

Corneal higher-order aberrations after cataract surgery: Manual phacoemulsification versus femtosecond-laser assisted technique

European Journal of Ophthalmology
2021, Vol. 31(6) 2955–2961
© The Author(s) 2021



Article reuse guidelines:
sagepub.com/journals-permissions
DOI: 10.1177/1120672121990611
journals.sagepub.com/home/ejo



Dominika Pohlmann^{ID}, Daniel Pilger^{ID}, Eckart Bertelmann
and Christoph von Sonnleithner^{ID}

Abstract

Purpose: To compare and evaluate corneal higher-order aberrations (c-HOA) between conventional manual phacoemulsification (Phaco), femtosecond laser-assisted cataract surgery (FLACS), and femtosecond laser-assisted cataract surgery with astigmatic keratotomy (FSAK).

Methods: In this retrospective single center study, 53 healthy individuals with cataract (73 eyes) underwent phacoemulsification with implantation of an intraocular lens. Three groups were formed: group A, Phaco ($n=27$ eyes of 21 patients); group B, FLACS ($n=25$ eyes of 15 patients); group C, FSAK ($n=21$ eyes of 17 patients). An iTrace aberrometer (Tracey Technologies, Houston, TX, USA) was used to perform aberrometry with a pupil scan size of 5.0 mm. We used ANOVA analysis and the paired sample *t*-test for statistical analysis.

Results: There was no difference in total c-HOA between the groups prior to surgery ($F(2,66)=2.2$, $p=0.128$), but some evidence for a difference between the groups after surgery ($F(2,65)=3.87$, $p=0.025$). After surgery, total c-HOA increased in all groups, but the greatest increase occurred FSAK.

Conclusion: Manual phacoemulsification and femtosecond laser-assisted cataract surgery seem to have less impact on corneal higher-order aberrations than the combination of femtosecond laser-assisted cataract surgery with astigmatic keratotomy.

Keywords

Cataract surgery, higher-order aberration, femtosecond-laser assisted, ray tracing

Date received: 11 September 2020; accepted: 21 December 2020

Introduction

Cataract surgery is considered as one of the safest and most efficient surgical procedures in ophthalmology. Over the past decades, innovations in cataract surgery have increased accuracy and improved refractive outcome. The most common technique nowadays is manual phacoemulsification (Phaco). On the other hand, femtosecond laser-assisted cataract surgery (FLACS) is becoming more popular.

The three main steps performed by FLACS are: corneal incisions, capsulotomy, and lens fragmentation. In addition, it is possible to reduce regular astigmatism with

Charité – Universitätsmedizin Berlin, corporate member of Freie Universität Berlin, Humboldt-Universität zu Berlin, and Berlin Institute of Health, Berlin, Germany

Corresponding authors:

Christoph von Sonnleithner, Department of Ophthalmology, Charité – University Medicine Berlin, Campus Virchow, Augustenburger Platz 1, Berlin 13353, Germany.
Email: Christoph.vonSonnleithner@charite.de

Dominika Pohlmann, Department of Ophthalmology, Charité – University Medicine Berlin, Campus Virchow, Augustenburger Platz 1, Berlin 13353, Germany.
Email: dominika.pohlmann@charite.de

keratotomies (femtosecond laser-assisted cataract surgery with astigmatic keratotomy, FSAK).¹ The procedure is safe and effective.² There are many proven advantages over manual surgery, such as better incision quality with reduction of induced astigmatism, increased reliability, reproducibility of the capsulotomy with increased stability of the implanted lens, and reduced use of ultrasound.^{2,3} Due to its precision, it may also be gentler to the internal structures of the eye.⁴ However, recent studies have reported that there is no superiority to manual Phaco in terms of primary outcomes, such as visual and refractive outcomes.^{4,5}

The visual quality of the eye depends on several optical factors, the most important one being lower-order aberrations. In addition, corneal higher-order aberrations (c-HOA) can influence visual quality.⁶ While the lower-order aberrations consist of hyperopia and myopia (defocus), as well as astigmatism, the c-HOAs compromise many varieties of aberrations such as coma, spherical aberration, and trefoil.⁶ Although conventional spherical intraocular lenses (IOL) provide good visual acuity, the spherical aberration is increased and simultaneously the visual quality worsens.⁷ Therefore, aspheric IOLs (AIOL) are used to reduce c-HOAs and improve contrast sensitivity and image quality.⁸⁻¹³ Also, the size of corneal incision might have an impact on c-HOAs in cataract surgery.¹⁴ Little is known about the effect of FLACS on c-HOAs.

In this study, we compare and evaluate c-HOAs between conventional manual Phaco, FLACS, and FSAK.

Patients and methods

Between April 2017 and December 2017, 53 patients (73 eyes) were enrolled at the Department of Ophthalmology, University Medicine Charité, Berlin, Germany. Inclusion criteria were patients with uncomplicated cataract requiring surgery, a minimum age of 18 years and preoperative, regular corneal astigmatism (less than 0.75 diopters in group A and B; more than 0.75 diopters in group C). Exclusion criteria were any clinically significant corneal abnormalities including endothelial dystrophy, superficial punctate keratitis, poorly dilated pupil, or other significant ocular abnormalities. Additionally, no cases had prior corneal surgery (e.g. laser-vision correction). This study was performed in accordance with the Declaration of Helsinki.

The femtosecond laser procedures were performed by one experienced surgeon (C.v.S). All the cataract surgeries (including the patients prior treated with femtosecond laser) were performed by another experienced surgeon (E.B.).

All patients underwent a full ophthalmic assessment by the same physician (D.P.) pre- and postoperatively after 4 weeks, including slit lamp examination and fundoscopy. Intraocular eye pressure was measured with Goldmann applanation tonometry. On study days, all patients' demographics were documented. This data included best

corrected visual acuity (BCVA). Optical biometry was performed using the IOL-Master 700 (Carl Zeiss Meditec AG; Jena, Germany) to measure keratometry and axial length. For IOL calculation, SRK/T- and Haigis-formula were used, depending on the length of the patients' eyes. Aberrometry with a pupil scan size of 5.0 mm was performed using iTrace aberrometer (Tracey Technologies, Houston, TX, USA).

Surgical techniques

Three groups were formed based on the surgical technique and the preoperative corneal astigmatism.

In groups A and B, we enrolled patients with regular corneal astigmatism of less than 0.75 diopters (D). In group C we enrolled patients with regular corneal astigmatism of more than 0.75 D.

Preoperatively, we used tropicamide/phenylephrine eyedrops for pupil dilation in all eyes.

In group A (Phaco) cataract surgery was undertaken in peribulbar anesthesia (Xylocaine® 2%, Naropin®, Hylase "Dessau"®). Oculopression was applied with approximately 25 mmHg for 10 min directly before each operation. The 2.2 mm incision was placed in dependence of the steep meridian of the cornea (superior or temporal). Additionally, we made two 1 mm incisions. The continuous curvilinear capsulorhexis, hydrodissection, hydrodelimitation, phacoemulsification, and aspiration of cortical material were performed under protection with Amvisc®. To perform Phaco we used the Centurion® Vision System (Alcon, Fort Worth, TX, USA).

In group B (FLACS) corneal incisions, capsulotomy, and lens fragmentation were performed with the LenSx® (Alcon, Fort Worth, TX, USA) in topical anesthesia (oxybuprocaine eye drops and lidocaine gel). The main corneal incision was always placed in the superior position. After the femtosecond laser-assisted procedure, the cataract surgery was concluded using the Centurion® Vision System (Alcon, Fort Worth, TX, USA).

In group C (FSAK) femtosecond laser procedure was performed in the same way as in group B. In addition, we used the femtosecond laser for astigmatic keratotomy to reduce regular corneal astigmatism using Donnenfeld Nomogram. One or two keratotomies were used depending on the axis of the astigmatism. The depth was 80% of the corneal thickness.

In all groups we implanted randomly different IOLs (Tecnis ZCB00, Abbott Medical Optics, Santa Ana, CA, USA; CT Asphina 409M, Carl Zeiss Meditec, Jena, Germany; Hoya iSert 251, Hoya, Tokyo, Japan).

Statistical analysis

All data was entered into a database and checked for data entry errors. Differences in c-HOAs between the groups

Table 1. Baseline and postoperative characteristics stratified by groups.

	Preoperative			Postoperative		
	Group A (Phaco)	Group B (FLACS)	Group C (FSAK)	Group A (Phaco)	Group B (FLACS)	Group C (FSAK)
	N=27	N=25	N=21	N=27	N=25	N=21
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Spherical equivalent (D)	-0.95 (4.51)	-0.69 (3.14)	-0.64 (4.62)	-0.54 (0.96)	-0.14 (0.38)	-0.32 (0.88)
Visual acuity (logMAR)	0.33 (0.15)	0.34 (0.16)	0.43 (0.31)	0.02 (0.06)	0.02 (0.06)	0.10 (0.14)
Axis length (mm)	23.98 (1.61)	23.48 (1.39)	23.76 (1.60)	24.86 (4.69)	23.38 (1.46)	23.50 (1.73)
Flat K (D)	42.89 (1.59)	42.73 (1.41)	42.68 (1.50)	42.77 (1.77)	40.72 (1.46)	42.80 (1.67)
Steep K (D)	43.52 (1.61)	43.23 (1.38)	43.82 (1.70)	43.7 (1.70)	43.29 (1.42)	43.72 (1.78)
Cylinder (D)	-0.67 (0.50)	-0.49 (0.45)	-1.13 (0.60)	-1.00 (0.77)	-0.70 (0.57)	-0.89 (0.58)
Axis (°)	70.61 (66.95)	82.57 (63.30)	87.10 (58.00)	101.64 (64.87)	77.60 (47.72)	90.20 (47.91)
Total cHOA mean in μm (SD)	0.277 (0.110)	0.269 (0.104)	0.345 (0.218)	0.353 (0.125)	0.335 (0.151)	0.460 (0.201)

cHOA: corneal higher-order aberrations; FLACS: femtosecond laser-assisted cataract surgery; FSAK: femtosecond laser-assisted cataract surgery with astigmatic keratotomy; K: keratometry; logMAR: logarithm of the minimum angle of resolution; μm : micrometer; SD: standard deviation.

were compared pre and post-surgery using an ANOVA analysis. We evaluated normal distribution and used a paired sample *t*-test to compare c-HOAs at postoperative stage to c-HOAs at preoperative stage. All statistical analysis was done using the statistical software package STATA (version 12.1, STATA Corporation, College Station, TX, USA). Plots were generated using ggplot2 of the R-platform. *p*-values below 0.05 were considered strong evidence for an effect.

Results

Demographics

A total of 53 patients with a mean age 74.1 years (SD 8) were enrolled. Thirty-three patients were female (62.3%). Surgery was performed on 69 eyes: Group A: 27 eyes (21 patients); group B: 25 eyes (15 patients); group C: 21 eyes (17 patients). Complete datasets were available for all eyes.

Refractive outcomes and visual acuity

Baseline analysis showed similar refractive values across all groups except for astigmatism. Astigmatism was highest in group C but comparable in group A and B (Table 1). Mean BCVA was low in all groups without important differences between the three groups ($p=0.49$).

At post-surgery, mean BCVA increased significantly in all groups (all groups: $p \leq 0.001$) without evidence for a difference between the three groups ($p=0.068$). The mean postoperative spherical equivalent showed no differences between all groups ($p=0.586$).

At post-surgery, astigmatism increased slightly in group A and B but decreased in group C (Table 1).

Corneal higher-order aberration

Comparing total c-HOAs between the groups showed no evidence for a difference prior to surgery ($F(2,66)=2.2$, $p=0.128$), but some evidence for a difference after surgery ($F(2,65)=3.87$, $p=0.025$). After surgery, total c-HOA increased in all groups (group A: $p=0.003$; group B: $p=0.019$; group C: $p=0.067$), with the greatest c-HOAs increase seen in group C (FSAK) (Figure 1). The amount of postoperative variation in c-HOA was highest in group C (FSAK).

When examining different types of c-HOAs, we found no evidence for an increase of c-HOA in group A (Phaco) (Table 2). In group B (FLACS), some evidence suggested an increase in Trefoil, whereas in group C (FSAK), some weak evidence was found for an increase in spherical aberration (Table 2).

Discussion

Several studies have shown potential advantages of the FLACS when compared to manual Phaco.²⁻⁵ One example is the reduction of phacoemulsification energy and effective phacoemulsification time (EPT) in comparison to conventional cataract surgery.¹⁵⁻²¹ Furthermore, FLACS is able to create a more circular and precise capsulorrhexis, which can facilitate phacoemulsification, IOL implantation, and provide more accurate refractive outcomes after surgery.²² Other studies report advantages in terms of endothelial cell loss, intraocular lens position, and corneal swelling.²³⁻²⁵

However, some studies investigated the differences between FLACS and conventional manual Phaco without demonstrating a superiority of either technique such as achieving better and faster visual rehabilitation and refractive outcomes.²⁶⁻³⁰

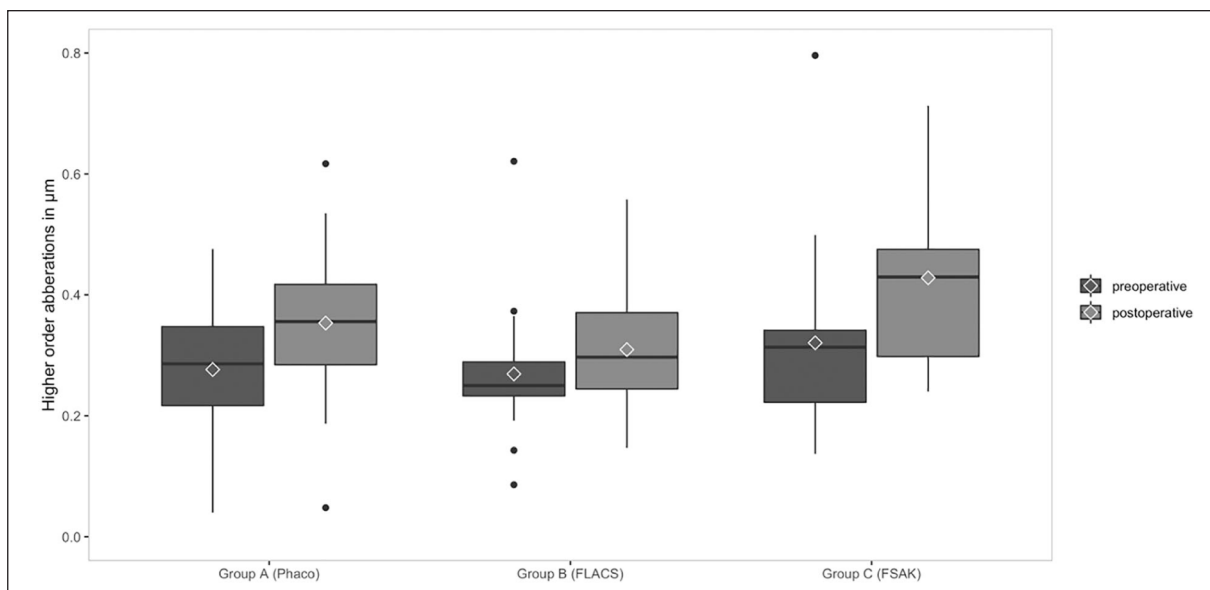


Figure 1. Comparison of corneal higher-order aberration in group A: conventional manual phacoemulsification (Phaco), group B: femtosecond laser-assisted cataract surgery (FLACS), and group C: femtosecond laser-assisted cataract surgery with astigmatic keratotomy (FSAK).

Table 2. Mean difference in corneal higher-order aberration pre- and post-surgery.

	Mean difference	95% CI	p-value
Group A (Phaco)			
Coma	-0.05	-0.13 to 0.37	0.265
Spherical	0.01	-0.17 to 0.04	0.371
Trefoil	-0.02	-0.11 to 0.06	0.660
Group B (FLACS)			
Coma	-0.03	-0.08 to 0.16	0.261
Spherical	-0.01	-0.04 to 0.02	0.681
Trefoil	-0.07	-0.13 to 0.14	0.015
Group C (FSAK)			
Coma	0.03	-0.08 to 0.13	0.621
Spherical	0.02	-0.27 to 0.06	0.041
Trefoil	-0.05	-0.17 to 0.05	0.322

The aim of refractive cataract surgeons is to achieve good results not only in lower-order aberrations (sphere and cylinder), but also in the outcome of c-HOAs. A reduction of spherical aberration can be achieved with the implantation of AIOL, which can lead to higher contrast sensitivity and a better retinal image quality.⁹⁻¹³

Denoyer et al.³¹ demonstrated that the corneal incision changes the morphology and is able to induce aberrations. The study of Marcos et al.³² postulated that with larger incision size, a higher value of c-HOA can be seen. In contrast, in our previous study Von Sonnleithner et al.¹⁴ showed in a study comparing three different incision sizes, 1.4 mm, 1.8 mm, and 2.2 mm, that the 1.8 mm incision induces less corneal HOA. In our current study, the incision size was 2.2 mm in all three groups.

Some studies reported that the difference of BCVA and uncorrected distance visual acuity (UDVA) between FLACS and manual Phaco were minimal to non-existent.^{33,34} In contrast, another study reported that FLACS achieved better visual outcome at 6 months of follow-up.²⁷ In addition, the incidence of relevant complications, such as intraoperative anterior capsule tear, postoperative macular edema, and elevated intraocular pressure did not increase.²⁷ However, in order to achieve best visual outcome, the c-HOAs must also be taken into account.

The main purpose of this trial was to investigate the effect of the cataract surgery technique (manual Phaco vs FLACS vs FSAK) on c-HOAs. Our results show that manual Phaco and FLACS induce c-HOAs, to a similar degree. We were able to demonstrate that in FSAK the increase of c-HOA is higher compared to manual Phaco and FLACS.

FSAK is useful in the reduction of corneal astigmatism and is comparable to toric intraocular lens implantation in eyes with low to moderate astigmatism.³⁵ As we know, HOAs are part of refractive errors, but they are not correctable with sphere and cylinder corrections. They can impair the quality of the retinal image^{36,37} and lead to symptoms such as difficulty with night vision, glare, halos, blurring, starburst patterns, and diplopia. Thus, c-HOAs have an impact on visual performance and on contrast sensitivity.³⁸⁻⁴⁰

One of the advantages of astigmatic keratotomies over toric IOLs is that there is no risk of unwanted IOL-rotation. Rotation leads to less correction of astigmatism and can induce a hyperopic shift.⁴¹ The correcting effect is even eliminated when rotating 30°. ⁴²

Chan et al.⁴³ investigated the stability of corneal astigmatism and c-HOAs after FSAK in 50 eyes of 50 patients. The

mean of preoperative corneal astigmatism was 1.35 ± 0.48 D, which could be reduced to 0.67 ± 0.54 D after 2 months and 0.74 ± 0.53 D after 2 years postoperatively. But the reduction in astigmatism was accompanied by an increase in c-HOAs.⁴³ In this study, the surgeons used a single FSAK opposite to the main corneal incision. In our clinical setting, the main corneal incision (in groups B and C) was always placed in superior position. In dependence of the steep meridian, we placed one or two astigmatic keratotomies. Due to the limited number of eyes, we did not analyze the differences between these two possibilities.

Lee et al.⁴⁴ compared conventional Phaco with FLACS in his study. In all eyes, a multifocal IOL was implanted. In addition, patients in the FLACS group with corneal astigmatism greater than 0.75 D also had arcuate keratotomy. Corneal higher-order aberrations were significantly higher in the FLACS group. In contrast to our study, it is important to note that in the FLACS group no difference was made between patients with and patients without arcuate keratotomy. In addition, satisfaction scores were significantly higher in the FLACS group.⁴⁴

Another advantage of FLACS is that without further effort astigmatism (with astigmatic keratotomy) can be reduced. In comparison to toric IOLs, no preoperative calculation and order of the appropriate toric IOL is necessary.

We did not fully investigate the effect of corneal HOAs on the actual visual acuity of the patients. The aim of this study, however, was not to detect difference in visual acuity or astigmatism as this would have meant a very large sample size, but to explore a possible impact of the three different techniques on c-HOA.

Another source of bias could come from the different injectors and cartridges required for the respective IOLs used in this study. It is possible, that the different system had an effect on c-HOA and hence confounded our findings. Baseline analysis, however, showed that the different IOLs used in this study were randomly distributed across all groups. This means that a possible effect of the IOL on c-HOA, would have affected our findings to a similar degree in all three groups and hence should not have compromised the comparison.

In conclusion, all three groups showed an increase in c-HOAs, while FSAK demonstrated the highest increase. In patients with high values of c-HOA and low to moderate regular astigmatism preoperatively, a further increase of c-HOAs with FSAK should be considered. In such cases, implantation of toric IOLs may help to avoid an increase in postoperative c-HOAs.

Author contributions

Dominika Pohlmann, MD: acquisition and interpretation of data, statistical analysis and interpretation, drafting of the manuscript. Daniel Pilger, MD: statistical analysis and interpretation, critical revision, grammar editing. Eckart Bertelmann, MD: cataract

surgeries, critical revision. Christoph von Sonnleithner: study conception and design, acquisition of data, statistical analysis and interpretation of data, critical revision.

Declaration of conflicting interests


The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: Dominika Pohlmann: Allergan®, Bayer®(R). Eckart Bertelmann has served as principal investigator or consultant for: Alcon, Johnson&Johnson, Zeiss, Human Optics. None of the authors have a direct proprietary interest in any of the products used in this study.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: Dr. Dominika Pohlmann and Dr. Daniel Pilger are participants in the BIH Charité Clinician Scientist Program funded by the Charité-Universitätsmedizin Berlin and the Berlin Institute of Health. We acknowledge support from the German Research Foundation (DFG) and the Open Access Publication Fund of Charité-Universitätsmedizin Berlin.

ORCID iDs

Dominika Pohlmann  <https://orcid.org/0000-0002-9866-0431>

Daniel Pilger  <https://orcid.org/0000-0003-3397-8139>

Christoph von Sonnleithner  <https://orcid.org/0000-0002-1599-7291>

References

1. Visco DM, Bedi R and Packer M. Femtosecond laser-assisted arcuate keratotomy at the time of cataract surgery for the management of preexisting astigmatism [published correction appears in *J Cataract Refract Surg* 2020; 46(4): 658]. *J Cataract Refract Surg* 2019; 45(12): 1762–1769.
2. Agarwal A and Jacob S. Current and effective advantages of femto phacoemulsification. *Curr Opin Ophthalmol* 2017; 28(1): 49–57.
3. Yesilirmak N, Diakonis VF, Batlle JF, et al. Comparison of phacoemulsification parameters between manual and femtosecond laser-assisted cataract surgery. *Can J Ophthalmol* 2018; 53(5): 542–547.
4. Kanellopoulos AJ and Asimellis G. Standard manual capsulorhexis/ultrasound phacoemulsification compared to femtosecond laser-assisted capsulorhexis and lens fragmentation in clear cornea small incision cataract surgery. *Eye Vis (Lond)* 2016; 3: 20.
5. Manning S, Barry P, Henry Y, et al. Femtosecond laser-assisted cataract surgery versus standard phacoemulsification cataract surgery: study from the European Registry of Quality Outcomes for Cataract and Refractive Surgery. *J Cataract Refract Surg* 2016; 42(12): 1779–1790.
6. Porter J, Guirao A, Cox IG, et al. Monochromatic aberrations of the human eye in a large population. *J Opt Soc Am A Opt Image Sci* 2001; 18(8): 1793–1803.

7. Holladay JT, Piers PA, Koranyi G, et al. A new intraocular lens design to reduce spherical aberration of pseudophakic eyes. *J Refract Surg* 2002; 18(6): 683–691.
8. Tzelikis PF, Akaishi L, Trindade FC, et al. Spherical aberration and contrast sensitivity in eyes implanted with aspheric and spherical intraocular lenses: a comparative study. *Am J Ophthalmol* 2008; 145(5): 827–833.
9. Tzelikis PF, Akaishi L, Trindade FC, et al. Ocular aberrations and contrast sensitivity after cataract surgery with AcrySof IQ intraocular lens implantation Clinical comparative study. *J Cataract Refract Surg* 2007; 33(11): 1918–1924.
10. Rocha KM, Soriano ES, Chalita MR, et al. Wavefront analysis and contrast sensitivity of aspheric and spherical intraocular lenses: a randomized prospective study. *Am J Ophthalmol* 2006; 142(5): 750–756.
11. Mester U, Dillinger P and Anterist N. Impact of a modified optic design on visual function: clinical comparative study. *J Cataract Refract Surg* 2003; 29(4): 652–660.
12. Kershner RM. Retinal image contrast and functional visual performance with aspheric, silicone, and acrylic intraocular lenses. Prospective evaluation. *J Cataract Refract Surg* 2003; 29(9): 1684–1694.
13. Denoyer A, Le Lez ML, Majzoub S, et al. Quality of vision after cataract surgery after Tecnis Z9000 intraocular lens implantation: effect of contrast sensitivity and wavefront aberration improvements on the quality of daily vision. *J Cataract Refract Surg* 2007; 33(2): 210–216.
14. Von Sonnleithner C, Pilger D, Homburg D, et al. Corneal higher-order aberrations after phacoemulsification: a comparison of 3 different incision sizes. *Eur J Ophthalmol* 2017; 27(4): 402–406.
15. Pahlitzsch M, Pahlitzsch ML, Sumarni U, et al. Can we improve the efficacy of modern cataract surgery by using different tip designs? A comparison of balanced and tapered tip in femtosecond laser-assisted cataract surgery and manual phacoemulsification. *Clin Exp Ophthalmol* 2018; 46(1): 35–45.
16. Saeedi OJ, Chang LY, Ong SR, et al. Comparison of cumulative dispersed energy (CDE) in femtosecond laser-assisted cataract surgery (FLACS) and conventional phacoemulsification. *Int Ophthalmol* 2019; 39(8): 1761–1766.
17. Ang RET, Quinto MMS, Cruz EM, et al. Comparison of clinical outcomes between femtosecond laser-assisted versus conventional phacoemulsification. *Eye Vis (Lond)* 2018; 5: 8.
18. Pahlitzsch M, Torun N, Pahlitzsch ML, et al. Impact of the femtosecond laser in line with the femtosecond laser-assisted cataract surgery (FLACS) on the anterior chamber characteristics in comparison to the manual phacoemulsification. *Semin Ophthalmol* 2017; 32(4): 456–461.
19. Abell RG, Kerr NM and Vote BJ. Toward zero effective phacoemulsification time using femtosecond laser pretreatment. *Ophthalmology* 2013; 120: 942–948.
20. Abell RG, Kerr NM and Vote BJ. Femtosecond laser-assisted cataract surgery compared with conventional cataract surgery. *Clin Exp Ophthalmol* 2013; 41: 455–462.
21. Conrad-Hengerer I, Hengerer FH, Schultz T, et al. Effect of femtosecond laser fragmentation on effective phacoemulsification time in cataract surgery. *J Refract Surg* 2012; 28: 879–883.
22. Friedman NJ, Palanker DV, Schuele G, et al. Femtosecond laser capsulotomy. *J Cataract Refract Surg* 2011; 37(7): 1189–1198.
23. Takács AI, Kovács I, Miháltz K, et al. Central corneal volume and endothelial cell count following femtosecond laser-assisted refractive cataract surgery compared to conventional phacoemulsification. *J Refract Surg* 2012; 28(6): 387–391.
24. Reddy KP, Kandulla J and Auffarth GU. Effectiveness and safety of femtosecond laser-assisted lens fragmentation and anterior capsulotomy versus the manual technique in cataract surgery. *J Cataract Refract Surg* 2013; 39(9): 1297–1306.
25. Conrad-Hengerer I, Al Juburi M, Schultz T, et al. Corneal endothelial cell loss and corneal thickness in conventional compared with femtosecond laser-assisted cataract surgery: three-month follow-up. *J Cataract Refract Surg* 2013; 39(9): 1307–1313.
26. Chen X, Chen K, He J, et al. Comparing the curative effects between femtosecond laser-assisted cataract surgery and conventional phacoemulsification surgery: a meta-analysis. *PLoS One* 2016; 11(3): e0152088.
27. Chen X, Xiao W, Ye S, et al. Efficacy and safety of femtosecond laser-assisted cataract surgery versus conventional phacoemulsification for cataract: a meta-analysis of randomized controlled trials. *Sci Rep* 2015; 5: 13123.
28. Day AC, Gore DM, Bunce C, et al. Laser-assisted cataract surgery versus standard ultrasound phacoemulsification cataract surgery. *Cochrane Database Syst Rev* 2016; 7: CD010735.
29. Popovic M, Campos-Möller X, Schlenker MB, et al. Efficacy and safety of femtosecond laser-assisted cataract surgery compared with manual cataract surgery: a meta-analysis of 14 567 eyes. *Ophthalmology* 2016; 123(10): 2113–2126.
30. Ye Z, Li Z and He S. A meta-analysis comparing post-operative complications and outcomes of femtosecond laser-assisted cataract surgery versus conventional phacoemulsification for cataract. *J Ophthalmol* 2017; 2017: 3849152.
31. Denoyer A, Denoyer L, Marotte D, et al. Intraindividual comparative study of corneal and ocular wavefront aberrations after biaxial microincision versus coaxial small-incision cataract surgery. *Br J Ophthalmol* 2008; 92(12): 1679–1684.
32. Marcos S, Rosales P, Llorente L, et al. Change in corneal aberrations after cataract surgery with 2 types of aspherical intraocular lenses. *J Cataract Refract Surg* 2007; 33(2): 217–226.
33. Mastropasqua L, Toto L, Mastropasqua A, et al. Femtosecond laser versus manual clear corneal incision in cataract surgery. *J Refract Surg* 2014; 30: 27–33.
34. Filkorn T, Kovács I, Takács A, et al. Comparison of IOL power calculation and refractive outcome after laser refractive cataract surgery with a femtosecond laser versus conventional phacoemulsification. *J Refract Surg* 2012; 28: 540–544.
35. Yoo A, Yun S, Kim JY, et al. Femtosecond laser-assisted arcuate keratotomy versus toric IOL implantation for correcting astigmatism. *J Refract Surg* 2015; 31(9): 574–578.

36. Hofer H, Chen L, Yoon GY, et al. Improvement in retinal image quality with dynamic correction of the eye's aberrations. *Opt Express* 2001; 8: 631–643.
37. Thibos LN. Retinal image quality for virtual eyes generated by a statistical model of ocular wavefront aberrations. *Ophthalmic Physiol Opt* 2009; 29: 288–291.
38. Yamaguchi T, Negishi K, Ohnuma K, et al. Correlation between contrast sensitivity and higher-order aberration based on pupil diameter after cataract surgery. *Clin Ophthalmol* 2011; 5: 1701–1707.
39. Bühren J, Martin T, Kühne A, et al. Correlation of aberrometry, contrast sensitivity, and subjective symptoms with quality of vision after LASIK. *J Refract Surg* 2009; 25: 559–568.
40. Oshika T, Okamoto C, Samejima T, et al. Contrast sensitivity function and ocular higher-order wavefront aberrations in normal human eyes. *Ophthalmology* 2006; 113: 1807–1812.
41. Jin H, Limberger IJ, Ehmer A, et al. Impact of axis misalignment of toric intraocular lenses on refractive outcomes after cataract surgery. *J Cataract Refract Surg* 2010; 36: 2061–2072.
42. Felipe A, Artigas JM, Diez-Ajenjo A, et al. Residual astigmatism produced by toric intraocular lens rotation. *J Cataract Refract Surg* 2011; 37: 1895–190.
43. Chan TC, Ng AL, Cheng GP, et al. Corneal astigmatism and aberrations after combined femtosecond-assisted phacoemulsification and arcuate keratotomy: two-year results. *Am J Ophthalmol* 2016; 170: 83–90.
44. Lee JA, Song WK, Kim JY, et al. Femtosecond laser-assisted cataract surgery versus conventional phacoemulsification: refractive and aberrometric outcomes with a diffractive multifocal intraocular lens. *J Cataract Refract Surg* 2019; 45(1): 21–27.