



Surgically induced astigmatism and coupling effect-mediated keratometric changes after conventional phacoemulsification cataract surgery

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Summary

Background The aim of the present study was to describe surgically induced astigmatism (SIA) and the coupling effect after conventional phacoemulsification cataract surgery (CPS) in relation to the incisional axis.

Material and methods A total of 42 patients were included in the retrospective case series study. Corneal topography was obtained for patients with significant cataract before and 6 weeks after CPS with a main clear corneal incision size of 2.4 mm. Patients were grouped according to the relationship of the incisional axis to the position of the steep axis into a steep incisional group and a flat incisional group.

Results In total, 46 eyes were included in the study. While the steep incisional group showed an SIA of $-0.15\text{ D} (\pm 0.35)$, the flat incisional group had a significantly higher SIA of $0.20\text{ D} (\pm 0.51)$ ($p=0.03$). The coupling ratio (CR) in the steep incisional group was $-0.38 (\pm 1.41)$ and in the flat incisional group it was $0.16 (\pm 0.97)$. Correspondingly, a coupling constant (CC) of -0.25 was found for group 1 and a CC of 0.0 for group 2.

Conclusion Our results suggest that the location of the main incision should be decided with consideration of the corneal astigmatism in order to minimize the SIA. The CR helps to understand the effect of induced astigmatism and the change in spherical equivalent.

Keywords Surgically induced astigmatism · Clear cornea incision · Conventional phacoemulsification cataract surgery · Coupling effects · Incisional axis

Chirurgisch induzierter Astigmatismus und keratometrische Veränderungen durch den Kopplungseffekt nach konventioneller Phakoemulsifikations-Kataraktoperation

Zusammenfassung

Hintergrund Ziel war die Beschreibung des chirurgisch induzierten Astigmatismus (SIA) und des Kopplungseffekts nach konventioneller Phakoemulsifikations-Kataraktchirurgie (CPS) in Abhängigkeit von der Inzisionsachse.

Material und Methoden In diese retrospektive Fallserienstudie wurden 42 Patienten einbezogen. Bei den Patienten mit signifikanter Katarakt wurde eine Hornhauttopographie am Tag vor der CPS mit einer Hauptinzisionslänge von 2,4 mm bei der „clear corneal incision“ und 6 Wochen postoperativ durchgeführt. Die Patienten wurden nach dem Verhältnis der Inzisionsachse zur Position der steilen Achse in eine Gruppe mit Inzision in der steilen Achse und eine Gruppe mit Inzision in der flachen Achse eingeteilt.

Ergebnisse Während von insgesamt 46 Augen die Gruppe mit der Inzision in der steilen Achse einen SIA von $-0,15\text{ D} (\pm 0,35)$ zeigte, wies die Gruppe mit Inzision in der flachen Achse einen signifikant höheren SIA von $0,20\text{ D} (\pm 0,51)$ auf ($p=0,03$). Das Kopplungsverhältnis (CR) in der Gruppe mit der Inzision in der steilen Achse betrug $-0,38\text{ D} (\pm 1,41)$ und in der Gruppe mit der Inzision in der flachen Achse $0,16\text{ D} (\pm 0,97)$. Entsprechend wurde in der Gruppe 1 eine Kopplungskonstante (CC) von $-0,25$ und in der Gruppe 2 eine CC von $0,0$ berechnet.

Schlussfolgerung Die vorliegenden Ergebnisse zeigen auf, dass die Lage des Hauptschnitts mit Rücksicht auf

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die Lage des kornealen Astigmatismus entschieden werden sollte, um den SIA gering zu halten. Die CR hilft, den Effekt des induzierten Astigmatismus und die Veränderung des sphärischen Äquivalents besser zu verstehen.

Schlüsselwörter Chirurgisch induzierter Astigmatismus · Nahtfreie Hauptinzision · Konventionelle Phakoemulsifikations-Kataraktchirurgie · Kopplungseffekt · Inzisionsachse

Introduction

Over the past few decades, phacoemulsification cataract surgery has evolved from a merely sight-restoring procedure to both a sight-restoring and refractive surgical intervention. Modern preoperative biometric measurements and precise intraocular lens (IOL) calculation have significantly increased patient and surgeon expectations of postoperative uncorrected visual acuity [1, 2]. In order to sustainably achieve a 0.50-D target margin of error, near-perfect preoperative planning and surgical technique are crucial [3]. Reliable prediction of the expected surgically induced astigmatism (SIA) is a prerequisite for excellent postoperative refractive outcome. However, SIA changes with width and architecture of a clear corneal incision, and the number and placement of corneal incisions [4, 5].

Firstly, it is known that limbal corneal incisions are associated with a flattening along the incisional meridian [6] and steepening at the opposite meridian, concordant with Gauss's law of elastic domes. It has been described that postoperative keratometric changes are more pronounced in incisions along steep meridians, while there is less effect on corneal astigmatism caused by incisions in the flat meridian [7].

Secondly, the cornea responds to incisional trauma with a coupling effect, that is, a proportional steepening in the meridian perpendicular to the incision [8–11], which leads to a relative stability of mean keratometric power in spite of astigmatic changes. This so-called coupling ratio (CR) is variable, depending on the symmetry of the incisions, architecture, and length, and is subject to ongoing investigations [12, 13]. The aim of the present study was to investigate the difference in SIA, CR, and mean keratometric power change between 2.4-mm clear cornea incisions (CCI) placed on a steep or flat axis in conventional phacoemulsification cataract surgery (CPS).

Material and methods

Patients

A retrospective study of 42 patients was performed in order to compare keratometric values and corneal structure preoperatively and 6 weeks after CPS. The

data of 46 eyes were included in the study between December 2016 and February 2017. Inclusion criteria were an age of at least 18 years with visual impairment caused by existence of senile cataract. Only patients with senile cataract and no other ocular pathology who underwent uneventful routine phacoemulsification surgery with implantation of a posterior chamber IOL were included. Patients were randomly assigned to either of three experienced surgeons involved in the audit who used the same surgical technique in every case. After inclusion, corneal topography was performed using a Scheimpflug tomography system (OCULUS Pentacam®, Wetzlar, Germany) pre- and 6 weeks postoperatively.

Exclusion criteria were a history of previous ocular surgery, any documented complications during cataract surgery, irregular astigmatism, previous corneal scarring, corneal dystrophy, suture placement, and postoperative endothelial dysfunction as evidenced by clinically visible corneal stromal edema at the follow-up examination.

This research was conducted in accordance with the regulations of the ethics committee of the Medical University of Innsbruck and the Declaration of Helsinki.

Surgical technique

Conventional phacoemulsification cataract surgery was undertaken using a bevel up 2.4-mm blade for a two-step main CCI that was always performed at 100° and two paracenteses at 140° and 60°. For phacoemulsification, the Alcon Infiniti Vision System (Alcon, Fort Worth, TX, USA) was used in conjunction with a 45-degree Kelmann tip. An aspheric acrylic posterior chamber IOL Acrysof natural SN60WF was implanted using a preloaded system (UltraSert®, Alcon) and wound-assisted IOL implantation technique in order to ensure stability of CCI size in all cases. The corneal incisions were hydrated and no sutures used for any included patient. All patients received routine postoperative topical dexamethasone and gentamicin eye drops (Dexagenta-POS, Ursapharm, Arzneimittel GmbH, Saarbrücken, Germany) for 4 weeks and topical ketorolac eye drops (Acular, Axicorp Pharma GmbH, Friedrichsdorf, Germany) for 2 weeks.

Clinical assessment

On the day of surgery and 6 weeks postoperatively, complete eye examinations were performed. Collected data included best-corrected visual acuity (BCVA) measured on a Snellen chart and converted to logarithm of the minimum angle of resolution (logMAR), refractive astigmatism measured by ARK-30 autorefractor (Nidek Co. Ltd, Aichi, Japan), corneal tomography using the Pentacam, slit-lamp biomicroscopy, and indirect funduscopy. The timing of the follow-up examination was chosen with respect to the

Table 1 Visual and refractive outcome of all patients grouped accordingly to the position of their incision

| | All (SD) | Group 1 (range) | Group 2 (range) | Group 3 (range) | <i>p</i> |
|------------------------------------|------------------------|-----------------------|-----------------------|------------------------|----------|
| <i>n</i> | 46 | 20 | 11 | 15 | – |
| Age (SD) | 74 (7) | 72 (7) | 76 (6) | 74 (8) | 0.63 |
| Male/female | 16/30 | 4/16 | 5/6 | 7/8 | – |
| Right/left | 25/21 | 11/9 | 4/7 | 10/5 | – |
| BCVA logMAR before surgery | 0.32 (0.10 to 0.60) | 0.31 (0.10, 0.6) | 0.26 (0.10 to 0.49) | 0.38 (0.20 to 0.60) | 0.32 |
| BCVA logMAR after surgery | 0.12 (–0.10 to 0.30) | 0.14 (–0.10, 0.49) | 0.13 (–0.10 to 0.30) | 0.11 (–0.10 to 0.30) | 0.32 |
| Target refraction | –0.58 (–0.67 to –0.12) | –0.42 (–0.6, –0.28) | –0.27 (–0.67 to –0.2) | –0.47 (–0.55 to –0.12) | 0.29 |
| Deviation from targeted refraction | 0.23 (–0.72 to 1.01) | –0.30 (–0.72 to 1.01) | –0.03 (–0.58 to 0.91) | –0.30 (–0.55 to –0.12) | 0.46 |

n number, BCVA best corrected visual acuity, logMAR logarithm of the minimum angle of resolution

findings of Hayashi et al. [14], who did not observe significant keratometric changes later than 4 weeks after surgery with a 2.4-mm CCI.

Keratometry and calculation of IOL was conducted with the IOLMaster (Carl Zeiss Meditec, Dublin, CA, USA) and refraction was calculated at a spheric equivalent of –0.50D. The expected postoperative refraction, as targeted by the chosen IOL at a range between 0.00 D and –0.50 D, was recorded for every patient and compared with actual postoperative refraction measurements on follow-up.

For comparison of pre- and postoperative corneal power and astigmatism, Pentacam readings were assessed using *k* values of the central 3-mm zone, namely, steep axis, flat axis, refractive power in both axes, anterior corneal astigmatism (ACA), and mean corneal power (*k*-mean). Surgically induced astigmatism was defined as the change in ACA. Additionally, manifest refraction was measured and compared with objective autorefractor refraction.

Coupling ratio (CR) and a coupling constant (CC) were calculated using *k* readings in the incisional meridian, 90 degrees, and mean corneal power. The CC has recently been defined as the change in mean corneal power in relation to the difference between the change in corneal power at the treatment meridian and the change in corneal power at the opposite meridian: $CC = \Delta K_{\text{Mean}} / (\Delta K_T - \Delta K_O)$ [15]. A CC of 0.33 therefore equals a 0.33 diopter change of SE for each diopter change in astigmatism. The CR is defined as the flattening of the incised meridian in relation to the opposite meridian: $CR = -\Delta K_T / \Delta K_O$ [15]. A CR of 0.33 therefore indicates that the change in corneal power at the opposite meridian was one third of the change in the incisional meridian.

Astigmatic change, calculated as the difference between preoperative and postoperative ACA, was defined as SIA.

For the analysis, patients were categorized into three groups according to the individual relation of the steep axis of corneal astigmatism to the incisional axis at 100°. Group 1: Patients with steep axis within 20 degrees to the incision (steep axis at 80–120 degrees). Group 2: Patients with steep axis at 70–110 degrees to the incision (flat axis at 80–120 de-

grees). Group 3 consisted of all other cases (steep axis from 120–170 and 30–80 degrees).

Statistical analysis

All statistical analyses were performed using SPSS version 14.0 (IBM SPSS Statistics, Armonk, NY, USA). The Shapiro–Wilk test of normality was used to test the distribution of continuous data. Hence, the nonparametric Wilcoxon signed rank test was used within groups and the Mann–Whitney *U* test or Kruskal–Wallis was used to compare differences between groups. Means are given with standard deviation. All *p* values <0.05 were considered significant.

Results

A total of 46 eyes of 42 patients at a mean age of 73.83 ± 7.18 years were analyzed.

There was no significant difference for age, preoperative and postoperative BCVA, and for preoperative ACA or any other keratometric characteristics at baseline between group 1 and 2 (see Tables 1 and 2). No intra- or postoperative complications were documented.

Surgically induced astigmatism

The mean (range) preoperative corneal astigmatism was 1.14 D (0.30–4.10) in group 1 and 0.85 D (0.30–2.00) in group 2 (*p*=0.24; see Table 2). Postoperative measurements were 0.99 D (0.10–0.50) and 1.05 D (0.20–2.30; *p*=0.38), respectively. Hence SIA in groups 1 and 2 was –0.15 D (–0.90–0.70; *p*=0.07) and 0.2 D (–1.10–0.40; *p*=0.22) amounting to a significant difference in SIA between the two groups of 0.35 D (*p*=0.03). There was no difference in SIA between group 3 (0.12; –0.6–1.5) and the other groups (*p*=0.07).

Refractive astigmatism showed a significant postoperative difference between group 1 (–0.70; –1.50–0.00) and group 2 (–1.70; –3.25–0.25; *p*=0.01; see Table 2).

Table 2 Keratometric values before and after surgery

| | Group 1 (range) | Group 2 (range) | <i>p</i> |
|---|--------------------|--------------------|----------|
| <i>N</i> | 20 | 11 | – |
| Coupling ratio | –0.38 (–2.50–1.50) | 0.16 (–2.50–8.00) | 0.22 |
| Coupling constant | –0.25 (–0.88–3.00) | 0.0 (–1.00–1.00) | 0.67 |
| <i>K</i> _{mean} before surgery | 45.38 (42.2–50.3) | 44.61 (42.3–46.5) | 0.24 |
| <i>K</i> _{mean} after surgery | 45.43 (42.4–51.0) | 44.51 (42.5–46.4) | 0.22 |
| ACA before surgery | 1.14 (0.30–4.10) | 0.85 (0.30–2.00) | 0.24 |
| ACA after surgery | 0.99 (0.10–0.50) | 1.05 (0.20–2.30) | 0.38 |
| SIA | –0.15 (–0.90–0.70) | 0.20 (–1.10–0.40) | 0.03* |
| Refractive astigmatism before surgery | –1.04 (–3.75–0.25) | –1.68 (–2.50–0.75) | 0.08 |
| Refractive astigmatism after surgery | –0.70 (–1.50–0.00) | –1.70 (–3.25–0.25) | 0.01* |

*K*_{mean} mean keratometric power, *ACA* anterior corneal astigmatism, *SIA* surgical induced astigmatism

Table 3 Keratometric changes after surgery and significance within groups

| | Group 1 (range) | Group 2 (range) | Group 3 (range) |
|------------------------|--------------------------------------|-------------------------------------|--------------------------------------|
| Maximum corneal power | 0.12 (–0.70–0.90; <i>p</i> = 0.11) | 0.04 (–0.40–0.70; <i>p</i> = 0.41) | 0.40 (–0.20–2.30; <i>p</i> = 0.04) |
| Steep meridian | 0.12 (–0.40–0.50; <i>p</i> = 0.04) | –0.11 (–0.70–0.50; <i>p</i> = 0.11) | –0.07 (–0.80–0.60; <i>p</i> = 0.69) |
| Flat meridian | –0.20 (–0.80–1.10; <i>p</i> = 0.82) | –0.02 (–0.50–0.80; <i>p</i> = 0.95) | 0.13 (–0.20–1.30; <i>p</i> = 0.98) |
| Mean corneal power | 0.05 (–0.70–0.50; <i>p</i> = 0.43) | –0.10 (–0.30–0.30; <i>p</i> = 0.18) | 0.05 (–0.40–0.40; <i>p</i> = 0.39) |
| Axis of ACA | –20.73 (–1.0–46.0; <i>p</i> = 0.003) | –41.50 (–60.0–6.0; <i>p</i> = 0.18) | –26.10 (–17.0–19.0; <i>p</i> = 0.29) |
| ACA | –0.15 (–0.90–0.70; <i>p</i> = 0.07) | 0.20 (–1.10–0.40; <i>p</i> = 0.22) | 0.12 (–1.5–0.60; <i>p</i> = 0.36) |
| Refractive astigmatism | –0.34 (–1.25–3.25 <i>p</i> = 0.14) | 0.02 (–2.00–2.00; <i>p</i> = 0.86) | 0.12 (–1.25–1.00; <i>p</i> = 0.68) |

BCVA best corrected visual acuity, *ACA* anterior corneal astigmatism

Change within groups

There was a significant increase in BCVA after surgery ($p < 0.01$) in all groups. In group 1 a significant change in the position of the steep axis of 20.73 (–1.0–46.0; $p = 0.003$) and significant increase in corneal power in the incisional (steep) axis in group 1 of 0.12 (–0.40–0.50; $p = 0.04$) was measured (see Table 3). Corneal power in the incisional (flat) axis in group 2 showed no significant flattening (0.12; –0.40–0.50; $p = 0.04$) at follow-up. Furthermore, there was a significant reduction of *K*_{max} in group 3 (0.40; –0.20–2.30; $p = 0.04$). While group 1 showed a distinct trend toward a significant reduction in corneal astigmatism (–0.15; –0.90–0.70; $p = 0.07$) group 2 showed a non-significant increase (0.20; –1.10–0.40; $p = 0.22$; see Fig. 1). Changes in refractive astigmatism did not show significances within any group (see Table 3).

Coupling effect

The CR of group 1 was –0.38 (–2.50–1.50) and the CR of group 2 was 0.16 (–2.50–8.00). Correspondingly, a CC of –0.25 (–0.88–3.00) was found for group 1 and a CC of 0.0 (–1.00–1.00) for group 2. A comparison across groups showed no significant differences in CR and CC ($p = 0.22$, $p = 0.67$, respectively).

Discussion

Reducing corneal astigmatism is an important refractive goal of CPS. Spectacle independency is an important objective of CPS in order to achieve patient satisfaction after surgery. An investigation by Wolffsohn et al. [16] showed that uncorrected astigmatism, even as low as 1.00 D, significantly affects patients' independence, quality of life, and well-being. There have been numerous reports on surgical options to reduce pre-existing astigmatism during cataract surgery: Besides opposite clear cornea incision, surgeons have the opportunity to reduce astigmatism by limbal relaxing incision, astigmatic keratotomy, and insertion of toric lenses [17–19]. A thorough understanding of SIA, keratometric changes, and the mechanism and prediction of corneal coupling following CPS is crucial in order to minimize residual astigmatism and to achieve optimal postoperative results.

In this study we observed a significant difference in SIA depending on the proximity of a 2.4-mm corneal incision to the steep axis of preoperative astigmatism. In spite of conflicting data on the extent of SIA in cataract surgery, the incision size has repeatedly been confirmed as the single most important contributing factor: While Kurz et al. [20] reported a SIA of 0.31 D associated with an incision size of 2.75 mm, others described a SIA of 0.76 D and 0.74 D at 2.8 mm and 2.84 mm incision size, respectively, in a central 6.0-mm zone [18, 21]. These study groups described SIA irrespective of the incisional relation to the axis of

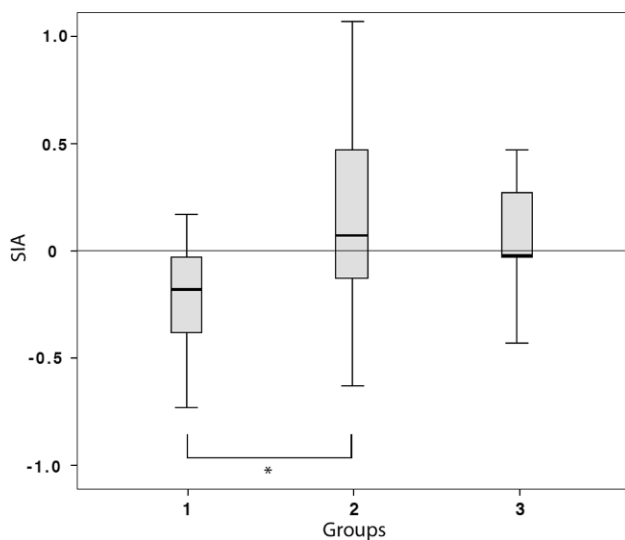


Fig. 1 Surgically induced astigmatism (SIA) in diopter compared across groups. *Group 1*: incision in steep axis ± 20 degrees; *Group 2*: incision in flat axis ± 20 degrees; *Group 3*: incision between flat and steep axis

corneal astigmatism. Our results on the other hand showed a significant difference in SIA depending on the incisional relation to the steep axis of corneal astigmatism in the central 3.0-mm zone. An overall SIA of 0.1 D regardless of the position of the steep axis of the astigmatism was measured. A comparison of SIA between group 1 and 2 showed a significant difference in SIA of 0.35D, depending on the incisional proximity to the steep axis of corneal astigmatism. We could not observe a difference in SIA between group 3 and the other groups. There were no significant changes in corneal astigmatism within the groups 6 weeks after CPS.

In contrast to previous studies [18, 20, 21], we employed a stricter methodical approach to observe the change in corneal astigmatism by using the measurement of the central 3.00-mm zone, where the corneal astigmatism is clinically more relevant [22].

It has been shown that a superior approach causes a greater astigmatic change than a temporal approach, most likely explained by the oval shape of the cornea, resulting in a more centrally located incision in a superior approach [23]. A recent study by Rho and Joo [24] recommended 3.0-mm main incisions at the steeper corneal meridian regardless of its axial position for CPS to achieve a stronger flattening at this meridian. Therefore, the greatest flattening effect can be expected for a superior approach in patients who have with-the-rule astigmatism.

The CR helps to understand the effect of induced astigmatism and the change in spherical equivalent. Its consideration in preoperative planning will influence the choice of IOL power. As described above, CR has been defined by Alpins et al. [15] as the relation of the difference of corneal power at the opposite meridian to the treated meridian. Our results

showed an overall CR of -0.19 . This describes a mean corneal power reduction in the opposite meridian equaling 20% of the power change effectuated in the incisional meridian. The CR in group 1 (incision in steep meridian) was -0.38 and a mean reduction of manifest corneal astigmatism of 0.15D was noted. The CR in group 2 was 0.16 and there was an increase of manifest corneal astigmatism of 0.20 D.

These findings confirm a flattening effect of CPS corneal incisions irrespective of their relation to the steep meridian of corneal astigmatism, leading to decreased postoperative astigmatism for CCIs placed in the steep meridian and increased postoperative astigmatism for main incisions placed in the flat meridian. The CR was different between the groups and confirmed a higher coupling effect (-38% versus $+16\%$) for incisions in the steep versus flat meridian. Thus, CCI in the steep meridian represents a useful step in CPS for achieving a reduction of corneal astigmatism even in cases of low preexisting astigmatism.

Limitations

Our study has some limitations, i.e., the limitation of follow-up examinations. We considered that for a proper comparison, good quality is achieved when there is enough time between surgery and examination and follow-up. Masker and Tennen [25] and Hayashi et al. [14] stated that the cornea stabilizes within 4 weeks of surgery at incisions smaller than 3.0 and 2.4 mm. The early stabilization of the cornea after CPS supports the timing of the keratometric examinations 6 weeks after surgery in our study. Even at 6 weeks after CPS we could not measure any significant difference in corneal astigmatism within the groups. Considering the rather small sample size, the study results should be interpreted with caution. Another limitation may be our approach to include CCI within a 20 degree angle to the steep or flat axis for our groups. It is to be expected that strict inclusion of exclusively on-axis CCI would have resulted in a greater difference between the groups. The influence of CCI placement in relation to corneal astigmatism may therefore be even greater, as found in this study. Accurate on-axis incisions may also result in a greater difference in CR and CC and should be addressed in future studies.

Conclusion

Our results show a significant difference in surgically induced astigmatism depending on the proximity of a 2.4-mm clear cornea main incision to the steep axis of corneal astigmatism. These results suggest that the location of the main incision should be decided in conjunction with corneal astigmatism in order to minimize SIA.

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Declarations

Conflict of interest R. Angermann, C. Palme, P. Segnitz, A. Dimmer, E. Schmid, M. Hofer and B. Steger declare that they have no competing interests.

Ethical standards The approval for retrospective studies is waived by the institutional review board of the Medical University Innsbruck, Innsbruck, Austria. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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