focus on the reading chart for the total period of the measurement and fluctuations in the accommodation amplitude are measured.

The Akkommodative 1CU PCIOL that our data were based on was developed to allow transmission of the contracting forces of the ciliary body into anterior movement of the lens optics to achieve pseudophakic accommodation. The lens positions in the nonaccommodated and the accommodated states were used in our study to derive the amplitude of pseudophakic accommodation through linear geometrical optics. This value was independent of any pseudoaccommodation, which may also be observed in patients with pseudophakic eyes with a nonaccommodative lens implant. Thus, the indirect method of measuring the change in ACD for the prediction of the accommodative response may be the first step toward objectively evaluating the true pseudophakic accommodation in cases in which the PCIOL is working according to the focus-shift principle.

In patients with pseudophakic eyes, the effects of accommodation and pseudoaccommodation are superimposed and make the separation of both effects difficult. With dynamic conditions, this separation is not possible and the subjective near point assessed with the push-up test and the defocusing or fogging technique yields the most stable results to determine accommodation amplitude, whereas videorefractometry with the PowerRefractor lacks accuracy owing to determination of the true Purkinje image I from the anterior corneal surface and elimination of the Purkinje images III and IV for calculation of the illumination gradient of the cornea. If we want to separate the effect of pseudophakic pseudoaccommodation in patients with a PCIOL working with the
focus-shift principle, it is useful to measure the change in ACD after pharmacological stimulation of the ciliary muscle. This maximum effect reached with miotic or mydriatic eyedrops may not be a realistic prediction for the true accommodation stimulus in patients with pseudophakic eyes but instead demonstrates the capability of a potential maximum forward movement of the intraocular lens during accommodation. Calculation of the object-side focal point was performed from the matrix representation of the eye both in the nonaccommodated and the accommodated states using linear geometrical optics. In the nonaccommodated state, we calculated the system matrix of the spectacle-corrected eye with the individual biometric data and with the PCIOL at the effective lens position. In the accommodated state, we calculated the system matrix with the spectacle correction derived from the nonaccommodated state and the PCIOL in a position shifted forward from the effective lens position with the individually measured change in ACD. From the system matrix derived from the accommodated state, we calculated the primary focal point (object distance for the focal plane at the retina) and converted this value to the theoretical pseudophakic accommodation amplitude.

Using subjective and objective criteria, pseudophakic accommodation with the Akkommodative 1CU PCIOL significantly exceeded that with a conventional intraocular lens. In the study group, the theoretical accommodation amplitude derived from the ACD change measured with the IOLMaster and ultrasound correlated with the defocusing technique and subjective near point but not with videorefractometry or streak retinoscopy.

Accommodation after implantation of an accommodative intraocular lens can be measured with a variety of clinical methods or derived from the biometric data of the eye and the measured ACD decrease using linear geometrical optics. This theoretical approach may be an additional indicator for the accommodative response in patients with pseudophakic eyes and may allow a subdivision of the measured accommodation into true pseudophakic accommodation and pseudo-accommodation.

Submitted for publication April 15, 2003; final revision received May 15, 2003; accepted June 6, 2003.

This study was supported by Freistaat Bayern (FUTUR-Programm zur Förderung des Forschungs und Wissenstransfers an den Bayerischen Universitäten) and Neurozentrum, University Erlangen-Nürnberg, Erlangen, Germany.

This study was presented in part at the annual meeting of the American Academy of Ophthalmology; October 23, 2002; Orlando, Fla.

Corresponding author and reprints: Achim Langenbucher, PhD, University Eye Hospital, University Erlangen-Nürnberg, Schwabachenlange 6, D-91054 Erlangen, Germany (e-mail: achim.langenbucher@augen.imed.uni-erlangen.de).

REFERENCES