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GLAUCOMA

Lens extraction combined with circumferential ab interno trabeculotomy to treat pigmentary glaucoma

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Abstract

Purpose To evaluate the 24-month outcomes of lens extraction combined with circumferential, 360-degree trabeculotomy in patients with progressive pigmentary glaucoma.

Methods This prospective, interventional case series included 32 eyes of 32 patients with progressive pigmentary glaucoma. All patients underwent phacoemulsification combined with gonioscopy-assisted transluminal trabeculotomy (GATT). Outcome measures included intraocular pressure (IOP), number of glaucoma medications, and success rates at 24 months. Qualified success was defined as IOP≤18 mm Hg with a 20% IOP reduction from baseline, without requiring further glaucoma surgery.

Results The mean preoperative IOP was 21.4 (SD 6.3) mm Hg on a mean of 2.2 (SD 1.5) glaucoma medications. At 24 months, mean IOP was reduced to 13.0 (SD 3.5) mm Hg (a 39% reduction), and mean medication use was reduced to 0.8 (SD 1.0). The Kaplan-Meier estimated probability of qualified success at 24 months was 75.0% (95% CI: 61.4% − 91.6%).

Conclusion Combined lens extraction and GATT effectively lowers IOP and medication use in pigmentary glaucoma. By targeting the source of pigment dispersion, lens extraction may halt the disease process, making this a very promising strategy.

Key messages

What is known

- The role of iridotomy in reducing iridolenticular contact in pigmentary glaucoma is established, but its effectiveness is variable and its use remains controversial.

What this study adds

- Combining lens extraction with trabeculotomy addresses both the underlying cause of pigment dispersion by eliminating iridolenticular contact and the pathological effect on the trabecular meshwork.
- By halting further pigment liberation, lens extraction may improve the long-term success of trabecular outflow surgery in patients with pigmentary glaucoma.
- Lens extraction is a safe and effective procedure that should be considered a key component in the surgical management of pigmentary glaucoma, enabling effective angle surgery in pigmentary glaucoma.

Keywords Pigmentary glaucoma · Trabeculotomy · GATT · Cataract · Pigment dispersion

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Introduction

Glaucoma, a progressive optic neuropathy, is the leading cause of irreversible blindness worldwide [1]. Pigmentary glaucoma (PG) is a specific form of glaucoma found in patients with pigment dispersion syndrome. Pigment dispersion syndrome is characterized by the mechanical disruption of the iris pigment epithelium and dispersion of the pigment granules within the eye. The liberated pigment damages the trabecular meshwork, impedes aqueous outflow and eventually leads to elevated intraocular pressure (IOP) [2]. In turn, this may lead to optic nerve damage and glaucoma. While pigment dispersion syndrome affects 2.5% of the United States population [3], its prevalence varies significantly by age, sex, and race/ethnicity, with the highest rates observed in young, myopic Caucasian males. The risk of developing pigmentary glaucoma in affected people is estimated to be between 15% and 30% [4].

In patients with pigment dispersion syndrome, laser iridotomy procedures are generally recommended prophylactically, before IOP elevation has taken place. Selective laser trabeculoplasty (SLT) and topical medical therapy are usually the first-line treatment in patients who develop elevated IOP [5]. SLT can reduce the IOP by 20%, although this effect is often short-lived [6].

The anatomical relationship between the iris, lens, and zonules plays a critical role in the pathophysiology of pigmentary glaucoma. Modifying this relationship is central to several glaucoma treatments. For instance, in primary angle closure, laser peripheral iridotomy (LPI) and lens extraction both widen the irido-corneal angle and can improve trabecular flow and IOP [7]. In pigment dispersion syndrome, LPI is also used [4], but the goal is to reduce irido-zonular contact, friction and liberation of iris pigment. This may be useful in slowing down pigment dispersion and is generally recommended before IOP elevation becomes established [8]. In patients with pigment dispersion syndrome, LPI has not been shown to reduce IOP or prevent visual loss in the long term [8], and, for these reasons, LPI in pigmentary glaucoma remains controversial [9]. Surgical lens extraction can completely eliminate irido-lenticular and irido-zonular contact and therefore avoid friction and liberation of pigment [2]. However, its specific role as a primary intervention to halt pigment dispersion in eyes without visually significant cataract had not been extensively established in the literature at the time this study was conceived, with reviews often discussing lens extraction in the context of co-existing cataract [3, 10].

In pigmentary glaucoma, once trabecular meshwork damage is established and IOP is uncontrolled despite maximum tolerated medical therapy, glaucoma filtration surgery such as trabeculectomy is generally indicated. Trabeculectomy however is traditionally associated with a relatively high complication rate [11]. We therefore sought to treat patients with pigmentary glaucoma, whose IOP was uncontrolled with maximum tolerated glaucoma medication, with combined lens extraction and 360-degree gonioscopy-assisted transluminal trabeculotomy (GATT). This combined surgical intervention aimed to both reduce IOP by increasing trabecular outflow and to eliminate further liberation of pigment into the surgically opened trabecular system.

Materials and methods

This prospective, consecutive, single-surgeon case-series study was conducted at the Swiss Eye Centre, Lausanne, Switzerland, following the standard of care. The study adhered to the principles of the Declaration of Helsinki and received approval from the Commission Cantonale d'Ethique, Canton of Vaud, Switzerland (project number 2020−00263). All participants provided written informed consent for both surgery and study participation.

Patients aged 18 years or older, diagnosed with pigmentary glaucoma, were recruited. The indication for surgery was evidence of glaucoma progression, defined as reproducible visual field worsening on consecutive exams or structural deterioration confirmed by Spectral-Domain OCT (Spectralis; Heidelberg Engineering GmbH, Heidelberg, Germany). Structural analysis included peripapillary Retinal Nerve Fiber Layer Thickness (RNFLT), Bruch's Membrane Opening-Minimum Rim Width (MRW), and macular Ganglion Cell Layer (GCL) parameters.

Only patients with phakic lens status at the time of enrolment were included. Eyes were excluded if they had previous intraocular incisional surgery (glaucoma filtration surgery such as trabeculectomy or glaucoma drainage device) or significant ocular co-morbidities that could confound surgical outcomes or IOP assessment, such as severe corneal opacity or active intraocular inflammation. A history of prior laser trabeculoplasty or laser iridotomy was permissible.

Clinical information was collected during preoperative visits that included slit-lamp examination, IOP measurements by Goldmann applanation tonometry, gonioscopy and funduscopy. The presence of at least two of the following three clinical signs was used to confirm the diagnosis of pigment dispersion syndrome: mid-peripheral radial trans-illumination defects of the iris; pigment deposits on corneal endothelium (Krukenberg spindles); and increased pigmentation of the trabecular meshwork. Complementary examinations such as visual fields and optic coherence tomography were used to document optic nerve damage and to confirm the diagnosis of pigmentary glaucoma. While we

did not routinely record posterior vitreous detachment status pre-operatively, all patients had a full fundus examination and were given preoperative information on retinal detachment risk and symptoms.

All patients underwent a combined procedure, as previously described [12]. Briefly, after phacoemulsification and intraocular lens implantation, the irido-corneal angle was visualized using a Swan Jacob gonioscope to make a 1–2 mm goniotomy, followed by the introduction of an illuminated catheter (iTrack™; Nova Eye Medical Limited, USA) or a thermally blunted 5.0 polypropylene thread. This catheter or thread was advanced parallel to the iris plane within Schlemm's canal and then externalized into the anterior chamber, creating a 360º ab interno trabeculotomy.

Follow-up visits were scheduled on day 1, week 1, and months 1, 3, 6, 12, 18 and 24, and more frequently if clinically indicated. Following surgery, all pre-existing topical glaucoma medications were discontinued. A standardized postoperative regimen was prescribed for all patients for the first month, consisting of a combination of topical dexamethasone 1 mg/ml and tobramycin 3 mg/ml (Tobra-Dex, Novartis Pharma Schweiz AG, Switzerland), tapered slowly, and pilocarpine 2% (Spersa-carpine, OmniVision AG, Neuhausen am Rheinfall, Switzerland) three times per day. After the first month, and cessation of routine pilocarpine, glaucoma medications were only (re)introduced if clinically indicated by an IOP spike or steroid response during follow-up, or if needed to maintain target IOP.

Outcome measures included IOP, number of glaucoma medications, and rates of perioperative and postoperative complications. IOP was measured using Goldmann applanation tonometry (GAT) at all study visits. As part of standard clinical care, screening tonometry was often performed with an iCare rebound tonometer, but these screening values were not recorded for study purposes. For the study, typically, a single GAT reading was recorded. However, if an initial GAT reading was ≤6 mmHg, ≥ 21 mmHg, or showed significant unexplained discrepancy from prior screening tonometry, two to three confirmatory GAT measurements were taken, and the final reading that appeared most consistent was recorded. To minimize bias, all GAT measurements for the study were performed by one of two experienced ophthalmologists (MLD, AG), who were not the operating surgeon (ES).

All intraoperative and postoperative adverse events were recorded up to the 24-month follow-up visit. Postoperative complications were defined and graded as follows: Hyphema: Any visible blood in the anterior chamber postoperatively was recorded as hyphema if it persisted more than 2 weeks or required an anterior chamber washout. Hypertony: Any postoperative IOP reading≥25 mm Hg at any visit was recorded as an IOP spike. Further details were documented, including the peak IOP, duration of IOP elevation (e.g., lasting≤2 weeks, ≥ 2 weeks), and any interventions required (e.g., additional temporary topical or oral medication, anterior chamber paracentesis). Hypotony: Defined as IOP<6 mm Hg, transient if resolved spontaneously or with conservative measures within the first postoperative month; persistent if beyond one month or associated with clinical signs such as choroidal effusion, hypotony maculopathy, shallow anterior chamber, or requiring surgical intervention at any time. Other potential complications such as wound leak, intraocular lens (IOL) malposition or decentration, cystoid macular edema (CME), endophthalmitis, and retinal detachment were systematically monitored and recorded. All patients underwent regular postoperative gonioscopy to detect the presence of re-pigmentation of the trabecular shelf.

Failure was defined if any of the following criteria were met at any time during the follow-up: IOP≥18 mm Hg or an IOP reduction of ≤20% from baseline, confirmed on two consecutive follow-up visits. Need for any additional glaucoma-related surgery (laser or incisional). Eyes requiring such interventions were censored at the time of the re-intervention and considered failures from that point. Loss of light perception vision attributable to the surgical procedure or glaucoma progression. Development of persistent, vision-threatening hypotony (IOP<6 mmHg), associated with clinical signs such as hypotony maculopathy or choroidal effusions, or requiring surgical intervention for hypotony. To account for the normal postoperative period of healing and IOP fluctuation, failure criteria were only applied from the 3-month follow-up visit onwards.

Qualified Success was defined as not meeting any of the failure criteria listed above and achieving both IOP≤18 mm Hg and IOP reduction≥20% from baseline.

Complete Success was defined as not meeting any of the failure criteria listed above and achieving all of the following: IOP≤18 mm Hg; IOP reduction≥20% from baseline; and discontinuation of all glaucoma medications.

Statistical analysis was performed with R version 4.5.2 (R: A language and environment for statistical computing. Foundation for Statistical Computing, Vienna, Austria). The normality of data distribution was assessed using the Shapiro-Wilk test. Variables were reported as means and standard deviations (SD) or as medians and interquartile ranges (IQR). Changes in IOP and medication burden from baseline were analysed using the Wilcoxon signed-rank test for paired samples. Kaplan-Meier survival analysis was used to estimate success rates over time. A p-value<0.05 was considered statistically significant.

Results

A total of 32 eyes from 32 patients were included in the study. The mean age was 56.0 (SD 13.7) years (range, 26.4 to 78.1 years). Biometric analysis revealed a mean axial length of 25.07 (SD 0.88) mm, a mean anterior chamber depth of 3.64 (SD 0.36) mm, and a mean spherical equivalent refraction of −2.61 (SD 2.41) Dioptres. The mean baseline OCT RNFL thickness was 68.8 (SD 16.1) µm, and the mean visual field mean deviation (MD) was 7.5 (SD 5.9) dB. The mean baseline IOP was 21.4 (SD 6.3) mm Hg on a mean of 2.2 (SD 1.5) glaucoma medications (median 2, IQR 1–3). 6 eyes (18.8%) had previously undergone SLT and all of them LPI. Detailed demographic and baseline data are shown in Table 1.

During the study period, a small group of 4 patients with PDS underwent phacoemulsification alone. In this subgroup, the mean age was 53.0 (SD 6.4) years. The mean IOP decreased from 17.8 (SD 2.9) mm Hg at baseline to 13.7 (SD 3.2) mm Hg at 12 months (a 23.0% reduction). At 24 months, the mean IOP was 14.5 (SD 0.7) mm Hg, representing a 18.3% reduction from baseline.

In the main study cohort receiving combined Phacoemulsification and GATT, outcomes demonstrated sustained IOP reduction. At 12 months, the mean postoperative IOP was 13.1 (SD 3.3) mm Hg, while the mean number of medications used was 0.6 (SD 1.0). At 24 months, the mean IOP was 13.0 (SD 3.5) mm Hg (a 39.4% reduction from baseline) with the use of 0.8 (SD 1.0) glaucoma medications. Details of preoperative and postoperative IOP and medication burden throughout the follow-up are presented in Fig. 1; Table 2.

Table 1 Demographics

Characteristic	Value
Number of eyes	32
Age (years), mean (SD)	56.0 (13.7)
Age (years), range	26.4–78.1
Axial Length (mm), mean (SD) [range]	25.07 (0.88) [23.19–26.43]
Ant. Chamber Depth (mm), mean (SD) [range]	3.64 (0.36) [3.26–4.45]
Spherical Eq. (D), mean (SD) [range]	−2.61 (2.41) [−8.75–1.00]
Baseline RNFL (µm), mean (SD) [range]	68.8 (16.1) [40–112]
Baseline MD (dB), mean (SD) [range]	7.5 (5.9) [0.8–27.7]
Baseline IOP (mm Hg), mean (SD)	21.4 (6.3)
Baseline Medications, mean (SD)	2.2 (1.5)
Baseline Medications, median [IQR]	2 [1–3]
Prior SLT, n (%)	6 (18.8%)

SD Standard deviation, *D* Dioptres, *RNFL* Retinal Nerve Fiber Layer, *MD* Mean Deviation (Visual Field), *IOP* Intraocular Pressure, *IQR* Interquartile Range, *SLT* Selective Laser Trabeculoplasty

No intraoperative complications were recorded in this series. All patients experienced a certain degree of hyphema during the first postoperative days. All but one of these cases resolved spontaneously during the first two weeks. One case of significant hyphema (1/32, 3.1%) required an anterior chamber washout. This 74-year-old patient experienced intermittent episodes of hypertony due to blood reflux into the trabecular meshwork, particularly while bending forward, during the first year of follow-up. Eleven eyes (11/32, 34.4%) experienced IOP spikes with a mean peak of 34.0 (SD 7.5) mm Hg (range 25–48). These episodes occurred predominantly at week 1 ($n=10$), with 1 case occurring at day 1. These were transient and successfully managed by tapering topical corticosteroids or adding temporary hypotensive medication. One case of sustained hypertony occurred but was controlled with two medications (a reduction from five preoperative medications). Early postoperative hypotony was observed in two eyes (2/32, 6.2%) during the first week. One of these cases required an intracameral injection of an ophthalmic viscosurgical device for resolution, while the other resolved without further treatment. Both cases had no long-term sequelae. There were no cases of choroidal effusions, persistent significant hypotony, endophthalmitis or retinal detachment during the 2-year follow-up period. One patient experienced a mild intraocular lens subluxation at three weeks after surgery. While no zonular dehiscence was noted during surgery, this complication was attributed to suspected subclinical zonular weakness associated with PDS. The patient remained asymptomatic, and the condition was managed with observation.

The Kaplan-Meier survival analysis estimated a qualified success rate of 75.0% at 24 months (95% CI: 61.4% −91.6%) (Fig. 2). Using the prospectively defined criteria, 8 of 32 eyes (25.0%) met failure criteria by the 24-month endpoint. When applying the stricter definition of complete success (without any glaucoma medications) 13 of the 32 eyes (40.6%)achieved this outcome, while the remaining successful patients maintained good IOP control with the use of topical medication (Fig. 3).

Discussion

We report the results of the first case series of pigmentary glaucoma patients treated by lens extraction combined with 360-degree GATT. After the first post-operative month, the mean IOP was reduced and consistently maintained below 15 mm Hg during the 24 months of follow-up. The use of anti-glaucoma medications was also reduced, and most patients remained without any for the first 18 months. At 24 months there was an increase in medications used, but

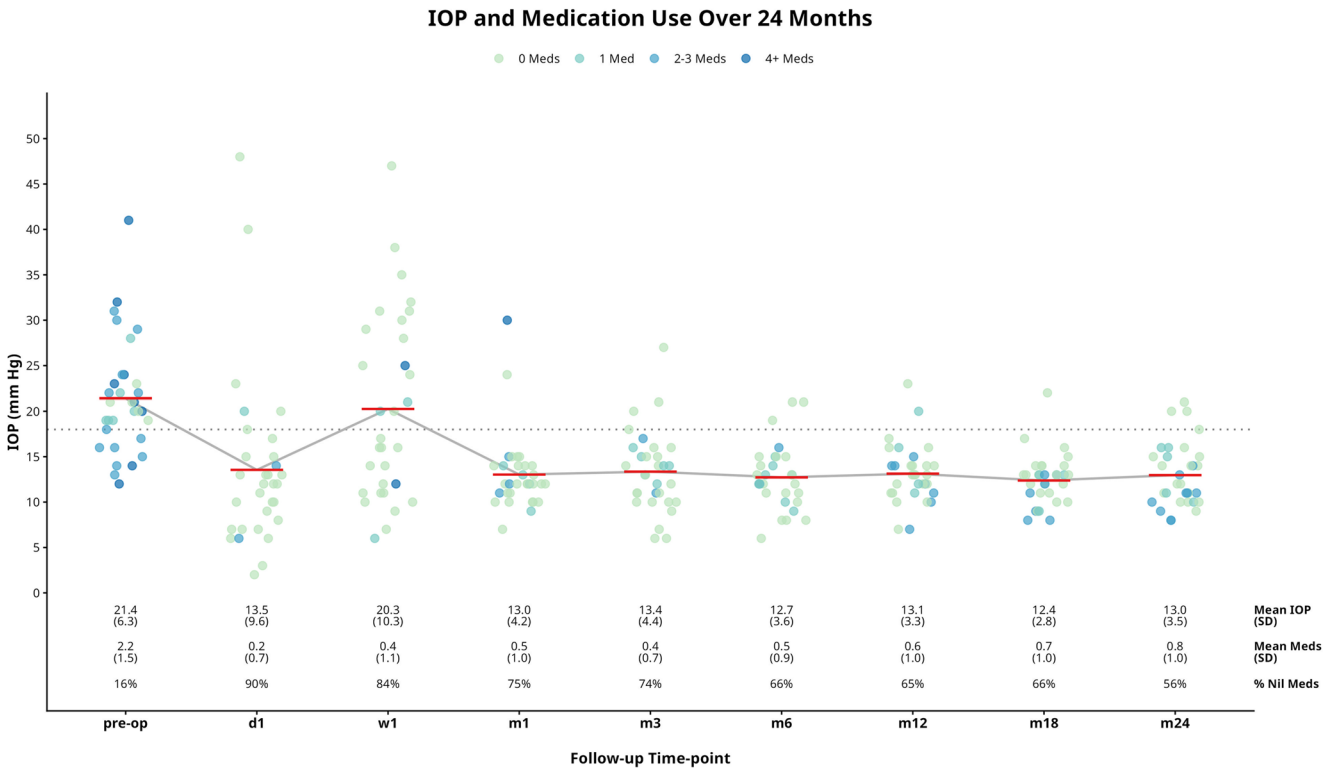

Fig. 1 Intraocular pressure (IOP) and number of medications at each time-point over 24 months of follow-up. Each eye is represented with different colours according to number of medications. The red horizontal line represents the mean IOP value at each time point. The horizontal dotted line indicates the IOP threshold of 18 mm Hg

Table 2 Intraocular pressure (mm Hg) and number of medications up to 24 month follow-up

Time-point	*n*	IOP Mean (SD)	IOP 95% CI	Meds Mean (SD)	Meds 95% CI	Meds Median [IQR]	Postoperative cases requiring no meds *n* (% of cases at time point)
Preoperative	32	21.4 (6.3)	19.2–23.6	2.2 (1.5)	1.7–2.7	2 [1–3]	-
3 months	31	13.4 (4.4)	11.8–14.9	0.4 (0.7)	0.1–0.6	0 [0–0]	23 (74%)
6 months	29	12.7 (3.6)	11.4–14.0	0.5 (0.9)	0.2–0.8	0 [0–1]	19 (66%)
12 months	31	13.1 (3.3)	12.0–14.3	0.6 (1.0)	0.3–1.0	0 [0–1]	20 (65%)
18 months	32	12.4 (2.8)	11.4–13.4	0.7 (1.0)	0.3–1.0	0 [0–1]	21 (66%)
24 months	32	13.0 (3.5)	11.8–14.2	0.8 (1.0)	0.4–1.1	0 [0–2]	18 (56%)

IOP Intraocular Pressure, *SD* Standard deviation, *CI* Confidence Interval, *IQR* Interquartile Range

more than half of the successful patients remained medication free.

Transient hypertony during the first postoperative weeks was self-limiting and easily managed by adjusting medication use. It is noteworthy that our definition of IOP spike (≥ 25 mm Hg) is broader than the threshold often used in similar studies (IOP > 30 mm Hg). Applying the standard definition of > 30 mm Hg to our cohort would result in a spike rate of 25.0%, which is comparable to previously reported rates for ab interno trabeculotomy. There were no cases of retinal detachment during the two-year follow-up, despite the known association between pigment dispersion syndrome and retinal pathology [13]. The main complication occurred in one patient with intermittent episodes of blood reflux into the trabecular meshwork and IOP spikes during the first postoperative year; this was managed with medical therapy. Delayed episodes of micro-hyphema with IOP elevation have previously been described as a rare complication during the initial postoperative months and up to 3 years after ab interno trabeculotomy. Occasionally, these cases may require subsequent surgery [14].

Anterior chamber depth decreases with age due to lens thickening [15]. Phacoemulsification can lower the IOP by widening the irido-corneal angle or by increasing tension on the zonules and stretching the trabecular meshwork, which decreases outflow resistance. Lens removal causes the

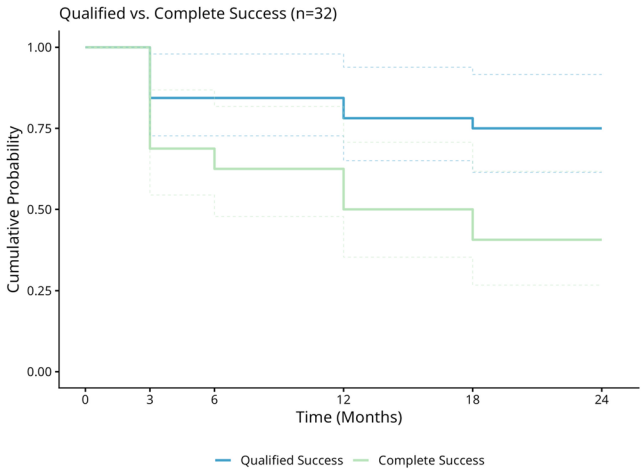

Fig. 2 Kaplan-Meier survival curve for qualified and complete success. The curve shows the cumulative probability of maintaining qualified (blue line) and complete (green line) success over the 24-month follow-up period. The dotted lines represents the 95% confidence interval

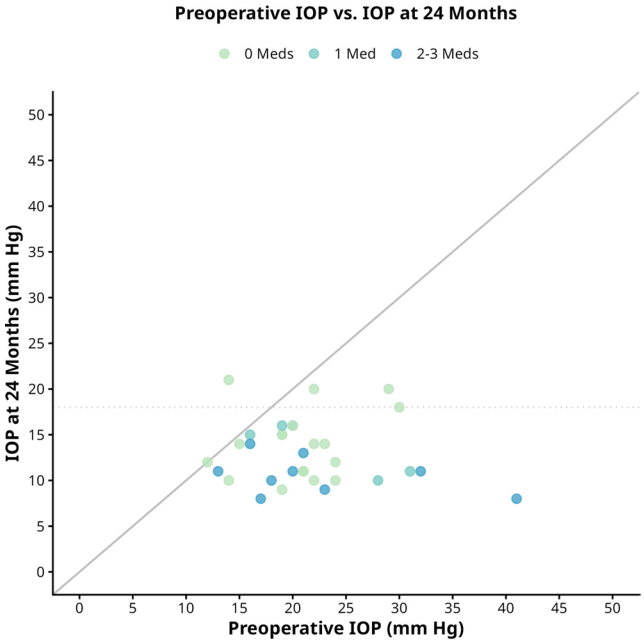

Fig. 3 Scatterplot of intraocular pressure (IOP) versus number of glaucoma medications at 24 months. Each point represents an individual eye. The plot illustrates the distribution of outcomes at the final follow-up visit. The horizontal dotted line indicates the IOP threshold of 18 mm Hg

capsule to collapse and the anterior zonules to shift posteriorly, creating more distance between the iris and the zonules, thereby reducing friction and eliminating irido-lenticular contact. This mechanistic benefit is supported by previous observations demonstrating that lens extraction can effectively flatten the iris profile in PDS, addressing the underlying reverse pupillary block [16]. However, addressing the anatomic predisposition alone does not resolve established outflow resistance caused by chronic pigment deposition. Therefore, the addition of trabeculotomy serves to cleave the compromised trabecular meshwork, directly targeting the downstream consequence of the disease while lens extraction prevents further pigment liberation. This result is not achieved by laser peripheral iridotomy, which only equalizes the pressure between the anterior and posterior chambers. In our cohort, laser peripheral iridotomy did not eliminate irido-lenticular contact as seen on pre-operative AS-OCT (Fig. 4a), while phacoemulsification effectively eliminated it (Fig. 4b).

One case failed at 9 months of follow-up, requiring further glaucoma surgery. This was a 37-year-old patient with advanced pigmentary glaucoma who required trabeculectomy because of glaucoma progression confirmed by visual field worsening. Preoperative IOP after SLT was 13 mmHg with 4 poorly tolerated anti-glaucoma medications. Postoperative IOP at 9 months was 21 mmHg with 5 anti-glaucoma medications. Despite failure due to elevated IOP, post-operative gonioscopy revealed no evidence of pigment deposition on the trabecular shelf.

This case highlights that elimination of irido-lenticular and reduction of irido-zonular contact is important to avoid further damage to the trabecular meshwork [17], as continued pigment dispersion and deposition onto the postoperative trabecular shelf may compromise the long-term efficacy of trabeculotomy. Interestingly, the concept of "burnt-out pigmentary glaucoma", where the disease is observed to wane over time, may be partially explained by cataract surgery, which is often performed in older patients. Conversely, the presence of Krukenberg's spindles and its association with long anterior zonule (LAZ) may lead to higher IOP, which has been proposed as an independent risk factor for glaucoma [18]. In our cohort, 12 out of 32 patients were over 60 years-old with progressive glaucoma, suggesting that waning of the disease does not always occur with age, at least in phakic patients. Therefore, waiting for this disease to wane may not be an ideal treatment strategy, and lens extraction should be considered in eyes with PDS and/or in the presence of LAZ.

The decision to perform lens extraction in younger patients, the youngest in our series being 26 years old, was made judiciously. In such cases, particularly our youngest patient who was myopic, the indication was driven by aggressive pigmentary glaucoma with significant ongoing pigment liberation and progressive optic neuropathy despite medical therapy. While lens-sparing alternatives such as repeat SLT, iridotomy, GATT alone, or trabeculectomy were considered, they were deemed less optimal for long-term management in this specific cohort. Trabeculotomy alone does not resolve the irido-zonular contact driving pigment release. Furthermore, while primary filtration surgery is a valid option, it is known to accelerate cataract formation,

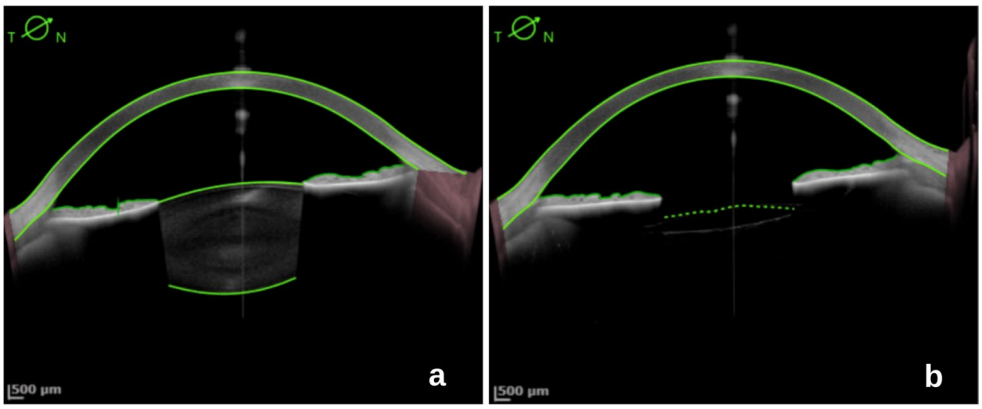

Fig. 4 Anterior segment optical coherence tomography (AS-OCT) from the same eye, before and after lens extraction. **A**: Preoperative assessment showing the characteristic concave iris configuration with irido-lenticular contact and a shallower anterior chamber (Aqueous Depth: 3.27 mm; Pupil Diameter: 6.2 mm). **B**: Postoperative assessment showing a significantly deepened anterior chamber (Aqueous Depth: 4.37 mm; Pupil Diameter: 5.3 mm) with a flat iris profile, confirming the complete resolution of reverse pupillary block and elimination of irido-zonular contact. Anterior chamber depth has increased by 1.10 mm and the anterior chamber angle remains wide open. Irido-lenticular and irido-zonular contact has been eliminated, as the anterior surface of the IOL (dotted-green line) is clearly separated from the back of the iris

and subsequent lens extraction can compromise bleb function, reducing long-term surgical success. Therefore, our combined approach aimed to provide a durable solution by addressing both the pigment source and outflow obstruction, while critically preserving the conjunctiva for future filtering surgery should it become necessary. Comprehensive counselling regarding the lifelong implications of pseudophakia versus the risks of uncontrolled progressive glaucoma led to a shared decision for combined surgery, aiming to provide a more durable solution by addressing both the pigment source and the compromised outflow pathway.

Our study found no evidence of postoperative pigmentation build-up on the trabecular shelf following phacoemulsification, indicating that lens removal may effectively reduce or prevent further pigment liberation. This suggests that surgical failure may be due to post-trabecular outflow insufficiency, which can occur in any glaucoma sub-type. However, we are continuing to monitor our cohort to determine whether additional pigmentation occurs over the long term.

Our cumulative qualified success rate of 75.0% is comparable to outcomes reported for other ab interno trabecular procedures. While traditional filtration surgery remains the gold standard for achieving the lowest absolute IOP, it carries a significant burden of potential complications. In this young and typically myopic cohort, the combined lens extraction with GATT procedure delivers substantial IOP reduction and medication independence while avoiding the lifelong risks associated with filtering blebs and preserving the conjunctiva for future intervention if necessary.

A significant limitation of this study is its prospective, non-comparative design, which lacks a control group. The decision for this design was based on the specific clinical context of the enrolled patients with pigmentary glaucoma, experiencing disease progression despite maximal tolerated medical therapy. For such patients, lens extraction as a standalone procedure, without a concomitant glaucoma-specific intervention, would generally not be considered clinically sufficient to address their advanced stage of disease. Conversely, performing GATT alone in these phakic eyes was considered less optimal due to the risk of peripheral anterior synechiae (PAS) formation and potential lens injury. Furthermore, prior studies on other trabecular microbypass stents have suggested lower success rates in phakic eyes with pigmentary glaucoma compared to combined procedures [19]. Therefore, a combined surgical approach was deemed the most appropriate strategy to address both the outflow obstruction and the underlying pathophysiological mechanism. Phacoemulsification alone was deemed appropriate for a separate cohort of four patients with stable pigment dispersion syndrome and cataract treated during the same period. While our findings demonstrate the potential of Phaco-GATT for progressive disease, comparative trials are needed to validate the added value of this combined intervention.

A further limitation is the absence of a standardized algorithm for medication reintroduction. Decisions to restart therapy were made at the discretion of the treating clinicians, prioritizing individual patient needs, such as medication tolerability and visual field status, over a rigid protocol. While this approach reflects real-world practice, it introduces variability that may influence the precision of medication-free success estimates in the survival analysis.

Nevertheless, the favourable safety profile and IOP-lowering effects observed in our study for the combined procedure, particularly the lens extraction component's role in addressing pigment liberation, support further investigation

into lens extraction, either alone or in conjunction with minimally invasive glaucoma surgery. Such approaches may be particularly valuable for patients with PDS prior to the development of significant glaucomatous neuropathy, or in carefully selected cases of PG where the primary aim is to mitigate ongoing pigment release.

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Declarations

Ethical approval All procedures performed in this study involving human participants was in accordance with the ethical standards of the Commission Cantonale d'Ethique, Canton of Vaud, Switzerland (approved, project number 2020−00263) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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