Lasers in Medical Science (2019) 34:1229–1234
https://doi.org/10.1007/s10103-019-02715-6

ORIGINAL ARTICLE

Impact of lens density and lens thickness on cumulative dissipated energy in femtosecond laser–assisted cataract surgery

Mehdi Shajari[1,2] · Vladimir Rusev[1] · Wolfgang Mayer[2] · Vasilios Diakonis[3] · Kerstin Petermann[1] · Thomas Kohnen[1]

Received: 19 March 2018 / Accepted: 2 January 2019 / Published online: 19 January 2019

Abstract

To evaluate the required cumulative dissipated energy (CDE) to fragment the crystalline lens in femtosecond laser–assisted cataract surgery (FLACS) in relation to lens density and lens thickness. Consecutive eyes that underwent FLACS between September 2014 and March 2017 by a single surgeon using in all cases the same femtosecond laser and phacoemulsification platform were included in our retrospective study. Prior to surgery, corrected distance visual acuity (CDVA), optical biometry corneal, and crystalline lens tomographies were performed to assess anterior chamber depth (ACD), axial length (AL), and crystalline lens parameters (i.e., lens density, thickness, and nucleus staging (NS)). After surgery, CDE was calculated and analyzed in relation to lens density (LD) and lens thickness (LT). Zero ultrasound expenditure cases were recorded and their occurrence analyzed. The chart review identified 236 eyes of 200 patients, 98 males and 102 females aged 65± 15 years which were included in the study. Mean LD was 11.26 ± 2.05 pixel intensity units (range 7.30–18.80), and the mean LT was 3417 ± 405.17 μm (range 2545–4701). LD and LT correlated moderately ($r = 0.50$, $p < 0.001$) and weakly ($r = 0.23$, $p < 0.001$), with post-laser CDE. Higher LD and LT were also associated with lower rates of zero phaco (eyes in which no phacoemulsification energy was necessary). Furthermore, NS ($r = 0.528$, $p < 0.001$) and CDVA ($r = -0.3524$, $p < 0.001$) also correlated with CDE. Higher LD, LT, NS values, and low CDVA are associated with higher ultrasound expenditure (CDE—cumulative dissipated energy) and with lower rates of zero ultrasound expenditure during FLACS.

Keywords Pentacam · Intraocular lens · Lens density · Lens thickness · Zero phaco · CDE · Cumulative dissipated energy · FLACS · Femtosecond laser · Cataract surgery

Introduction

Cataract surgery is the most commonly performed ophthalmic procedure, and phacoemulsification (cracking the natural lens into smaller pieces with ultrasound energy) has been the most commonly used surgical technique since its introduction by Charles Kelman in 1967 [1]. The continued development of technology related to phacoemulsification machines and handpiece tips and the recent addition of the femtosecond laser (FLACS) [2] have provided ophthalmologists with tools to advance their capabilities as cataract surgeons. The femtosecond laser can assist in three steps during cataract surgery: in performing clear corneal incisions, in performing the capsulorhexis, and in fragmentation of the lens. The primary advantage in the first two steps is that they can be performed with greater precision. Lens fragmentation with the laser, however, has the main advantage that the whole procedure can be performed with less phacoemulsification energy, which might be harmful to the eye, particularly to the corneal endothelium. The corneal endothelium has an extraordinarily important role for clear vision—it pumps fluid which moves into the cornea (which causes opacification) out to the anterior chamber. Especially in patients with a reduced endothelial cell density, the laser can be used to protect the corneal endothelium. Although it is assumed that the laser energy is not harmful to the eye, it would be good to know preoperatively which laser settings should be used to achieve the target of lens fragmentation without exposing the eye to unrequired laser energy.

✉ Thomas Kohnen
kohnen@em.uni-frankfurt.de

[1] Department of Ophthalmology, Goethe-University, Theodor-Stern-Kai 7, 60590 Frankfurt am Main, Germany

[2] Department of Ophthalmology, Ludwig Maximillian University, Munich, Germany

[3] Bascom Palmer Eye Institute, Miami, USA

Ultrasound energy expenditure (CDE—cumulative dissipated energy) during phacoemulsification depends on a variety of parameters that mainly include crystalline lens density (cataract grade), surgical technique used, FLACS usage for pretreatment, and a surgeon's experience. Other parameters may include crystalline lens thickness and preoperative visual acuity. The goal in modern cataract surgery is to minimize ultrasonic expenditure during cataract extraction in order to minimize potential collateral ocular tissue damage and avoid potential postoperative complications associated with increased CDE (corneal endothelial decompensation, corneal wound burn, increased postoperative inflammation, etc.).

Before surgery, it is mandatory to measure the corneal curvature, anterior chamber depth, and the axial length in order to calculate the power of the artificial lens which needs to be placed into the eye during surgery. Surgeons have started to additionally measure the natural lens density as well as lens thickness as this has an effect on ultrasound expenditure. The aim of this study is to provide a thorough analysis of the relationship between the crystalline lens biometrical parameters (crystalline lens central thickness and lens density) with ultrasound expenditure (CDE) during FLACS.

Materials and methods

The retrospective chart review included consecutive eyes that underwent FLACS in the Department of Ophthalmology at the Goethe University in Frankfurt, Germany, between September 2014 and March 2017 by a single experienced surgeon (T.K.).

Exclusion criteria were defined as follows: ocular comorbidity (acute infections, autoimmune disease, wound-healing disorders, keratoconus, pseudoexfoliation syndrome, ocular tumors), including any kind of previous intraocular or corneal surgery, optic atrophy, central corneal scarring, severe ocular pathology and trauma, or abnormal examination results from a slit lamp, IOL Master, or Pentacam. Preoperative patient data is shown in Table 1.

Optical biometry

The IOL Master 500 (Zeiss, Jena, Germany) was used to perform all biometry assessments. This biometry platform is an ocular non-contact biometry capable of determining the axial length (AL) of the eye using partial coherence interferometry (PCI) in addition to measurement of the anterior chamber depth (ACD) by visual pachymetry [1]. The AL is measured on a scale of 14–39 mm with a precision of ± 0.01 mm [1].

Corneal tomography and crystalline lens densitometry

The Pentacam HR Scheimpflug Imaging System (Oculus, Wetzlar, Germany) was used to determine the preoperative nucleus staging (NS). All examinations were carried out after application of mydriatic eye drops (tropicamide 5 mg/ml, every 10 min, total of three times). Pentacam software has the capability of analyzing the overall three-dimensional lens volume and lens optical density by measuring the backward scatter. The higher the lens density, the more light is reflected increasing backward scatter which leads to a higher PNS value. As a result, the device calculates a value between 0 and 5, referred to as PNS (Pentacam nucleus staging) which reflects the overall average opacity using an ordinal scale [2, 3]. In addition, a three-dimensional lens region of interest may be defined manually, the value referred to as PNS-P, and represents the opacity percentage [4]. Lens thickness was assessed with the software provided by the LenSx system.

Surgical procedure

All surgeries were performed by the same surgeon (T.K.) using the same phacoemulsification platform (Centurion Vision System, Alcon Laboratories, Fort Worth, TX, USA) under topical anesthesia with oxybuprocaine hydrochloride 4.0 mg/ml unit dose (Conjucain® EDO, Bausch & Lomb) eye drops. Prior to phacoemulsification, all eyes received FLACS using the LenSx femtosecond laser platform (Alcon Laboratories, Fort Worth, TX, USA)—a 50-kHz infrared laser

Table 1 Demographics of analysed population

n=236	Mean ± SD	Range
Age (years)	66.67 ± 11.5	32 to 89
Sphere (dpt)	-1.01 ± 4.7	-17.75 to 14.00
Cylinder (dpt)	-1.31 ± 1.08	-6.00 to 0
CDVA (Snellen)	0.61 ± 0.29	0.01 to 1.25
Anterior chamber depth (mm)	3.21 ± 0.41	2.10 to 4.15
Axial length (mm)	24.46 ± 2.01	20.23 to 32.94

SD (Standard deviation), CDVA (Corrected Distance Visual Acuity)

Table 2 Lens characteristics and required cumulative dissipated energy

n=236	Mean ± SD	Range
Pentacam Nucleus Staging	1.00 ± 0.73	0 to 3
Lens Density	11.26 ± 2.05	7.30 to 18.80
Lens thickness (μm)	3417.42 ± 405.17	2545 to 4701
Cumulative Dissipated Energy	3.65 ± 4.78	0.00 to 26.72

with a pulse width of 600–8002 femtosecond, a central laser wavelength of 1030 nm, and maximum pulse energy of 15 μJ. Corneal incisions, capsulotomy, and lens fragmentation parameters were visualized by spectral domain optical coherence tomography (OCT). Every procedural step was manually confirmed before laser treatment was performed. Primary corneal incisions were set between 2.2 and 2.4 mm, and the attempted capsulotomy diameter was 5.0 mm in all cases. A standardized lens-softening pattern (3 cross sections with a chop diameter of 4.8 mm and 1 central chop cylinder with a diameter of 2 mm) was used. The laser pulse energy was set to 7 μJ for corneal incisions and 5 μJ for capsulotomy and lens fragmentation.

After hydrodissection, if necessary, phacoemulsification was performed with a 45° Kelman, 0.9 mm Turbosonics Mini-Flared ABS Tip (Alcon). The anterior chamber was filled with a 1% sodium hyaluronate viscoelastic solution and lens segmentation was undertaken using a divide-and-conquer approach. Eventually, after the removal of the lens cortex, a foldable intraocular lens was implanted into the capsular bag. Cases where no extra phacoemulsification was necessary were recorded (zero phaco). An intraocular lens was placed in the capsular bag in all cases. Postoperatively, all patients received the same treatment regimen consisting of a combination of an antibiotic, steroid, and non-steroidal anti-inflammatory drop.

Statistical analysis

All patient data from the Pentacam (Oculus, Wetzlar, Germany), IOL Master (Zeiss, Jena, Germany), LenSx (Alcon Laboratories, Fort Worth, TX, USA), and Centurion Vision System (Alcon Laboratories, Fort Worth, TX, USA) were exported, saved, and combined into a single Microsoft Excel spreadsheet (Microsoft Office 2016 for Windows). In addition, STATA 13 (StataCorp) was used for data analysis. Statistical methods were applied and included: correlation and regression analysis, likelihood-ratio test, logistic regression, and a chi-squared test. Differences were considered statistically significant when p values were less than 0.05.

Results

The preoperative Pentacam analysis showed a mean crystalline lens density of 11.26 ± 2.05 PSU (Pixel Intensity Units) and a mean lens thickness of 3417.42 ± 405.17 μm. Summarized preoperative patient data is shown in Table 2.

One hundred and fifteen eyes required no ultrasound expenditure after laser fragmentation, referred to as zero phaco (CDE = 0). A detailed correlation analysis was performed to find relationships among the parameters examined in our study. Table 3 contains Pearson's Correlation Coefficients providing the measure of association between every two of the examined parameters, including the corresponding p values.

We observed a weak correlation but statistically significant between LT and CDE ($r = 0.23$, $p < 0.001$) as well as a moderate correlation that was statistically significant between LD and CDE ($r = 0.50$, $p < 0.001$).

To analyze the impact of each factor on CDE independently, we used regression analysis, which showed a significant dependency on LD ($-10.4 + 0.91x$, $R^2 = 0.30$, $p = 0.009$) and

Table 3 Correlation of cumulative dissipated energy and variables measured preoperatively

n=236	CDE	LT	LD	PNS
LT	0.2266			
	p<0.001			
LD	0.4965	0.1747		
	p<0.001	p=0.0071		
PNS	0.528	0.3021	0.8336	
	p<0.001	p<0.001	p<0.001	
CDVA	-0.3524	-0.0465	-0.3392	-0.3126
	p<0.001	p=0.4794	p<0.001	p<0.001

CDE (Cumulative dissipated energy), LT (Lens Thickness), LD (Lens Density), PNS (Pentacam Nucleus Staging), CDVA (Corrected Distance Visual Acuity)

Table 4 Regression analysis showing the impact of lens density (LD), lens thickness (LT), and corrected distance visual acuity (CDVA) on zero phacos with $p < 0.05$ for all three variables. Decreased lens density, decreased lens thickness, and better corrected distance visual acuity lead to a higher incidence of procedures where no ultrasound energy is required

$n = 115$	Constant	Regression coefficient	p value
LD	− 6.76 (95% CI − 8.83 to − 4.70)	0.61 (95% CI 0.43 to 0.80)	< 0.001
LT	− 3.22 (95% CI − 5.51 to − 0.94)	0.001 (95% CI 0.0003 to 0.0016)	0.005
CDVA	1.54 (95% CI 0.87 to 2.20)	− 2.41 (95% CI − 3.40 to − 1.42)	< 0.001

CI confidence interval

LT ($-10.4 + 0.002x$, $R^2 = 0.30$, $p < 0.001$). In addition, we calculated the regression coefficient of BCVA ($-10.4–3.47x$, $R^2 = 0.30$, $p < 0.001$).

Considering that 115 eyes did not require ultrasound expenditure after FLACS, we also focused our analysis on the impact of LD, LT, and BCVA on zero phaco. We used logistic regression analysis in our model, coded zero phaco as 0, and the necessity of phacoemulsification as 1. The logistic regression showed the impact of LD, LT, and BCVA on zero phaco as displayed in Table 4.

According to our analysis, lower LD, LT, and higher BCVA are associated with higher probability of zero phaco.

We also studied the impact of PNS on zero phaco. Table 5 shows the occurrence of zero phaco in relation to the preoperative PNS value. Eighty percent of the eyes staged at PNS 0 needed no extra phacoemulsification. Furthermore, we observed a 50% zero phaco rate in PNS 1 and a substantial drop in higher PNS stages.

Discussion

Phacoemulsification has been a well-established method of cataract surgery for many years as it allows the surgeon to crack and emulsify the crystalline lens, avoiding the necessity of large incisions which leads to a faster healing process and a reduction in complication rates. Nevertheless, phacoemulsification itself can also lead to complications, mainly related to collateral ocular tissue damage.

Lately, femtosecond lasers have been utilized for pretreatment prior to phacoemulsification-assisted cataract extraction, performing clear corneal incision, anterior capsulotomies, and crystalline lens fragmentation. FLACS has been reported as more efficient and beneficial compared to manual cataract surgery (MCS) in multiple studies over the past years as it demonstrates reduced CDE, more accurate refractive outcomes, and optimal visual outcomes after cataract surgery [2, 4–10].

Mayer et al. concluded in their study that FLACS leads to significant reduction of effective phacoemulsification time (EPT): 1.58 ± 1.02 s in the femtosecond laser group (FS-Laser group) versus 4.17 ± 2.06 s in the MCS group ($p = 0.001$). One of the reasons for this was that they had several "zero-phaco eyes" in the FLACS group, which is similar to the finding in our study. Furthermore, they reported a reduction in endothelial cell loss during surgery which was likely to be associated with the reduction of EPT and CDE [9]. Additional benefits of FLACS include better centration and size of capsulotomy and the implanted intraocular lens [11], as well as the reduction of postoperative corneal edema [9].

The study of Ecsedy et al. [12] confirmed the non-inferiority of FLACS in relation to postoperative macular thickness measured by OCT. Their results also showed significantly less macular thickness increase postoperatively in the FS-Laser group versus the conventional phacoemulsification group 1 week after surgery. The most probable reason for this is that less ultrasound energy is needed in eyes with prior laser fragmentation. However, femtosecond laser treatment is often not capable of fragmentizing the crystalline lens completely, and so additional phacoemulsification is needed.

With aging, the natural lens gets harder and lens density increases. This leads to the situation that pure vacuum is insufficient to aspirate the lens during surgery. Phacoemulsification energy is necessary to first crack the lens into smaller pieces which can then be aspirated. If the lens is not too hard, a prior laser fragmentation is sufficient to form small enough lens pieces which can then be directly aspirated without requiring additional ultrasound energy (CDE = 0).

According to our results, both of the lens values that we focused on in our study, that is LD and LT, correlate significantly positively with needed CDE after femtosecond laser

Table 5 Number of zero-phaco procedures depending on preoperative Pentacam nucleus staging (PNS)

PNS Stage:	0	1	2	3	All Stages:
Zero phaco:	44	68	3	0	115
FS-Laser plus phaco:	11	64	35	8	118
Total:	55	132	38	8	233

treatment. Lower LD and LT values are also related to higher rates of zero phaco.

Successful FLACS assumes objective assessment of the preoperative cataract stage [2]. Hence, the Lens Opacities Classification System III (LOCS III), which has been commonly used, involves subjective evaluation by a slit lamp using standard photographic charts [2, 13]. Gupta et al. [13] reported linear correlation between LOCS III and PNS, assessing the cataract nuclear staging and CDE ($r = 0.607$ and $r = 0.847$, respectively). This confirms that lenses which had a higher PNS stage in our study most probably had also a higher lens density. Faria-Correia et al. [14] also confirmed the correlation between the average optical lens density measured by a Pentacam and EPT ($r = 0.596$, $p < 0.001$). They did not find significant correlation between PNS and EPT which was probably due to low PNS in their cohort (0.66 ± 0.479, range 0.00–1.00). In eyes with low density (low PNS), ultrasound energy is often not required which makes a correlation analysis difficult. In contrast, in our study, we were able to include eyes with a high lens density allowing to perform a proper correlation analysis which actually confirmed the findings of Mayer et al. who showed that a higher lens density leads to an increase in required ultrasound energy.

According to our results, we can confirm the correlation between PNS, LT, and CDE. These variables can be used preoperatively to predict the probable required energy and the likelihood of a zero phaco procedure.

This study is limited by its retrospective nature, but our findings nevertheless suggest that not only does lens density play a role in the required CDE for patients undergoing femtosecond laser–assisted lens surgery, but also the lens thickness itself.

Acknowledgements Alison Rowan McEwan and Leon de'Lorenzo, Goethe University, Frankfurt, Germany, provided additional support in the proof reading and preparation of this manuscript.

Compliance with ethical standards

Ethical approval The study was designed in compliance with the principles of the Declaration of Helsinki and approved by the local ethics committee. For this type of study, formal consent is not required.

Conflict of interest Mehdi Shajari: Oculus, Zeiss, Staar, Santen, Oertli. Vladimir Rusev: none. Wolfgang Mayer: Consultant or Advisory Board—Alcon, Allergan, Polytech/Domilens, Zeiss Meditec, Ziemer. Vasilios Diakonis: none. Kerstin Petermann: none. Thomas Kohnen: Research Funding—Hoya, J&J Vision (Abbott), Novartis (Alcon), Oculentis, Oculus, Schwind, Zeiss. Consultant or Advisory Board—Geuder, J&J Vision (Abbott), Novartis (Alcon), Oculus, Santen, Schwind, STAAR, TearLab, Thea Pharma, Thieme Compliance, Ziemer, Zeiss. *Consultant and Research for* Abbott/J&J, Alcon/Novartis, Schwind, Zeiss. *Consultant for* Allergan, Bausch & Lomb, Dompe, Geuder, Med Update, Oculentis, Oculus, Rayner, Santen, Staar, Thea, Tear Lab, Thieme, Unimed Verlag, Ziemer. *Research for* Avedro, Hoya, Presbia.

The authors declare that they have no conflict of interest.

References

1. Labiris G, Ntonti P, Ntitsos K, Katsanos A, Sideroudi H, Kozobolis V (2017) Comparison of the biometric measurements calculated with Zeiss IOL-master and WaveLight OB-820. Clin Ophthalmol 11:753–758. https://doi.org/10.2147/OPTH.S133207
2. Mayer WJ, Klaproth OK, Hengerer FH, Kohnen T (2014) Impact of crystalline lens opacification on effective phacoemulsification time in femtosecond laser-assisted cataract surgery. Am J Ophthalmol 157:426–432.e1. https://doi.org/10.1016/j.ajo.2013.09.017
3. Magalhães FP, Costa EF, Cariello AJ, Rodrigues EB, Hofling-Lima AL (2011) Comparative analysis of the nuclear lens opalescence by the Lens Opacities Classification System III with nuclear density values provided by Oculus Pentacam: a cross-section study using Pentacam Nucleus Staging software. Arq Bras Oftalmol 74:110–113
4. Al-Khateeb G, Shajari M, Vunnava K, Petermann K, Kohnen T (2017) Impact of lens densitometry on phacoemulsification parameters and usage of ultrasound energy in femtosecond laser-assisted lens surgery. Can J Ophthalmol 52:331–337. https://doi.org/10.1016/j.jcjo.2017.01.004
5. Reddy KP, Kandulla J, Auffarth GU (2013) Effectiveness and safety of femtosecond laser–assisted lens fragmentation and anterior capsulotomy versus the manual technique in cataract surgery. J Cataract Refract Surg 39:1297–1306. https://doi.org/10.1016/j.jcrs.2013.05.035
6. Krarup T, Morten Holm L, la Cour M, Kjaerbo H (2014) Endothelial cell loss and refractive predictability in femtosecond laser-assisted cataract surgery compared with conventional cataract surgery. Acta Ophthalmol 92:617–622. https://doi.org/10.1111/aos
7. Daya SM, Nanavaty MA, Espinosa-Lagana MM (2014) Translenticular hydrodissection, lens fragmentation, and influence on ultrasound power in femtosecond laser–assisted cataract surgery and refractive lens exchange. J Cataract Refract Surg 40:37–43. https://doi.org/10.1016/j.jcrs.2013.07.040
8. Abell RG, Kerr NM, Vote BJ (2013) Femtosecond laser-assisted cataract surgery compared with conventional cataract surgery. Clin Exp Ophthalmol 41:455–462. https://doi.org/10.1111/ceo.12025
9. Abell RG, Kerr NM, Vote BJ (2013) Toward zero effective phacoemulsification time using femtosecond laser pretreatment. Ophthalmology 120:942–948. https://doi.org/10.1016/j.ophtha.2012.11.045
10. Abell RG, Kerr NM, Howie AR, Mustaffa Kamal MAA, Allen PL, Vote BJ (2014) Effect of femtosecond laser–assisted cataract surgery on the corneal endothelium. J Cataract Refract Surg 40:1777–1783. https://doi.org/10.1016/j.jcrs.2014.05.031
11. Kránitz K, Takacs A, Miháltz K, Kovács I, Knorz MC, Nagy ZZ (2011) Femtosecond laser capsulotomy and manual continuous

curvilinear capsulorrhexis parameters and their effects on intraocular lens centration. J Refract Surg 27:558–563. https://doi.org/10.3928/1081597X-20110623-03

12. Ecsedy M, Miháltz K, Kovács I, Takács Á, Filkorn T, Nagy ZZ (2011) Effect of femtosecond laser cataract surgery on the macula. J Refract Surg 27:717–722. https://doi.org/10.3928/1081597X-20110825-01
13. Gupta M, Ram J, Jain A, Sukhija J, Chaudhary M (2013) Correlation of nuclear density using the Lens Opacity Classification System III versus Scheimpflug imaging with phacoemulsification parameters. J Cataract Refract Surg 39:1818–1823. https://doi.org/10.1016/j.jcrs.2013.05.052
14. Faria-Correia F, Lopes B, Monteiro T, Franqueira N, Ambrósio R (2017) Correlation between different Scheimpflug-based lens densitometry analysis and effective phacoemulsification time in mild nuclear cataracts. Int Ophthalmol. https://doi.org/10.1007/s10792-017-0566-7

Precis

Not just the central lens density but also the lens thickness has an impact on cumulative dissipated energy during femtosecond laser–assisted lens surgery.