RESEARCH ARTICLE

Post-phacoemulsification iris changes in eyes with glaucoma or glaucoma suspect status

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Abstract

Purpose
This prospective study used anterior segment optical coherence tomography (AS-OCT) to determine how phacoemulsification (phaco) changes iris parameters in eyes with glaucoma or glaucoma suspect status.

Methods
Using Visante AS-OCT (Carl Zeiss Meditec AG), the following pre- and post-phaco parameters were measured: IT750 = iris thickness at 750 μm from the scleral spur; IT2000 = iris thickness 2000 μm from the scleral spur; ITCM = the maximum iris thickness at the middle one third of the iris; ICURV = iris curvature; IAREA = iris area; and pupil size = pupil diameter (mm). Only high-quality images with an identifiable scleral spur were included, and only the nasal quadrant was analyzed. A single glaucoma specialist analyzed the parameters according to the Zhongshan Angle Assessment Program (ZAAP, Guangzhou, China). Multivariate analysis was performed using mixed effects regression correcting for age, gender, and ethnicity.

Results
89 subjects and 110 eyes were included in this study. The mean age of subjects was 74.83 +/- 8.69 years old. Most common diagnoses were POAG and glaucoma suspect (23% and 52%, respectively), and 16% of subjects had an LPI. In multivariate analysis of AS-OCT parameters, decreases in IT750, IT2000, ITCM, ICURV, and pupil size were statistically significant (p<0.05).

Conclusions
After phacoemulsification, eyes with glaucoma as well as glaucoma suspect eyes have thinner irises and smaller pupils. This may lead to less iris-mediated aqueous outflow obstruction, providing support for early phacoemulsification glaucoma treatment.
Translational relevance
Our AS-OCT imaging findings may guide clinical practice as iris parameters become increasingly relevant in preoperative phaco planning.

Introduction
Glaucoma and cataract, two well-known disease entities with an estimated comorbidity of 19.1%, are the leading causes of blindness worldwide [1–3]. Currently, the only modifiable glaucoma risk factor is intraocular pressure (IOP), which is often but not always elevated in glaucoma patients [4]. Additionally, in patients with primary glaucoma, specific treatment regimens and prognoses depend not only on IOP, but also on anterior chamber angle morphology [4,5]. Existing literature demonstrates that cataract surgery, one of the most commonly performed surgical procedures around the world, tends to lower IOP as well as favorably modify anterior chamber parameters such as lens vault and iris thickness [5–10].

The IOP-lowering and anterior chamber-altering effect of phacoemulsification cataract surgery (phaco) has been studied in both nonglaucomatous and glaucomatous eyes [9, 11–31]. Given the improved safety profile of modern phaco compared to traditional incisional glaucoma surgeries, phaco has been advocated as an early means of lowering IOP [7,32]. Specifically, patients with primary angle closure (PAC) and primary angle closure glaucoma (PACG) derive greater benefit from clear lens extraction compared to laser peripheral iridotomy [23,33,34]. In OAG, studies have also demonstrated post-operative IOP reduction [12–14] and significant post-operative changes in anterior segment parameters such as angle-opening distance (AOD500), supporting the theory that anatomical changes in the anterior segment may be responsible for the IOP-lowering effects of phacoemulsification [7,12].

Anterior segment optical coherence tomography (AS-OCT) allows quantification of various anterior segment parameters and has provided valuable information regarding pre- and post-phaco changes in the anterior segment [35]. Previously studied AS-OCT parameters include: anterior chamber volume (ACV), anterior chamber width (ACW), iris area, and iris curvature (I-curve) [12,14]. It is now well-established that phaco deepens the anterior chamber and widens the angle [6,12,14,36–38], but there is less dedicated research into how this surgery impacts the iris itself [7,12].

The iris is a permeable, sponge-like structure whose cross-sectional area and volume vary under certain conditions [39,40]. The spongy quality of the iris stroma may exert significant influence on anterior chamber anatomy [40]. While phaco demonstrably alters the anterior chamber angle and other parameters, the impact of phaco on the iris is unknown. As such, we conducted a prospective study evaluating the effect of phaco on AS-OCT iris parameters in glaucoma and glaucoma suspect patients.

Patients and methods
This was a prospective study approved by the institutional review board (IRB) at the University of California, San Francisco (UCSF), California, USA. Written informed consent was obtained from all patients prior to enrollment. Patients were consecutively recruited from the UCSF glaucoma clinics from May 2012 through March 2017.
Inclusion criteria
Inclusion criteria included age older than 18 years, presence of visually significant cataract(s) that were removed via uncomplicated phacoemulsification, and completion of at least 1 pre-operative and 1 post-operative AS-OCT imaging session. Both glaucoma and glaucoma suspect eyes were included; eyes were determined to have a diagnosis of glaucoma as defined by 1) the use of glaucoma medications plus 2) the presence of glaucomatous disc excavation and glaucomatous visual field defects, OR glaucomatous disc cupping of 0.9 or greater in patients unable to undergo visual field testing. Glaucoma suspects were defined as eyes with glaucomatous disc excavation without glaucomatous visual field defects. Both eyes of patients were included in the study if they met inclusion criteria.

Exclusion criteria
Exclusion criteria included age less than 18 years; phaco with complicated intraoperative (e.g., vitreous loss, need for Malyugin ring) and/or postoperative course; prior history of intraocular surgery (e.g. iStent, trabeculectomy); other ocular conditions affecting visual acuity and/or IOP; ocular trauma; evidence of pigment dispersion or pseudoexfoliation; peripheral anterior synechiae (PAS) seen on gonioscopy; and/or issues with AS-OCT image analysis. Eyes that have undergone laser peripheral iridotomy (LPI) or laser trabeculoplasty were not excluded.

Demographic information, preoperative assessment, and post-operative values from 176 patients and 240 eyes were initially obtained from our database of subjects who enrolled to be followed with anterior segment imaging. Ultimately, 87 subjects and 130 eyes were excluded based on the exclusion criteria above. Clinical data of interest included glaucoma diagnosis and IOP. Of note, IOP was measured in the same manner (e.g., undilated eye, Goldmann applanation tonometry), by the same clinician (S.C.L), during the same time of day (between 1PM and 4PM). The IOP was checked twice and mean IOP was used in this study. If the IOP measurement from the 2 tests differed by more than 2mmHg, a third value was obtained and the median was chosen.

Surgical technique
Phacoemulsification was performed by the same surgeon (S.C.L) using standard techniques. A temporal clear corneal incision was used, and a single piece acrylic intraocular lens (IOL) (Acrysof SN60WF, Alcon Laboratories, Inc., Fort Worth, TX) was implanted in all operative eyes. The standard postoperative eyedrop regimen included topical antibiotics 4 times daily for 1 week, prednisolone acetate 1.0% 4 times daily with a weekly taper, and ketorolac tromethamine 0.5% 4 times daily with a weekly taper.

Postoperative follow-up
Postoperative follow-up visits were performed at 3 months, 6 months, and 1 year after surgery. Each visit included visual acuity testing, IOP measurement, a complete slit lamp examination, and AS-OCT imaging.

Anterior segment optical coherence tomography (AS-OCT) and definition of parameters
Pre- and post-operative AS-OCT data were gathered using a Visante AS-OCT device (Carl Zeiss Meditec AG, Dublin, CA). Details of the imaging procedures and analysis have been previously described [14]. The following iris parameters were measured at baseline and at post-operative month 3 and beyond: IT750 = iris thickness measured at 750 μm from the scleral...
spur; IT2000 = iris thickness 2000 μm from the scleral spur; ITCM = the maximum iris thickness at the middle one third of the iris; ICURV = iris curvature; and IAREA = iris area. Pupil size, or pupil diameter in mm, was also evaluated. Only high-quality images with an identifiable scleral spur were included, and only the nasal quadrant was analyzed, as the other quadrants may have been distorted by eyelid manipulation or phacoemulsification trauma. Of note, only images obtained in the dark were used in this study.

A single glaucoma specialist analyzed the AS-OCT parameters according to established protocols using the Zhongshan Angle Assessment Program (ZAAP, Guangzhou, China). Image analysis was performed on post-operative AS-OCT images taken anywhere from 3 months to 1 year after the initial surgery; these different end points were due to inconsistent image availability arising from ZAAP segmentation issues encountered during analysis. Of note, current literature suggests that anterior segment parameters do not undergo much change beyond post-operative month 3 [14]. Therefore, all reported post-operative measurements taken after post-operative month 3 were treated equivalently. Multivariate analysis was subsequently performed using mixed effects regression correcting for age, gender, and ethnicity.

**Statistical analysis**

The Student’s *t* test was used to calculate statistical differences between paired continuous variables. Categorical variables were compared using the chi-square test. Linear mixed-effects regression analysis was used to assess the correlation between AS-OCT parameters, change in AS-OCT parameters (pre-operative values [in mm] – post-operative values), change in IOP (postoperative IOP minus preoperative IOP), and presence of LPI in univariate analysis and multivariate analysis. A *P* value less than 0.05 was considered statistically significant.

**Results**

This study enrolled a total of 176 subjects and 240 eyes; 89 subjects and 110 eyes were included for analysis after study exclusion criteria were applied. Data were also excluded if ZAAP segmentation issues (e.g., negative iris values, *n* = 57) were encountered during analysis. Of included subjects, 63 were women and 47 were men. Subjects had a range of glaucoma-related diagnoses as outlined in Table 1. The majority of subjects carried a diagnosis of POAG and glaucoma suspect (23% and 52%, respectively), and 16% of subjects had an LPI performed in one or both eyes previously.

Table 2 outlines pre- and post-operative IOP data and AS-OCT parameters in all 110 eyes. Post-operative AS-OCT parameters, including pupil size, were obtained up to 1 year after uncomplicated phaco. These values were noted to be uniformly lower than pre-operative values in eyes with glaucoma or glaucoma suspect status. Univariate analysis (Table 3) found this pattern to be statistically significant for IT750, IT2000, ITCM, pupil size (*p* < 0.005 for all 4), and ICURV (*p* = 0.04); after adjusting for age, gender, and ethnicity, the change between pre- and post-operative IT750, IT2000, ITCM, and pupil size was still statistically significant (*p* < 0.005).

Of note, in Table 4, pupil size and presence of an LPI were not found to impact pre- and post-operative iris parameters. While the association between pre- and post-operative IT2000 (*p* = 0.018) and ICURV (*p* = 0.005) were statistically significantly affected by an LPI, the β coefficients for these two parameters were extremely low (0.13, and -0.13, respectively).

Table 5 demonstrates that the post-phaco IOP change experienced by eyes with glaucoma or glaucoma suspect status is not statistically significantly associated with pre-operative AS-OCT iris parameters, post-operative AS-OCT iris parameters, and ΔIris (or, pre-operative minus post-operative iris values in mm).
Discussion

The iris is a dynamic, light-responsive organ comprised of the following structures from anterior to posterior: a surface layer of irregular cells, a fibrovascular stroma, the dilator and sphincter muscles, and a two-cell layer thick iris pigment epithelium (IPE) [41]. It is highly permeable to even macroscopic particles, and, being fully immersed in aqueous humor, allows the free passage of fluid between stroma and aqueous [40,41]. This fluid exchange is best demonstrated by the observation that a normal iris routinely loses area and volume after pupil dilation both in dark and pharmacologic conditions [40,42–44].

Table 1. Baseline patient demographics.

| Parameter               | Subjects (n) | % Total |
|-------------------------|--------------|---------|
| Age                     | Mean ± SD: 74.83 ± 8.69 Age Range: 55, 97 |         |
|                         |              |         |
| Sex                     |              |         |
| Female                  | 63           | 57.27   |
| Male                    | 47           | 42.73   |
| Race                    |              |         |
| Asian                   | 51           | 46.36   |
| Caucasian               | 34           | 30.91   |
| Hispanic                | 12           | 10.91   |
| Other                   | 13           | 11.82   |
| Glaucoma Diagnosis†     |              |         |
| NTG                     | 3            | 3.37    |
| PACG                    | 3            | 3.37    |
| PACG + MMG              | 1            | 1.12    |
| PACS                    | 1            | 1.12    |
| POAG                    | 23           | 25.84   |
| Suspect                 | 52           | 58.43   |
| Other                   | 6            | 6.74    |
| Previous LPI            | 18           | 16.36   |

†NTG = Normal Tension Glaucoma; PACG = Primary Angle Closure Glaucoma; PACG + MMG = Primary Angle Closure Glaucoma + Mixed Mechanism Glaucoma; PACS = Primary Angle Closure Suspect; POAG = Primary Open Angle Glaucoma

https://doi.org/10.1371/journal.pone.0208776.t001

Table 2. Pre and post-operative IOP and anterior segment-OCT (AS-OCT) parameters†.

| Parameter   | Pre-Op (mean ± SD) | Post-Op* (mean ± SD) |
|-------------|--------------------|----------------------|
| IOP         | 15.3±3.31          | 12.52±2.53           |
| IT750 (mm)  | 0.47±0.16          | 0.45±0.12            |
| IT2000 (mm) | 0.49±0.19          | 0.45±0.08            |
| ITCM (mm)   | 0.63±0.23          | 0.61±0.19            |
| IAREA (mm²) | 1.62±0.53          | 1.38±0.48            |
| ICURV (mm)  | 0.30±0.18          | 0.16±0.08            |
| Pupil Size (mm) | 4.19±0.85 | 3.89±0.84           |

Iris parameter definitions: IT750 = iris thickness measured at 750 μm from the scleral spur; IT2000 = iris thickness 2000 μm from the scleral spur; ITCM = the maximum iris thickness at the middle one third of the iris; ICURV = iris curvature; IAREA = iris area. Pupil size = pupil diameter.

†In dark conditions.

*Post-op includes data ranging from 3 months to 1 year after surgery.

https://doi.org/10.1371/journal.pone.0208776.t002
Such changes are thought to be due to movement of extracellular water in and out of the loose connective tissue of the iris stroma, demonstrating Quigley’s comparison of the iris to a sponge [39]. It is believed that the spongier an iris, the greater its volume loss during pupil dilation; presumably, greater volume loss prevents aqueous obstruction at the trabecular meshwork and potentially at the iris-lens channel, leaving an eye less vulnerable to increases in IOP [39,40,42–45].

There has been heightened interest in this area of iris anatomy, with recent research aimed at identifying surface iris landmarks that may accurately approximate iris sponginess. For instance, iris crypts and furrows, landmarks that are easily identified at the slit lamp, have been found to be potential surrogates for iris sponginess—irises with longer, more numerous furrows may lose less volume on pupil dilation; those with more crypts may lose more volume on pupil dilation [46–48]. In this study, AS-OCT, a reproducible and easy-to-learn imaging method, may offer yet another noninvasive method of directly assessing iris stromal characteristics. Potentially representative parameters include IT750, IT2000, and ITCM.

This study demonstrates that after phaco, eyes with either glaucoma or glaucoma suspect status undergo statistically significant decreases in iris thickness, specifically IT750, IT2000, and ITCM, in dark conditions (Table 3). There is also a significant decrease in pupil size after phaco. Of note, after pre- and post-op iris values were adjusted for pre- and post-op pupil size respectively, it was found that pupil size did not impact any of the iris parameters. Therefore, phacoemulsification may lead to thinner irises and less dark-adapted pupil dilation in eyes with glaucoma as well as eyes with glaucoma suspect status. The “dark” AS-OCT values included in this paper may need to be compared to future “light” values in order to definitely clarify phaco effects on dynamic iris parameters as well as iris sponginess.

It has previously been noted that the presence of a peripheral iridotomy does not change the degree of iris volume loss with dilation, suggesting that iris sponginess is an innate

| Parameter | Univariate Analysis | Multivariate Analysis* |
|-----------|---------------------|------------------------|
|           | β  | 95% CI  | p-value | SD  | β  | 95% CI  | p-value | SD  |
| IT750 (mm) | 0.40 | 0.16, 0.64 | <0.005 | 0.12 | 0.30 | 0.07, 0.52 | <0.005 | 0.11 |
| IT2000 (mm) | 1.05 | 0.62, 1.47 | <0.005 | 0.22 | 0.46 | 0.04, 0.88 | 0.032 | 0.21 |
| ITCM (mm)  | 0.63 | 0.43, 0.83 | <0.005 | 0.10 | 0.59 | 0.39, 0.80 | <0.005 | 0.11 |
| IAREA (mm²) | 0.04 | -0.17, 0.25 | 0.711 | 0.11 | -0.01 | -0.21, 0.18 | 0.896 | 0.10 |
| ICURV (mm)  | 0.42 | 0.02, 0.81 | 0.040 | 0.20 | 0.38 | -0.03, 0.80 | 0.066 | 0.21 |
| Pupil Size  | 0.61 | 0.47, 0.76 | <0.005 | 0.76 | 0.62 | 0.47, 0.76 | <0.005 | 0.75 |

*multivariate analysis was performed using mixed effects regression correcting for age, gender and ethnicity

https://doi.org/10.1371/journal.pone.0208776.t003

Table 4. Multivariate* analysis of the association between Iris parameters, pupil size, and LPI.

| Parameter | Pre-Op Pupil Size | Post-Op Pupil Size | LPI |
|-----------|-------------------|-------------------|-----|
|           | β  | 95% CI  | p-value | SD  | β  | 95% CI  | p-value | SD  |
| IT750 (mm) | 0.32 | -0.01, 0.06 | 0.106 | 0.02 | 0.02 | 0.00, 0.05 | 0.113 | 0.01 |
| IT2000 (mm) | 0.06 | 0.14, 0.10 | 0.310 | 0.02 | 0.02 | 0.00, 0.03 | 0.024 | 0.01 |
| ITCM (mm)  | -0.03 | 0.16, 0.09 | 0.595 | 0.06 | -0.02 | -0.04, -0.01 | 0.012 | 0.01 |
| IAREA (mm²) | 0.10 | 0.06, 0.13 | 0.148 | 1.48 | -0.13 | -0.23, -0.04 | 0.005 | 0.05 |
| ICURV (mm)  | -0.07 | -0.11, 0.03 | <0.005 | 0.02 | 0.32 | -2.57, 3.12 | 0.828 | 1.48 |

*multivariate analysis was performed using mixed effects regression correcting for age, gender and ethnicity

https://doi.org/10.1371/journal.pone.0208776.t004
property that cannot be altered [38]. In this study, a subgroup analysis was performed on the 18 subjects with an LPI. As shown in Table 4, AS-OCT iris parameters of eyes with an LPI were not significantly impacted by the LPI (β coefficients ranged from 0.13, and -0.13) and therefore experienced the same degree of thickness loss and change in pupil size compared to irises without an LPI. In other words, LPI does not appear to alter the degree of phaco-induced iris change, at least under static, dark-only conditions.

Our study suggests that phacoemulsification thins the iris and leads to smaller pupil diameters up to a year after the initial surgery. Potential mechanisms of iris thinning during routine phacoemulsification include direct trauma from the phaco probe and indirect damage to iris structures from the cavitation energy generated by the phaco tip [49]. While the exact effects of mechanical phacoemulsification energy on iris stroma are unknown, existing literature suggests that on a histopathological level, phaco-generated ultrasonic waves induce intracytoplasmic vacuolation within the sphincter and dilator muscles of both human and simian irises [50,51]. Our data indicates that these post-op changes may decrease the extent of pupil dilation in the dark, pointing to reduced iris movement in dark conditions and therefore potentially reduced incidence of iris-trabecular meshwork apposition. It is difficult to draw definitive conclusions, however, without iris data gathered in photopic conditions; both lights on and lights off data will be needed to make conclusions about dynamic post-operative iris changes.

Iris parameters may be important data points in preoperative phacoemulsification planning. For example, in eyes with advanced cataract and therefore increased lens vault [12], the resultant anteriorization of the lens-iris diaphragm narrows the anterior chamber angle and obstructs aqueous outflow; there may also be concomitant narrowing of the iris-lens channel, creating additional obstruction to aqueous outflow at the level of the pupil and then subsequent the angle through pupillary block. It is possible that thinner irises are less prone to such obstructions and can help favorably modulate IOP. Therefore, preoperative measures such as IT750, IT2000, and ITCM may shed light on which glaucoma and glaucoma suspect patients may be more at risk for IOP spikes and therefore may benefit most from the iris-thinning effects of phacoemulsification.

Along this vein, the present study found that iris parameters were not associated with post-operative IOP changes. Post-phaco IOP reduction has previously been found to be a mean of 2.1 mmHg, without any change to glaucoma medication regimen [12]. Based on this information, this study may not have been powered appropriately to detect a statistically significant IOP change, for at least 100 subjects would be needed to yield an 80% power to detect a difference of 1.9 mmHg in IOP; unfortunately, while this study initially enrolled 176 subjects, it ultimately included only 89 subjects and 110 eyes. Future research along these lines should include more subjects as well as AS-OCT iris data from both light and dark conditions.

### Table 5. Multivariate analysis of the association between AS-OCT Iris parameters and changes in IOP: Is IOP change after phacoemulsification related to pre, post, and changes in AS-OCT Iris parameter values?

| Parameter | IOP change and Pre-Op Iris Values | IOP change and Post-Op Iris Values | IOP change and ΔIris Parameters (Pre-Post) |
|-----------|----------------------------------|-----------------------------------|-------------------------------------------|
|           | β      | 95% CI | p-value | SD | β      | 95% CI | p-value | SD | β      | 95% CI | p-value | SD |
| IT750 (mm) | 0.30 | -2.60, 3.18 | 0.843 | 1.47 | -1.16 | -5.25, 2.93 | 0.579 | 2.09 | 0.53 | -2.10, 3.16 | 0.694 | 1.34 |
| IT2000 (mm) | 1.33 | -1.06, 3.71 | 0.275 | 1.22 | -0.51 | -7.32, 6.30 | 0.884 | 1.22 | 1.32 | -1.01, 3.70 | 0.279 | 1.22 |
| ITCM (mm) | 1.38 | -0.77, 3.53 | 0.207 | 1.10 | -0.37 | -2.97, 2.22 | 0.778 | 1.33 | 1.07 | -0.95, 3.10 | 0.300 | 1.03 |
| IAREA (mm²) | 0.03 | -0.80, 0.85 | 0.949 | 0.42 | -0.85 | -1.85, 0.14 | 0.093 | 0.51 | 0.35 | -0.27, 0.97 | 0.262 | 0.32 |
| ICURV (mm) | -1.63 | -4.10, 0.81 | 0.190 | 1.24 | -5.87 | -11.73, -0.01 | 0.050 | 2.99 | -0.95 | -3.37, 1.47 | 0.443 | 1.24 |

ΔIris = pre-op minus post-op iris parameter values

https://doi.org/10.1371/journal.pone.0208776.t005
Using AS-OCT, our study demonstrates that iris thickness (as approximated by IT750, IT2000, and ITCM) may be altered by phacoemulsification in eyes with glaucoma as well as in eyes with glaucoma suspect status. However, these findings only apply to static data gathered in dark conditions. Our study has several limitations, including the small number of subjects, high exclusion rates (largely due to ZAAP segmentation issues), and the inclusion of iris parameters from dark conditions only. There are also very few subjects representing categories of glaucoma other than POAG. Additionally, since measurements of anterior segment parameters are partly dependent on manual identification of the scleral spurs, there is an element of human error and bias. We sought to minimize these factors through the use of a single grader of the AS-OCT images masked to the clinical results. Also, iris values (IT750, IT2000, IAREA, ICURV) represent focal anterior segment parameters and were not averaged over the temporal and nasal sectors in this report as has been done in some prior studies using AS-OCT. Due to concerns that temporal surgical sites may affect postoperative measurements, we utilized only the nasal segments of the AS-OCT images in our analyses. Finally, our post-operative AS-OCT images were obtained at different endpoints; while the current literature suggests that anterior segment parameters do not undergo much change beyond post-operative month 3, this may have still introduced some confounding elements.

Our findings not only highlight the importance of iris anatomy in early surgical glaucoma management, but also supports the potential role of AS-OCT imaging in current clinical glaucoma practice and future glaucoma research.

Supporting information
S1 Data. Limited data set containing pre and post-phaco iris values. (XLSX)

Author Contributions

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References

1. Quigley HA. Number of people with glaucoma worldwide. Br J Ophthalmol. 1996; 80(5):389–393. PMID: 8695555

2. Tham Y, Li X, Wong TY, Quigley HA, Aung T, Cheng C. Global prevalence of glaucoma and projections of glaucoma burden through 2040: A systematic review and meta-analysis. Ophthalmology. 2014; 121(11):2081. https://doi.org/10.1016/j.ophtha.2014.05.013 PMID: 24974815

3. Tseng VL, Yu F, Lunn F, Coleman AL. Risk of fractures following cataract surgery in medicare beneficiaries. JAMA. 2012; 308(5):493–501. https://doi.org/10.1001/jama.2012.9014 PMID: 22851116

4. Leske MC, Heijl A, Hussein M, Bengtsson B, Hyman L, Komaroff E. Factors for glaucoma progression and the effect of treatment: The early manifest glaucoma trial. Arch Ophthalmol. 2003; 121(1):46–56. PMID: 12523884
5. Sihota R, Midha N, Selvan H, Sidhu T, Swamy DR, Sharma A, et al. Prognosis of different glaucomas seen at a tertiary center: A 10-year overview. *Indian J Ophthalmol*. 2017; 65(2):128–132. https://doi.org/10.4103/ijo.IJO_875_16 PMID: 28345568

6. Lee W, Bae HW, Kim CY, Seong GJ. The change of anterior segment parameters after cataract surgery in normal-tension glaucoma. *Int J Ophthalmol*. 2017 Aug 18; 10(8):1239–1245. https://doi.org/10.18240/ijo.2017.08.09 PMID: 28861349

7. Lin S, Masis M, Porco TC, Pasquale LR. Predictors of intraocular pressure after phacoemulsification in primary open-angle glaucoma eyes with wide versus narrower angles (An American Ophthalmological Society Thesis). *Trans Am Ophthalmol Soc*. 2017; 115:T6. PMID: 29147104

8. Wang W, Yan W, Fotis K, Prasad NM, Lansingh VC, Taylor HR, et al. Cataract surgical rate and socioeconomic: A global study. *Invest Ophthalmol Vis Sci*. 2016 Nov 1; 57(14):5872–5881 https://doi.org/10.1167/iovs.16-19894 PMID: 27802517

9. Masis M, Mineault PJ, Phan E, Lin S. The role of phacoemulsification in glaucoma therapy: A systematic review and meta-analysis. *Surv Ophthalmol*. 2017.

10. Shrivastava A, Singh K. The effect of cataract extraction on intraocular pressure. *Curr Opin Ophthalmol*. 2010; 21(2):118–122. https://doi.org/10.1097/ICU.0b013e3283360ac3 PMID: 20040874

11. Chen PP, Lin SC, Junik AK, Radhakrishnan S, Singh K, Chen TC. The effect of phacoemulsification on intraocular pressure in glaucoma patients. *Ophthalmology*. 2015; 122(7):1294–1307. https://doi.org/10.1016/j.ophth.2015.03.021 PMID: 25943711

12. Hsia YC, Moghimi S, Coh P, Chen R, Masis M, Lin SC. Anterior segment parameters as predictors of intraocular pressure reduction after phacoemulsification in eyes with open-angle glaucoma. *J Cataract Refract Surg*. 2017; 43(7):879–885. https://doi.org/10.1016/j.jcrs.2017.03.044 PMID: 28823432

13. Yang HS, Lee J, Choi S. Ocular biometric parameters associated with intraocular pressure reduction after cataract surgery in normal eyes. *Am J Ophthalmol*. 2013; 156(1):89. https://doi.org/10.1016/j.ajo.2013.02.003 PMID: 23628350

14. Huang G, Gonzalez E, Peng PH, Lee R, Leeungurasen T, He M, et al. Anterior chamber depth, irido-corneal angle width, and intraocular pressure changes after phacoemulsification: Narrow vs open irido-corneal angles. *Arch Ophthalmol*. 2011; 129(10):1283–1290. https://doi.org/10.1001/archophthalmol.2011.272 PMID: 21987670

15. Poley BJ, Lindstrom RL, Samuelson TW, Schulze RJ. Intraocular pressure reduction after phacoemulsification with intraocular lens implantation in glaucomatous and nonglaucomatous eyes: Evaluation of a causal relationship between the natural lens and open-angle glaucoma. *J Cataract Refract Surg*. 2009; 35(11):1946. https://doi.org/10.1016/j.jcrs.2009.05.061 PMID: 19878628

16. Kashiwagi K, Kashiwagi F, Tsukahara S. Effects of small-incision phacoemulsification and intraocular lens implantation on anterior chamber depth and intraocular pressure. *J Glaucoma*. 2006; 15(2):103–109. PMID: 16633222

17. Hayashi H, Hayashi F, Hayashi K, Nakao F. Changes in anterior chamber angle width and depth after intraocular lens implantation in eyes with glaucoma. *Ophthalmology*. 2000; 107(4):698–703. PMID: 10768331

18. Mathalone N, Hyams M, Neiman S, Buckman G, Hod Y, Geyer O. Long-term intraocular pressure control after clear corneal phacoemulsification in glaucoma patients. *J Cataract Refract Surg*. 2005; 31(3):479–483. https://doi.org/10.1016/j.jcrs.2004.06.046 PMID: 15811734

19. Hayashi H, Hayashi F, Hayashi K, Nakao F. Effect of cataract surgery on intraocular pressure control in glaucoma patients. *J Cataract Refract Surg*. 2001; 27(11):1779–1786. PMID: 11709251

20. Singleton B, Pasternack J, Hung J, O’Donoghue M. Three and five year changes in intraocular pressures after clear corneal phacoemulsification in open angle glaucoma patients, glaucoma suspects, and normal patients. *J Glaucoma*. 2006; 15(6):494–498. https://doi.org/10.1097/01.jig.0000212294.31411.92 PMID: 17106361

21. Slabaugh MA, Bojikian KD, Moore DB, Chen PP. The effect of phacoemulsification on intraocular pressure in medically controlled open-angle glaucoma patients. *Am J Ophthalmol*. 2014; 157(1):26. https://doi.org/10.1016/j.ajo.2013.08.023 PMID: 24182743

22. Sengupta S, Venkatesh R, Krishnamurthi P, Nath M, Mashruwala A, Ramulu PY, et al. Intraocular pressure reduction after phacoemulsification versus manual small-incision cataract surgery: A randomized controlled trial. *Ophthalmology*. 2016; 123(8):1685. https://doi.org/10.1016/j.ophtha.2016.04.014 PMID: 27234929

23. Azuara-Blanco A, Burr J, Ramsay C, Cooper D, Foster PJ, Friedman DS, et al. Effectiveness of early lens extraction for the treatment of primary angle-closure glaucoma (EAGLE): A randomised controlled trial. *Lancet*. 2016; 388(10052):1389–1397. https://doi.org/10.1016/S0140-6736(16)30956-4 PMID: 27707487
24. Damji KF, Konstan AGP, Liebmann JM, Hodge WG, Ziakas NG, Giannikakis S, et al. Intraocular pressure following phacemulsification in patients with and without exfoliation syndrome: A 2 year prospective study. Br J Ophthalmol. 2006; 90(8):1014–1018. https://doi.org/10.1136/bjo.2006.091447 PMID: 16672324

25. Moghimi S, Johari M, Mahmoudi A, Chen R, Mazloumi M, He M, et al. Predictors of intraocular pressure change after phacemulsification in patients with pseudoxfoliation syndrome. Br J Ophthalmol. 2017; 101(3):283. https://doi.org/10.1136/bjoophthalmol-2016-306601 PMID: 27281754

26. Samuelson TW, Katz LJ, Wells JM, Duh Y, Giamporcaro JE. Randomized evaluation of the trabecular micro-bypass stent with phacemulsification in patients with glaucoma and cataract. Ophthalmology. 2011; 118(3):459–467. https://doi.org/10.1016/j.ophtha.2010.07.007 PMID: 20688289

27. Vold S, Ahmed II, Craven ER, Mattox C, Stamper R, Packer M, et al. Two-year COMPASS trial results: Supraciliary microstenting with phacemulsification in patients with open-angle glaucoma and cataracts. Ophthalmology. 2016; 123(10):2103–2112. https://doi.org/10.1016/j.ophtha.2016.06.032 PMID: 27506486

28. Issaa SA, Pacheco J, Mahmood U, Nolan J, Beaty S. A novel index for predicting intraocular pressure reduction following cataract surgery. Br J Ophthalmol. 2005; 89(5):543–546. https://doi.org/10.1136/bjo.2004.047662 PMID: 15834080

29. Moghimi S, Abd F, Latif G, Fakhraie G, Ramezani F, He M, et al. Lens parameters as predictors of intraocular pressure changes after phacemulsification. Eye. 2015; 29(11):1469–1476. https://doi.org/10.1038/eye.2015.141 PMID: 26228292

30. Hsu C, Kakigi CL, Lin S, Wang Y, Porco T, Lin SC. Lens position parameters as predictors of intraocular pressure reduction after cataract surgery in nonglaucomatous patients with open angles. Invest Ophthalmol Vis Sci. 2015; 56(13):7807. https://doi.org/10.1167/iovs.15-17926 PMID: 26650901

31. Huang G, Gonzalez E, Lee R, Chen Y, He M, Lin SC. Association of biometric factors with anterior chamber angle widening and intraocular pressure reduction after uneventful phacemulsification for cataract. J Cataract Refract Surg. 2012; 38(1):108. https://doi.org/10.1016/j.jcrs.2011.06.037 PMID: 22055073

32. Gedde S, Singh K, Schiffman J, Feuer W. The tube versus trabeculectomy study: Interpretation of results and application to clinical practice. Curr Opin Ophthalmol. 2012; 23(2):118–126. https://doi.org/10.1097/ICO.0b013e32834f2d1 PMID: 22249295

33. Melese E, Peterson JR, Feldman RM, Baker LA, Bell NP, Chuang AZ, et al. Comparing laser peripheral iridotomies to cataract extraction in narrow angle eyes using anterior segment optical coherence tomography. PLoS One. 2016; 11(9):e0162283. https://doi.org/10.1371/journal.pone.0162283 PMID: 27606482

34. Moghimi S, Chen R, Hamzeh N, Khatibi N, Lin SC. Qualitative evaluation of anterior segment in angle closure disease using anterior segment optical coherence tomography. J Curr Ophthalmol. 2016; 29(4):170–175. https://doi.org/10.1016/j.joco.2016.06.005 PMID: 27830199

35. Radhakrishnan S, Rollins AM, Roth JE, Yazdanfar S, Westphal V, Bardenstein DS, et al. Real-time optical coherence tomography of the anterior segment at 1310 nm. Arch Ophthalmol. 2001; 119(8):1179–1185. PMID: 11483086

36. Muzyka-Wozniak M, Ogar A. Anterior chamber depth and iris and lens position before and after phacemulsification in eyes with a short or long axial length. J Cataract Refract Surg. 2016; 42(4):563–568. https://doi.org/10.1016/j.jcrs.2015.12.050 PMID: 27113879

37. Shao T, Hong J, Xu J, Le Q, Wang J, Qian S. Anterior chamber angle assessment by anterior-segment optical coherence tomography after phacemulsification with or without goniosynechialysis in patients with primary angle closure glaucoma. J Glaucoma. 2015; 24(9):647–655. https://doi.org/10.1097/IJG.000000000000061 PMID: 24844542

38. Foo LL, Nongpial ME, Allen JC, Perera SA, Friedman DS, He M, et al. Determinants of angle width in chinese singaporeans. Ophthalmology. 2012; 119(2):278–282. https://doi.org/10.1016/j.jophtha.2011.07.049 PMID: 22118998

39. Quigley HA. The iris is a sponge: A cause of angle closure. Ophthalmology. 2010; 117(1):1–2. https://doi.org/10.1016/j.ophtha.2009.11.002 PMID: 20114108

40. Quigley HA, Silver DM, Friedman DS, He M, Pleyer RJ, Eberhart CG, et al. Iris cross-sectional area decreases with pupil dilation and its dynamic behavior is a risk factor in angle closure. J Glaucoma. 2009; 18(3):173–179. https://doi.org/10.1097/IJG.0b013e31818624ce PMID: 19295366

41. Borrias T. The cellular and molecular biology of the iris, an overlooked tissue: The iris and pseudoxfology. J Glaucoma. 2014; 23:S42.

42. Aptel F, Denis P. Optical coherence tomography quantitative analysis of iris volume changes after pharmacologic miydrasis. Ophthalmology. 2010; 117(1):3–10. https://doi.org/10.1016/j.ophtha.2009.10.030 PMID: 19923002
43. Mak H, Xu G, Leung CK. Imaging the iris with swept-source optical coherence tomography: Relationship between iris volume and primary angle closure. Ophthalmology. 2013; 120(12):2517–2524. https://doi.org/10.1016/j.ophtha.2013.05.009 PMID: 23850092

44. Silver D, Quigley H. Aqueous flow through the Iris–Lens channel: Estimates of differential pressure between the anterior and posterior chambers. J Glaucoma. 2004; 13(2):100–107. PMID: 15097254

45. Quigley H, Friedman D, Congdon N. Possible mechanisms of primary angle-closure and malignant glaucoma. J Glaucoma. 2003; 12(2):167–180. PMID: 12671473

46. Sidhartha E, Gupta P, Liao J, Tham YC, Cheung CY, He M, et al. Assessment of iris surface features and their relationship with iris thickness in asian eyes. Ophthalmology. 2014; 121(5):1007–1012. https://doi.org/10.1016/j.ophtha.2013.11.028 PMID: 24405741

47. Chua J, Thakku SG, Pham TH, Lee R, Tun TA, Nongpiur ME, et al. Automated detection of iris furrows and their influence on dynamic iris volume change. Sci Rep. 2017; 7.

48. Chua J, Thakku SG, Tun TA, Nongpiur ME, Tan MC, Girard MJ, et al. Iris crypts influence dynamic changes of iris volume. Ophthalmology. 2016; 123(10):2077–2084. https://doi.org/10.1016/j.ophtha.2016.06.034 PMID: 27521171

49. Zacharias J. Role of cavitation in the phacoemulsification process. J Cataract Refract Surg. 2008; 34(5):846–852. https://doi.org/10.1016/j.jcrs.2008.01.013 PMID: 18471645

50. Komatsu M, Uga S, Oono S, Shimizu K, Kohara M. Histopathological study of the effect of phacoemulsification-aspiration on iris muscles. Ophthalmologica. 1998; 212(3):169–174. https://doi.org/10.1159/000027270 PMID: 9562090

51. Komatsu M, Oono S, Shimizu K. The effects of phaco-emulsification-aspiration and intra-ocular lens implantation on the pupil: Pupillographic and pharmacologic study. Ophthalmologica. 1997; 211(6):332–337. https://doi.org/10.1159/000310823 PMID: 9380348