Anterior Chamber Depth and IOL Calculations

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In biometry, the anterior chamber depth (ACD) is defined as the distance between the central anterior corneal epithelium and the anterior lens capsule of the crystalline lens [1]) or the anterior surface of the intraocular lens (IOL) or the anterior surface of the remaining anterior capsule or anterior iris surface in aphakic eyes. The thickness of the central cornea is included. This is important since ACD is often confused with aqueous depth (AQD), which is measured as the distance between the corneal endothelium and the anterior lens capsule of the crystalline lens [1].

Many different devices are available to measure the ACD, such as optical coherence tomography (OCT), partial coherence interferometry (PCI), Scheimpflug imaging, and ultrasound and ultrasound biomicroscopy (UBM). However, Nakakura et al. showed that ACD measurements of those devices were significantly different except for OCT and PCI measurements which were interchangeable [2]. Although good agreement was found for those devices, recent findings suggest that even in two different swept source OCT based biometry devices (Zeiss IOL Master 700 vs Heidelberg Engineering ANTERION) devices should not be used interchangeably [3]. Further, good agreement between OCT and PCI was not confirmed [4] and interchangeability might differ between phakic and pseudophakic eyes [5].

A cross-sectional study (The Singapore Chinese Eye Study) found that the determinants of ACD are mainly the lens vault (LV) and the posterior corneal arc length (PCAL) [6]. LV was defined as the perpendicular distance from the horizontal line between the 2 scleral spurs to the anterior pole of the crystalline lens, and the PCAL was defined as the arc distance of the posterior corneal border between scleral spurs.

In clinical practice, the dynamics of ACD change after cataract surgery is an essential factor for refractive outcome since 1 mm in ACD change results in a 1.44 diopter spherical equivalent change in a normal eye [7].

Impact of Postoperative ACD

In cataract surgery, the natural crystalline lens is replaced by an IOL. Nowadays, patients' expectations are high and cataract surgery is not only restoring vision it is also optimizing refraction.

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However, between 10 and 20% [8–10] and with up-to-date formulae between 2% and 5% [11] of the patients post-operatively need a refractive correction of more than ±1 diopter (spherical equivalent). In these patients, unaided visual acuity is low, and consequently, satisfaction is reduced. Moreover, these refractive surprises are a common cause for IOL explantation [12].

Uncertainty about the refractive outcome is triggering the research field of biometry and power calculation. Investigating the error distribution of different factors on the postoperative manifest refraction, many factors were shown to have a significant impact [7] such as axial eye length [13–15], corneal anterior apical radius (mm), corneal posterior/anterior radius ratio [14, 16, 17], corneal anterior and posterior asphericity [14, 16, 17], corneal thickness [14, 16, 17] and the refractive indices of aqueous and vitreous, as well as pupil size (mm)[18], the error of the postoperative manifest subjective refraction itself [19], and most importantly the prediction of the postoperative ACD [20]. Taking into account the three variables axial eye length, corneal power, and prediction of the postoperative ACD, an impact of 36%, 22%, and 42% was found, respectively [21]. The principles of basic optics tell us that the impact of postoperative change of ACD increases with IOL power. This effect is multiplied by the fact that the relative change in ACD after cataract surgery is larger in short eyes than in long eyes [22, 23].

Postoperative ACD Prediction

Consequently, the main source of error for the refractive outcome is the prediction of the postoperative IOL position, or postoperative ACD. Today, most conventional IOL power calculation formulae are including a factor correcting for the postoperative IOL position. To estimate the postoperative IOL position/ postoperative ACD, the concept of the effective lens position (ELP) was introduced for thin lens formulas, i.e., using simplified models for the cornea and the lens. The ELP does not correspond to the anatomical IOL position and is used as a "fudge" factor to optimize the formulae for empirical data. In thick lens formulas, the total power of the IOL is not located in the ELP but is assumed to be distributed on the anterior and posterior IOL surface, therefore using powers and positions of both anterior and posterior IOL surfaces. To date, there are several approaches to estimate the postoperative IOL position/postoperative ACD:

1. Retzlaff et al. [24], Hoffer [24, 25], and Holladay et al. [26] used axial eye length (AL) and corneal power (K).
2. Haigis [27] used AL and preoperative ACD.
3. Olsen [28] developed a thick lens formula using AL, ACD, crystalline lens thickness (LT), corneal radius (CR), and preoperative refraction. Similarly, the Okulix algorithm (not published) used AL, ACD, and LT. Later, Olsen established the C-constant method, which is not dependent on the K-reading or the axial length. The C-constant defines the physical IOL position from the preoperative ACD and lens thickness [29].
4. Barrett [30] used a theoretical model eye in which ACD is related to AL and K and is also determined by the relationship between the A-constant and a "lens factor."
5. Fourth- and fifth-generation formulae use more variables.

.Olsen [28] included the LT as a predictor for the postoperative IOL position, and this was debated controversially. Initially, Norrby also incorporated the LT as a predictor for the haptic plane [31, 32]. Finally, however, Norrby et al. showed that LT was not a relevant prediction parameter [33]. In this study, Norrby et al. aimed to develop algorithms for preoperative estimation of the true postoperative IOL position. Fifty patients were implanted randomly with a 3-piece IOL model in one eye and a single-piece model in the other eye. Preoperatively, the IOLMaster was used to determine axial length, ACD, and mean corneal radius. Lens thickness and corneal width were measured with the ACMaster. Postoperative IOL position was measured with partial coherence laserinterferometry (Zeiss ACMaster). Data for both IOL models were pooled, and partial least-square regressions in various combinations of prediction parameters were calculated. It was shown that nothing was gained when including more parameters than axial length and preoperative ACD. In fact, preoperative ACD alone was a sufficient predictor. The following relationship was found (Formula 1).

$$\text{Postoperative anterior lens position} = 4.415 + 0.3587 \times \text{Preoperative ACD}$$

Formula 1 True Postoperative ACD

Postoperative ACD prediction is a challenging field of biometry, and there is only little literature on dealing with the true IOL position like Norrby et al. described it [33]. Naeser designed a formula that used the preoperative posterior lens capsule as a predictor for the postoperative IOL position/ACD [34] (Formula 2)

$$\begin{aligned} \text{PLC} &= 2.4 + 0.011 \times \text{Age} + 0.171 \times \text{ACD} + 0.051 \times \text{AL} \text{ACDpostOP} = \text{PLC} - \text{LPCD} - \text{IOLT} \text{PLC} \\ &= 2.40 + 0.011 \times \text{Age} + 0.171 \times \text{ACD} + 0.051 \times \text{AL} \text{ACDpostOP} = \text{PLC} - \left(\text{LPCD} + \text{IOLT}\right) \end{aligned}$$

Formula 2 Naeser's Prediction Algorithm for the Posterior Lens Capsule (PLC) and the Postoperative ACD

PLC = postoperative posterior lens capsule.

ACD = preOP ACD

AL = axial eye length

LPCD = lens posterior capsule distance

IOLT = thickness of the IOL

Naeser et al. intended to come up with a true way of predicting the postoperative IOL position; however, it turned out to be an empirical regression model. Three factors in their models were observed to be good predictors: age, preoperative ACD, and axial eye length. And again lens thickness was identified to have almost no influence. This is most likely due to "intercorrelation" (collinearity) of the data in their study. That applies to lens thickness and age, but also to ACD (inversely). Moreover, weaker zonules in the elderly population could cause a more posterior position of the posterior lens capsule resulting in a deeper ACD.

Norrby picked up the idea of predicting a true way of the postoperative IOL position/post-operative ACD and further developed this concept by introducing the lens haptic plane concept for normal looped lenses (LHP) [31, 32, 35]. The LHP is defined as the plane through the vertices of the loops approximating the equator of the lens. Since the measurement of this position was not possible, the LHP was estimated (Formula 3).

LHP = lens haptic plane ≈ equator of the lens capsule

ACD = preOP ACD

PLC = 2.4 + 0.011 × Age + 0.171 × AC D + 0.051 × AL

ACDpostOP = PLC – LPCD – IOLT

PLC = 2.40 + 0.011 × Age + 0.171 × A CD+ 0.051 × AL

ACDpostOP = PLC – (LPCD + IOLT)

LHP = ACD + Const × LEN

LEN = Lens thickness (preOP)

Formula 3 Lens Haptic Plane Formula

The LHP defines the haptic plane but does not predict the position of the anterior IOL surface. Therefore, the term "compressed vault height" was suggested to describe the distance between the LHP and the anterior IOL surface. Major forces that have an impact on the position of the anterior IOL surface are postoperative shrinkage of the lens capsule and the IOL haptics, which will be described later. To overcome the LHP estimation, intraoperative optical coherence tomography (OCT) scans of the anterior lens capsule of the aphakic eye enable measurements of a position close to the theoretical LHP. This new approach was introduced by us [36, 37]. Figure 35.1 shows the significant change of ACD before and after removing the crystalline lens.

The best intraoperative prediction factor for the postoperative IOL position/ postoperative ACD in this study was the anterior lens capsule after implanting a capsular tension ring (CTR_A) (Fig. 35.2), followed by the anterior lens capsule without a CTR (aphak_a). Overall, the posterior lens capsule was a poor predictor.

Moreover, we showed that the intraoperative optical coherence tomography mea-

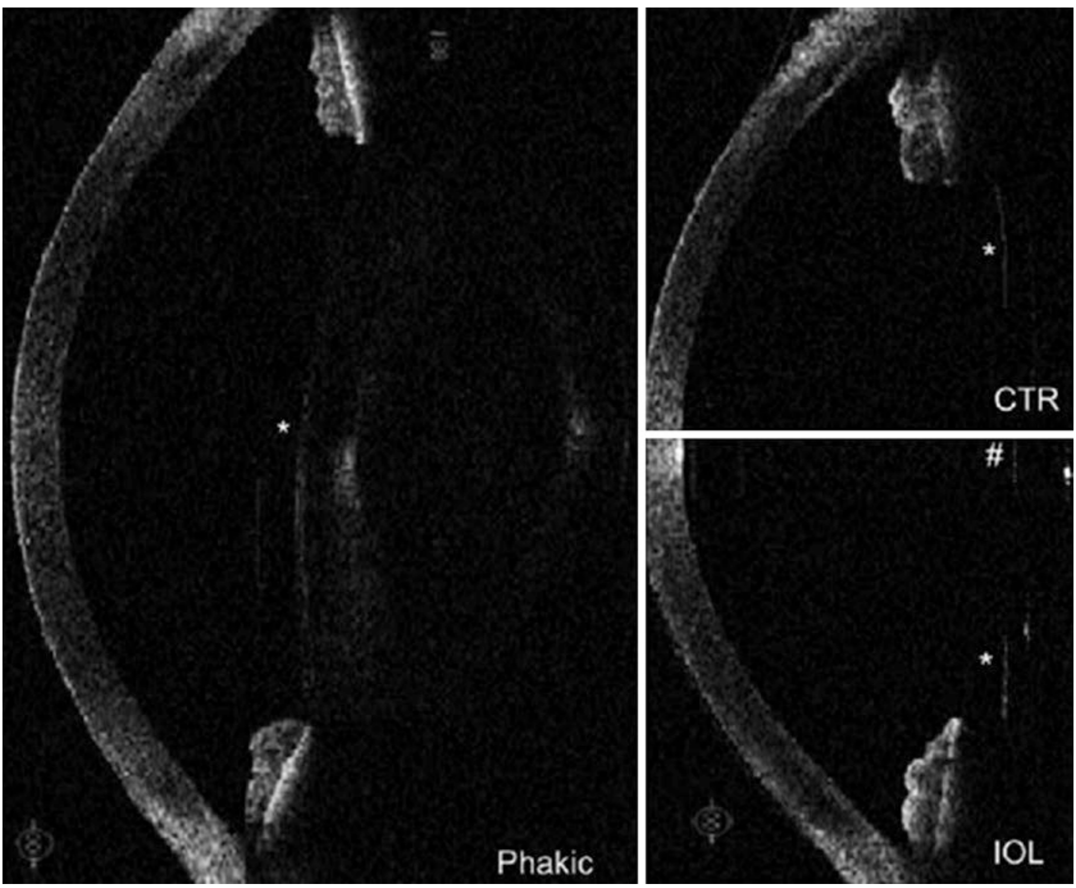


Fig. 35.1 OCT of the anterior segment before cataract surgery and intraoperative after phacoemulsification and capsular tension ring (CTR) implantation [36, 37]. * Anterior lens capsule # center of the anterior surface of the IOL

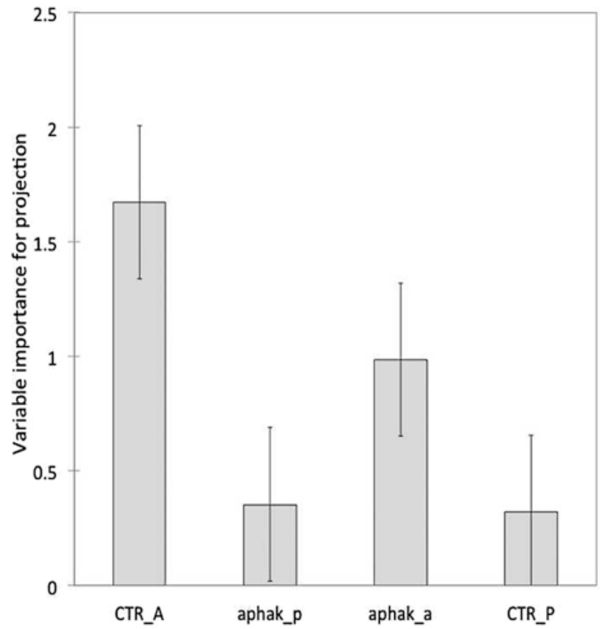


Fig. 35.2 Influence of intraoperative measurements (explanatory variables) on the postoperative ACD (dependent variable) (Hirnschall, Amir-Asgari, et al. 2013). Anterior lens capsule after implanting a capsular tension ring (CTR_A), anterior lens capsule without a CTR (aphak_a), posterior lens capsule after implanting a capsular tension ring (CTR_P), posterior lens capsule without a CTR (aphak_p)

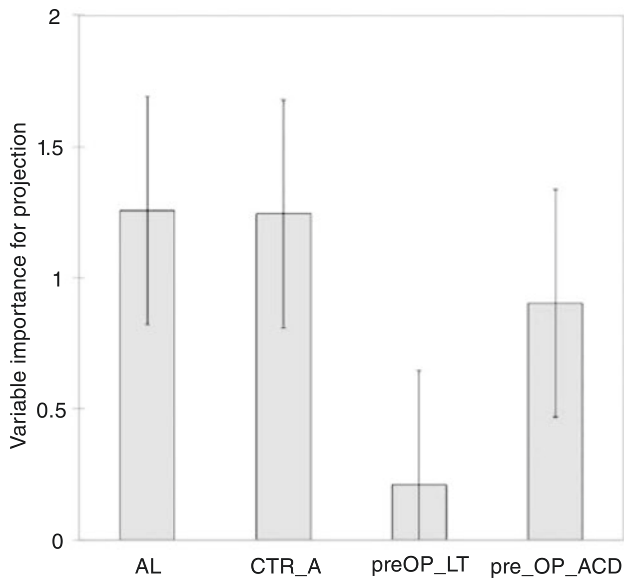
surements of the anterior capsule are a better predictor of the postoperative IOL position/ postoperative ACD compared with preoperatively measured factors (Fig. 35.3). This is especially true in the first hours after lens extraction and then becomes less obvious (but in total still significant) 3 months after cataract surgery due to a further shift of the ACD that is probably more due to lens capsule shrinkage than due to the overall anterior segment anatomical situation [36, 37].

As a consequence, using the intraoperative aphakic ACD for lens power calculation helps to better predict the refractive outcome [38]

Reflecting on our concept measuring the anterior lens capsule after CTR implantation it might be possible that CTR implantation by itself could alter ACD. However, CTR implantation had no significant influence on the postoperative axial IOL position (Fig. 35.4) [39]. Moreover, Weber et al. showed that there was no effect of a CTR on the A-constant for the SRK/T formula (predicting ELP instead of the real IOL position).

Recently, we confirmed that intraoperative aphakic ACD (time-domain OCT) measurements (aphakic eye) predict the postoperative ACD better than preoperative ACD (swept source OCT) measurements [40]. This was independent of whether an open-loop IOL or plate haptic IOL was implanted. Moreover, combining intraoperative aphakic ACD measurements and preoperative ACD measurements resulted in the best postoperative ACD prediction. In detail, the combined prediction was based on partial least-square regression as follows (Formula 4 + Formula 5). Furthermore, a corrected intraoperative ACD value was obtained by adding the mean difference between the 2-month ACD and intraoperative ACD to the intraoperative ACD. The corrected intraoperative ACD value was then calculated to 0.699 ± 0.502 mm. Table 35.1 demonstrates the predictive power of each formula and the effect on the refractive outcome.

$$\text{Postop ACD} = 2.86 + 0.31 \times \text{Intraoperative ACD} + 0.2 \times \text{Preoperative ACD}$$



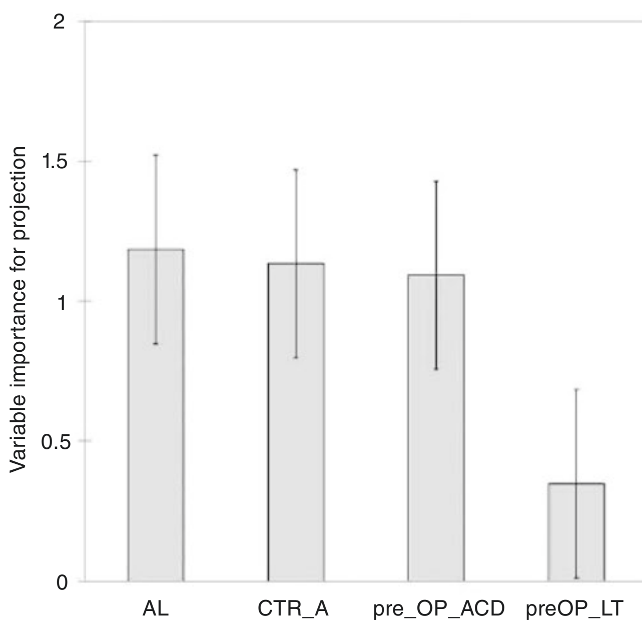


Fig. 35.3 Variable importance for projection on the ACD (1 h after surgery: upper graph; 3 month after surgery: lower graph) [36, 37]

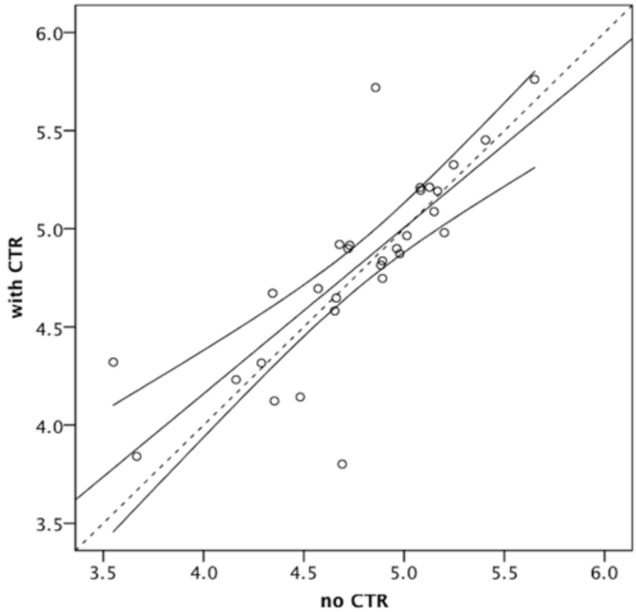


Fig. 35.4 Correlation of the postoperative ACD in eyes with and without a CTR in mm [39]

Table 35.1 Influence of the Formulas 4–6 on postACD prediction and the effect on postoperative refraction [40]

	Absolute difference to 3-month ACD (mm) mean (SD); median (max)	Influence on refraction (D) mean (SD); median (max)
PreACD	1.64 (0.56); 1.49 (3.83)	2.75 (1.23); 2.46 (9.06)
intraopACD	0.72 (0.48); 0.48 (2.19)	1.15 (0.79); 0.93 (3.79)
Formular 4 (partial least square regression)	0.35 (0.30); 0.27 (1.37)	0.56 (0.48); 0.41 (2.36)
Formular 5 (no constant)	0.37 (0.38); 0.25 (1.64)	0.59 (0.62); 0.38 (2.82)
Formular 6 (corrected intraopACD)	0.37 (0.34); 0.26 (1.49)	0.58 (0.54); 0.42 (2.58)

Formula 4 Postoperative ACD Prediction with Constant

$$\text{Postop ACD} = 2.86 + 0.31 \times \text{Intraoperative ACD} + 0.20 \times \text{Preoperative ACD}$$

Formula 5 Postoperative ACD prediction Without Constant

$$\text{Postop ACD} = 0.92 \times \text{Intraoperative ACD} + 0.31 \times \text{Preoperative ACD}$$

Formula 6
Corrected Intraoperative ACD

Problems of Intraoperative ACD Measurements

Still unsolved is the problem of intraoperative hydration of the vitreous. As a consequence of vitreous hydration, the anterior chamber is artificially shallow and therefore interfering with the aphakic ACD measurements. Following a washout phase of some hours to days after surgery the hydration vanishes, though leaving a discrepancy between the intraoperatively measured ACD and the postoperatively measured ACD.

Intraoperative accuracy could be improved by using a swept source OCT since until now it was limited to time-domain OCT.

Postoperative ACD Shift

Within the first weeks of cataract surgery, the ACD shifts. This is because of the interaction of forces between the collapsing and then shrinking lens capsule and as well as the memory of the IOL haptics. So far, lens capsule shrinking is not preventable. Therefore, the only remaining variable that is controllable is lens haptic design. Today, three main lens haptic types are on the market: plate haptics, single-piece open-loop haptics, and three-piece open-loop haptics.

ACD Shift in Plate Haptics IOL Vs Standard Three-Piece Open-Loop Haptics IOL of the Same Acrylic Material [36, 37]

We demonstrated that plate haptics IOL showed a slight backward shift in the first month after surgery that was not found to be significantly different compared to the standard three-piece open-loop haptics IOL (Fig. 35.5). At the one-year follow-up visit, the ACD was similar in both groups.

The tendency for backward shifts in plate haptics is supported by Findl et al. for another plate haptic IOL [41].

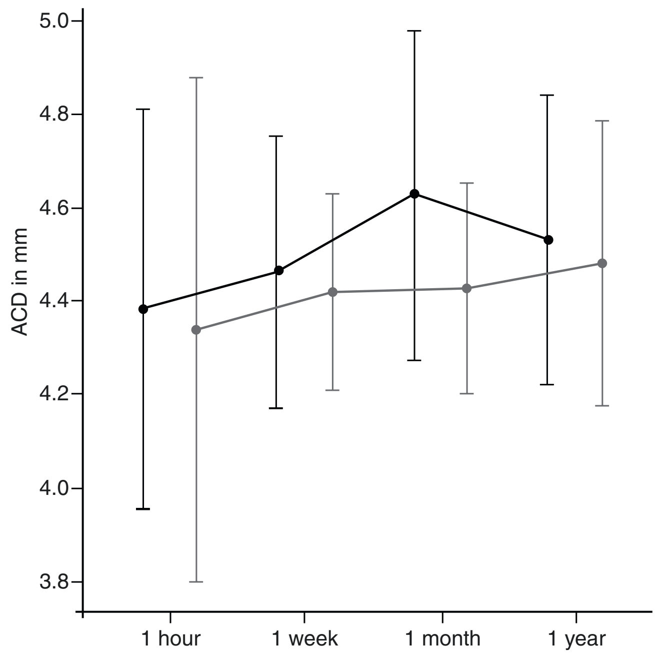


Fig. 35.5 ACD shift haptic dependance: standard three-piece open-loop haptic IOL (gray) and plate haptic IOL (black) [36, 37]

ACD Shift in Single-Piece Open-Loop haptics IOL Vs Three-Piece Open-Loop Haptics IOL of the Same Acrylic Material [42]

Findl et al. showed that angulated three-piece open-loop haptics IOL have a slightly more pronounced ACD shift compared to single-piece IOLs (Fig. 35.6).

The more pronounced ACD shift in 3 piece open loops haptics was recently confirmed by Sato et al. [43] and was also found in multipiece haptics [44]. Moreover, analyzing different open-loop haptic IOLs with a different haptic thickness, no significant difference regarding ACD was observed [45].

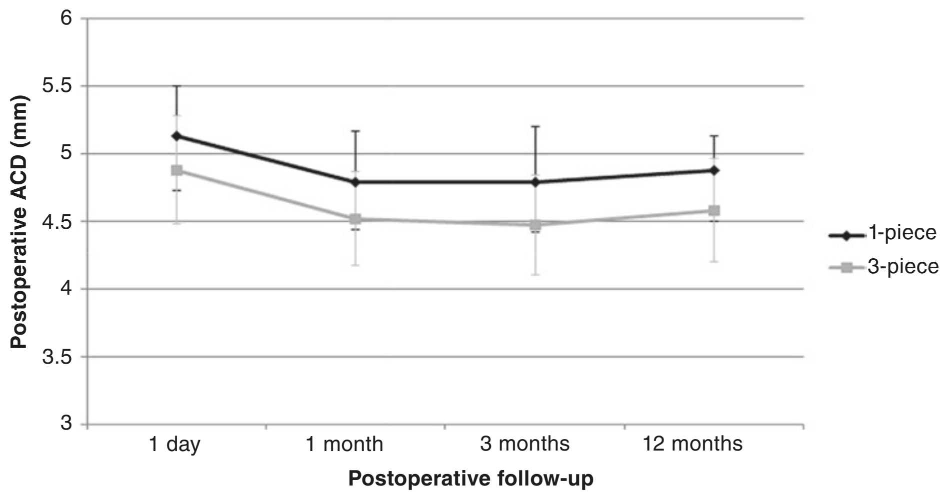


Fig. 35.6 ACD changes in mm between the first postoperative day and 1 year for a 1-piece open-loop and a 3-piece IOL [42]

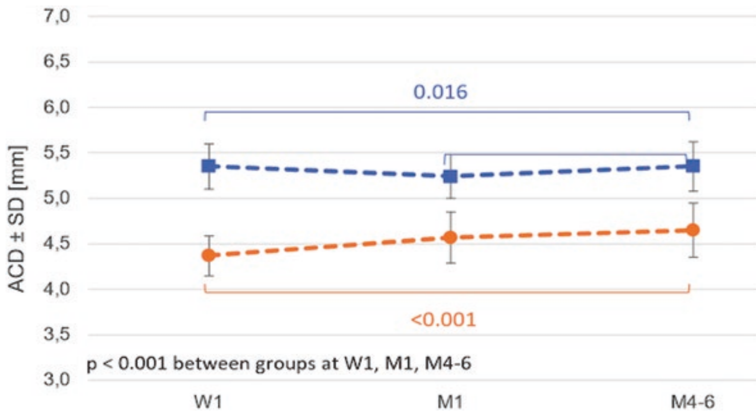


Fig. 35.7 ACD changes in mm between the first postoperative week (W1), first month (M1) and 4–6 months (M4–6) for a single-piece open-loop (blue) and plate haptic IOL (orange) [46]

ACD Shift in Single Piece Open-Loop Haptics IOL Vs Plate Haptics IOL of the Same Acrylic Material [46]

Hienert et al. reported that single-piece open-loop haptics IOL and plate haptics IOL resulted in significantly different ACD values at all time points from the first postoperative to 4–6 months after surgery (Fig. 35.7). The overall IOL shift was 0.25 ± 0.16 mm for the plate haptics and 0.14 ± 0.09 mm for the open-loop haptics. Although ACD was shifting, there was no impact of ACD on manifest refraction at any follow-up visit.

Postoperative ACD Shift and Rhexis Shape and Size

Size and shape of the manual continuous curvilinear capsulorrhexis (CCC) could play a major role in determining the postoperative ACD shift. Findl et al. investigated manual CCC and rhexis size and shape [47]. They defined RSF as the rhexis shape factor (1.0 is a perfect circle and a lower value describes the imperfection of the roundness), A as the area in mm^2 of the rhexis and C as the circumference of the rhexis in mm (Formula 7).

RSF = A/((⟦⟦C ^ 2⟧ _ /4π⟧^))

Formula 7 Rhexis Shape Factor (RSF) Formular

A = Area of rhexis $\left(\text{mm}^2\right)$

C = Circumference of the rhexis $\left(\text{mm}\right)$

No difference concerning postoperative ACD shift was found between those eyes with a perfect rhexis and those patients with an eccentric, or small rhexis (Figs. 35.8 and 35.9). However, patients with an incomplete rhexis-IOL overlap had a higher risk of postoperative unexpected large ACD. Cekic demonstrated in their study that the postoperative ACD shifted significantly, when comparing a 4.0 mm rhexis and a 6.0 mm

rhexis [48]. Major weaknesses of that study were that it was not randomised and that an older PMMA IOL design was used. Consequently, it is not clear whether their finding holds true for more modern IOLs.

Assuring a 100% rhexis-IOL overlap like in precision pulse capsulotomy was shown to result in an overall reduction of variability in ACD shift [49], thus creating more axial stability.

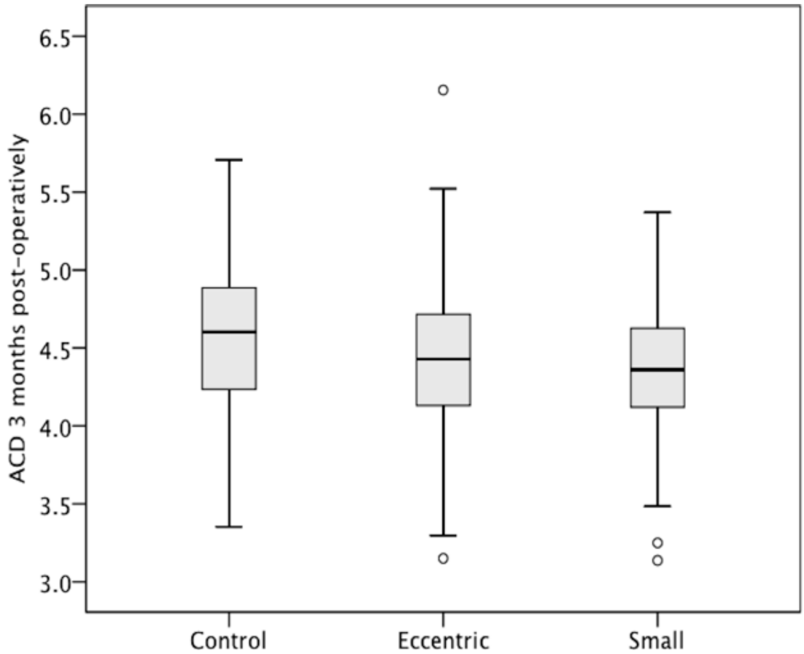


Fig. 35.8 ACD in mm for eyes with normal eccentric and small rhexis (<4.5 mm) eyes [47]

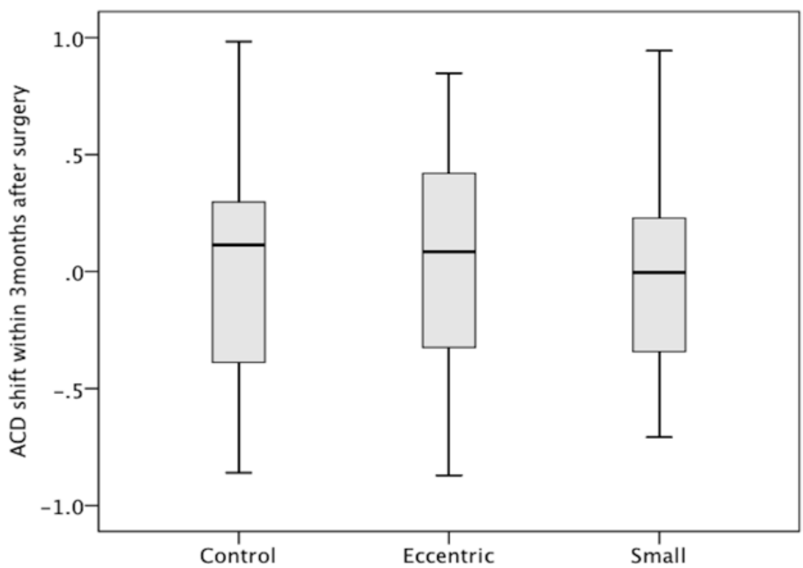


Fig. 35.9 ACD shift in mm for eyes with normal eccentric and small rhexis (<4.5 mm) eyes [47]

Postoperative ACD Shift and Capsular Shrinkage

Besides haptic design, a major factor responsible for postoperative axial IOL movement is capsular bag shrinkage. Strenn et al. introduced a CTR as a measuring device for quantification of capsular bag diameter (CBD) and postoperative capsular shrinkage [50]. We found that CBD within the first postoperative month after implanting a three-piece open-loop haptics IOL and a CTR shrank by 0.29 ± 0.15 mm (range 0.55 to 0.07 mm) ($P < 0.005$). This shrinkage of the capsule significantly correlated (0.67; ($P < 0.005$) with the postoperative change of ACD [51].

Summary

ACD has become a major player in the field of biometry and power calculation due to the increasing demands of good refractive outcomes. Measurements of ACD with one device should not be used interchangeably with other devices. Referring to refractive outcomes, postoperative ACD is the most influencing parameter. Intraoperative measurements of aphakic ACD have shown to significantly improve estimations of postoperative ACD especially when combined with preoperative ACD measurements. Postoperative ACD stabilizes in the first months, and postoperative ACD shift is dependent on IOL haptic design as well as the extent of capsule shrinkage. Postoperative ACD shift is most prominent in three piece IOL haptics followed by plate IOL haptics and is least pronounced in single piece open-loop IOL haptics. Finally, postoperative ACD shift seems not to be dependent of rhexis size, centering, and shape as long as there is a complete rhexis-IOL overlap. However, there remains some variability of ACD shift probably due to patient factors such as zonule insertion and integrity as well as differences in capsule shrinkage after surgery.

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