Two-year Outcomes of Combined Gonioscopy-Assisted Transluminal Trabeculotomy and Cataract Extraction in Ocular Hypertension and Primary Open-Angle Glaucoma

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SUMMARY

Aim: To evaluate the 24-month data on efficacy and safety of gonioscopy-assisted transluminal trabeculotomy (GATT), combined with cataract extraction (CE) in patients with ocular hypertension (OHT) and primary open-angle glaucoma (POAG).
Materials and Methods: A retrospective chart review was conducted of patients undergoing GATT combined with CE from November 2018 to November 2021. The primary outcome was surgical success, defined as a composite endpoint: ≥ 20% intraocular pressure (IOP) reduction AND/OR ≥ 1 medication reduction, without further IOP-lowering procedures, and IOP maintained between 5 and 21 mmHg. Secondary outcomes included: IOP, number of glaucoma medications (NGM), best corrected visual acuity (BCVA), complications, and failure-associated factors.
Results: A statistically significant reduction in mean IOP (from 18.6 ±3.8 mmHg preoperatively to 15.6 ±3.3 mmHg at 24 months) and NGM (from 2.1 ±1.3 medications to 0.8 ±1.2 medications) was observed ($P < 0.001$). At 24 months, the overall success rate was 84.2%. Age ≤ 65 years (HR 7.06) and male sex (HR 11.12) were associated with an increased risk of GATT failure. No statistically significant differences were observed in the mean IOP or NGM at the final visit between the OHT and POAG groups. No serious ocular adverse events were reported. Mean BCVA improved from 0.51 ±0.2 logMAR preoperatively to 0.10 ±0.1 logMAR at 24 months postoperatively ($P < 0.001$).
Conclusion: Combined GATT and cataract surgery is an effective and safe procedure for reducing IOP and NGM in patients with OHT and POAG.
Key words: glaucoma; open-angle; ocular hypertension; minimally invasive surgical procedures; trabeculectomy; cataract extraction

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INTRODUCTION

Ocular hypertension (OHT) increases the risk of primary open-angle glaucoma (POAG). Lowering intraocular pressure (IOP) can help to prevent glaucoma neuropathy [1]. Gonioscopy-assisted transluminal trabeculotomy (GATT) is a minimally invasive glaucoma surgery (MIGS) that reduces IOP by disrupting the trabecular meshwork [2]. Previous studies have shown GATT effectiveness in reducing IOP and the number of glaucoma medications (NGM), when combined with cataract extraction (CE) [3–5]. However, data on the GATT impact on OHT patients are lacking. Hence, this study aims to evaluate 24-month data on the efficacy and safety of GATT combined with CE in patients with OHT and POAG.

MATERIALS AND METHODS

A retrospective chart review was performed from a consecutive series of patients with OHT and POAG who underwent GATT combined with CE at "Fundación

Oftalmologica de Santander – FOSCAL" (Santander, Colombia), from November 2018 to November 2021. Informed consent was obtained from all patients before surgery and the study was in accordance with the Declaration of Helsinki. The study was approved by the Research Ethics Committee of FOSCAL (reference: 007931).

Study Population and Surgical Indications

Patients aged ≥ 18 years with OHT or POAG were included. The indication for the combined procedure was based on a surgical algorithm where the goal was either to achieve significant IOP reduction (≥ 20% from baseline), or to reduce the patient's dependence on NGM at the time of the planned CE. The study cohort was exclusively composed of patients of Hispanic/Latino ethnicity, reflecting the local demographic of Santander, Colombia. No individuals identifying as Black were included in this study.

Preoperative Definitions and Exclusion Criteria

OHT was defined as an IOP ≥ 22 mmHg, without documented visual field or optic nerve damage. POAG severity was defined using the Hodapp-Parrish-Anderson classification system, based on the mean deviation of the visual field test. Baseline angle anatomy was assessed using the Shaffer classification system. Exclusion criteria included other types of open-angle glaucoma, primary or secondary angle closure glaucoma, prior incisional glaucoma surgery, or laser procedure within the last 3 months, significant corneal disease that precluded clear intraoperative visualization of the angle structures, high-risk patients on anticoagulant therapy, or the presence of any preoperative peripheral anterior synechiae (PAS). In addition, patients with inadequate follow-up records of less than 3 months were excluded from the analysis.

Surgical Procedure

All procedures were carried out by a single surgeon (GE). Depending on cataract density and the surgeon's preference for visualization, GATT surgery was performed either before or after CE. The GATT technique has been described previously [2].

Briefly, a 2.2-mm temporal clear corneal incision was created, followed by the injection of OVD into the anterior chamber. A tangential paracentesis track was then created toward the nasal angle, typically in the superonasal or inferonasal quadrant, using a 23-gauge MVR blade. The patient's head and the operating microscope were both tilted to about 35°, to allow a clear view of the nasal angle structures with a surgical gonioprism. Under direct visualization, a small goniotomy was created, using a 23-gauge MVR blade (Figure 1). A 5-0 Prolene suture with a thermally modified blunted tip was introduced through the tangential paracentesis, inserted into Schlemm's canal using 23-gauge microsurgical forceps (Figure 2) and advanced circumferentially around the entire canal.

After passing the suture 360°, the distal tip was retrieved into the anterior chamber, using microsurgical forceps and pulled to create a 360° trabeculotomy (Figure 3). Finally, the OVD was removed, followed by injection of an air bubble filling approximately 70% of the anterior chamber.

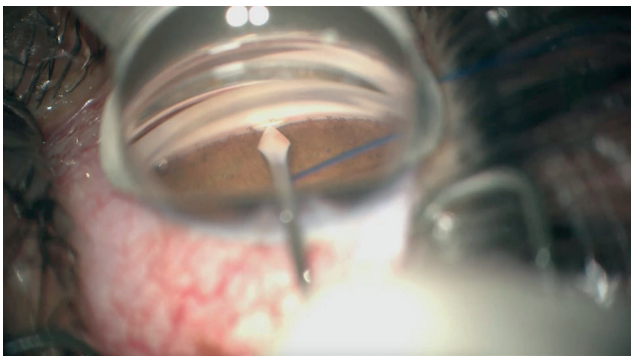

Figure 1. Goniotomy created with a 23 g MVR blade

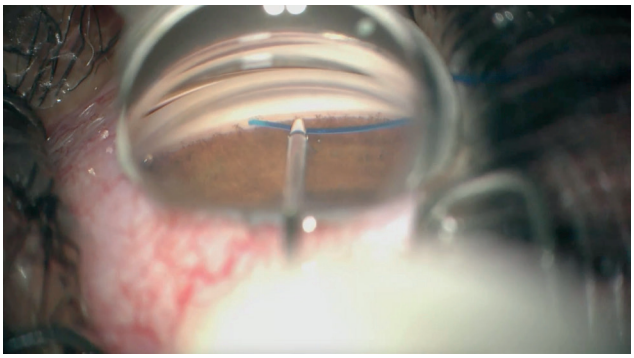

Figure 2. Prolene 5-0 suture insertion into the Schlemm's canal using a 23 g microsurgical forceps

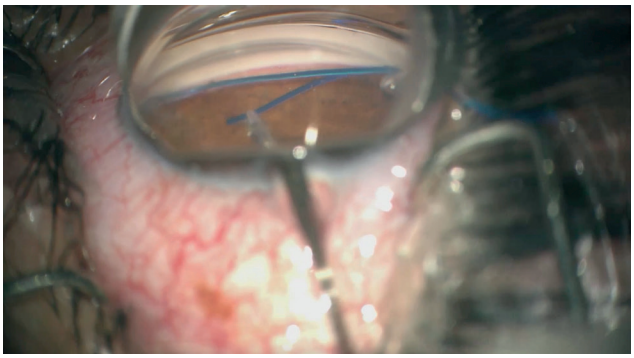

Figure 3. Retrieval of the distal tip of the 5-0 prolene within the anterior chamber using the microsurgical forceps and pulled to create a 360° trabeculotomy

Assessment and Management of Suture Migration

To assess for potential suture migration and to ensure complete 360° cannulation, we first estimated the circumference of the corneoscleral limbus, using the suture itself. The suture was then intentionally bent at this measured length. If, during the procedure, the suture extended beyond the bent mark while passing inside the canal, it indicated possible partial migration or incomplete cannulation. In such cases, an additional paracentesis was created, and the suture was passed in the opposite direction through a second goniotomy to complete the 360° cannulation.

Postoperative Care

Postoperative treatment included a standardized regimen of topical medications. Moxifloxacin 0.5% was prescribed four times a day for two weeks. A topical NSAID, Bromfenac 0.09%, was prescribed twice a day for four weeks. Topical corticosteroid eye drops (Prednisolone Acetate 1.0%) were prescribed five times a day during the first week after surgery and subsequently tapered over a four-week period.

All preoperative topical glaucoma medications were suspended immediately following the procedure to evaluate the surgical outcome. In cases of IOP spikes (IOP ≥ 10 mmHg from baseline during the first postoperative month), acute medical management was initiated with topical Pilocarpine and/or aqueous suppressants, at the surgeon's discretion, and discontinued once the IOP normalized. Glaucoma medications were permanently reintroduced only if the customized target IOP was not achieved or maintained after the third postoperative month, according to the surgeon's clinical judgment. These thresholds served as the primary management guidelines and were defined by disease severity (OHT ≤ 21 mmHg; Mild POAG ≤ 18 mmHg; Moderate-Advanced POAG ≤ 15 mmHg).

Clinical information, obtained through chart review, was collected for the following postoperative visits: day 1, week 1, month 1, month 3, month 6, month 12, and month 24. At every follow-up visit, the following data were collected: Snellen best corrected visual acuity (BCVA) converted into logarithm of the minimum angle resolution (logMAR), IOP measurement with Goldmann applanation tonometer, gonioscopic findings, NGM, optic nerve evaluation, and surgery-related complications. In cases where PAS were identified, they were clinically monitored through periodic gonioscopy and managed conservatively; no surgical interventions, such as goniosynechialysis, were required or performed.

Outcomes' Measures

The primary outcome measure was surgical success, defined as the achievement of either ≥ 20% IOP reduction AND/OR ≥ 1 medication reduction compared to baseline, while maintaining IOP strictly between 5 and 21 mmHg and without the need for additional IOP-lowering procedures (including laser trabeculoplasty). Secondary outcomes were mean IOP and NGM. Safety evaluation included postoperative BCVA (a reduction of ≥ 2 lines was considered clinically significant), surgical procedures related to GATT surgery, intraoperative and postoperative complications. A serious ocular adverse event was explicitly defined as any event posing a significant threat to visual function or globe integrity, including sustained BCVA loss of ≥ 2 lines, persistent hypotony (IOP < 5 mmHg), suprachoroidal hemorrhage or effusion, and retinal detachment. We also analyzed success based on alternative lower IOP thresholds of ≤ 18 and ≤ 15 mmHg. Failure was considered when the success criteria were not met at two consecutive visits after the third postoperative month, or if additional glaucoma surgery was needed.

Statistical Analysis

Continuous variables were expressed as mean ± standard deviation (SD), and categorical variables as frequencies and percentages. Differences between preoperative and postoperative IOP and medications (day 1, week 1, month 1, month 3, month 6, month 12, and month 24) were assessed, using a paired-sample T-test. Kaplan-Meier survival analyses were applied to assess the success rate of the procedure at 24-months follow-up, with each IOP cut-off. Eyes that did not complete 24 months of follow-up were right-censored at the time of their last visit. Cox's proportional hazard regression analysis was used to explore predictive factors for failure.

A significance level (alpha) of 0.05 was employed for all analyses, and Stata 16.0 statistical software was used to conduct the calculations.

RESULTS

Demographic Characteristics

A total of 47 medical charts were reviewed: of these, 43 patients (53 eyes) fulfilled the criteria. Four eyes were excluded due to follow-up < 3 months, and 2 eyes due to previous glaucoma surgery.

The participants had a mean age of 70.1 ±7.1 years (range 35–82 years), and 62.3% were female. Twenty-four eyes had OHT (45.3%) and 29 (54.7%) had POAG. Table 1 summarizes the demographic characteristics at baseline.

IOP Reduction and Medical Therapy

Baseline and postoperative data for IOP and the NGM for the entire cohort, OHT patients and POAG patients, are presented in Table 2. From a mean preoperative IOP of 18.6 ±3.8 mmHg while using 2.1 ±1.3 topical IOP-lowering medications, a statistically significant reduction in both mean IOP and mean NGM was evident across the entire study group, starting from postoperative month 1 and sustained through 24 months of follow-up ($P < 0.001$ for all time points).

At the 24-month follow-up visit, mean IOP was 15.6 ±3.3 mmHg (a mean reduction of 3.0 mmHg from baseline; $P < 0.001$), with 0.8 ±1.2 medications on average (a mean reduction of 1.3 medications from baseline; $P < 0.001$). Moreover, 62.7% of eyes were free of IOP-lowering medications at the 24-month follow-up visit.

Preoperatively, patients diagnosed with POAG exhibited a significantly higher mean NGM compared to OHT patients (2.4 ±1.2 vs. 1.7 ±1.4, respectively; $P = 0.03$). Despite these baseline differences, no statistically significant differences between the OHT and POAG groups were observed in the mean IOP and the NGM administered during most follow-up visits. An exception was noted during the first postoperative week, where a higher NGM count was evident in the POAG cohort ($P = 0.03$).

At the 24-month follow-up visit, both groups demonstrated a highly significant reduction in mean IOP and NGM compared to baseline ($P < 0.001$). Specifically,

OHT subjects showed an IOP reduction from a mean of 19.0 ±4.1 mmHg to 15.1 ±2.7 mmHg (a mean reduction of 3.9 mmHg from baseline). Similarly, NGM was reduced by 1.3 medications from baseline. For POAG subjects, mean IOP was reduced from 18.3 ±3.6 mmHg preoperatively to 16.0 ±3.7 mmHg at 24 months (a mean reduction of 2.3 mmHg from baseline), with NGM also decreasing by 1.3 medications from baseline.

Surgical Success

Overall success, using the primary success criteria (IOP ≤ 21 mmHg, either ≥ 20% IOP reduction OR ≥1 medication reduction) was 91.9% at 12 months and 84.2% at 24 months. During the follow-up period, 7 eyes experienced surgical failure. The primary cause of failure was attributed to insufficient long-term IOP control in 6 eyes, with the remaining eye failing due to reoperation within the first

Table 1. Demographics characteristics at baseline

	OHT	POAG	Total	*P*
No. eyes	24	29	53	
Age (y), mean ± SD	69.8 ±8.4	70.4 ±5.9	70.1 ±7.1	0.786
Range (y)	35–80	55–82	35–82	
Gender				0.974
Males, *N* (%)	9 (37.5%)	11 (37.9%)	20 (37.7%)	
Females *N* (%)	15 (62.5%)	18 (62.1%)	33 (62.3%)	
Severity				
None, *n*	24	0	24	
Mild, *n*	0	10	10	
Moderate, *n*	0	9	9	
Severe, *n*	0	10	10	
BCVA logMAR, mean ±SD	0.57 ±0.2	0.45 ±0.2	0.51 ±0.2	0.09

BCVA – best corrected visual acuity, OHT – ocular hypertension, POAG – primary-open angle glaucoma, SD – standard deviation, y – year

Table 2. Intraocular pressure and the number of glaucoma medications change over 24 months of follow-up

	OHT		POAG		Total		*P*
	N	Mean ±SD	*N*	Mean ±SD	*N*	Mean ±SD	
IOP in mmHg							
Baseline	24	19.0 ±4.1	29	18.3 ±3.6	53	18.6 ±3.8	0.49
Day 1	24	19.2 ±6.3	29	22.6 ±10.9	53	21.1 ±9.2	0.19
Week 1	24	18.6 ±7.9	29	15.7 ±5.6	53	17.0 ±6.8	0.13
Month 1	23	16.4 ±6.2	25	14.0 ±5.0	48	15.1 ±5.7	0.15
Month 3	18	13.8 ±2.1	24	12.6 ±2.6	42	13.1 ±2.4	0.10
Month 6	20	14.0 ±2.5	24	12.8 ±3.4	44	13.3 ±3.1	0.20
Month 12	17	16 ±1.9	20	14.9 ±4.5	37	15.4 ±3.6	0.38
Month 24	20	15.1 ±2.7	23	16.0 ±3.7	43	15.6 ±3.3	0.38
Medications							
Baseline	24	1.7 ±1.4	29	2.4 ±1.2	53	2.1 ±1.3	**0.03**
Day 1	24	0.2 ±0.8	29	0.4 ±0.7	53	0.3 ±0.7	0.27
Week 1	24	0.6 ±1.0	29	1.3 ±1.3	53	1.0 ±1.2	**0.03**
Month 1	23	1.1 ±1.5	25	1.3 ±1.3	48	1.2 ±1.4	0.65
Month 3	18	0.8 ±1.4	24	0.8 ±1.3	42	0.8 ±1.3	1.00
Month 6	20	0.3 ±1.0	24	0.7 ±1.3	44	0.5 ±1.2	0.24
Month 12	17	0.5 ±1.2	20	1.0 ±1.3	37	0.8 ±1.3	0.24
Month 24	20	0.4 ±1.1	23	1.1 ±1.3	43	0.8 ±1.2	0.08

The data are displayed as mean ±SD or N, with statistical significance highlighted in bold
IOP – intraocular pressure, OHT – ocular hypertension, POAG – primary-open angle glaucoma, SD – standard deviation

Table 3. Risk factors for GATT failure at 24 months

	Hazard ratio	95% CI	*P*
Age ≤ 65 years	7.06	1.57–31.62	**0.011**
Men (compared to women)	11.12	1.33–92.50	**0.026**
POAG (compared to OHT)	1.13	0.25–5.09	0.865
Number of baseline medications	0.42	0.08–2.17	0.303
Hyphema (compared to no hyphema)	1.38	0.31–6.20	0.668
PAS (compared no PAS)	0.24	0.04–1.24	0.089
IOP spike (compared to no IOP spike)	3.55	0.79–15.88	0.097

Bold indicates statistical significance
CI – confidence interval, IOP – intraocular pressure, OHT – ocular hypertension, PAS – peripheral anterior synechiae, POAG – primary-open angle glaucoma

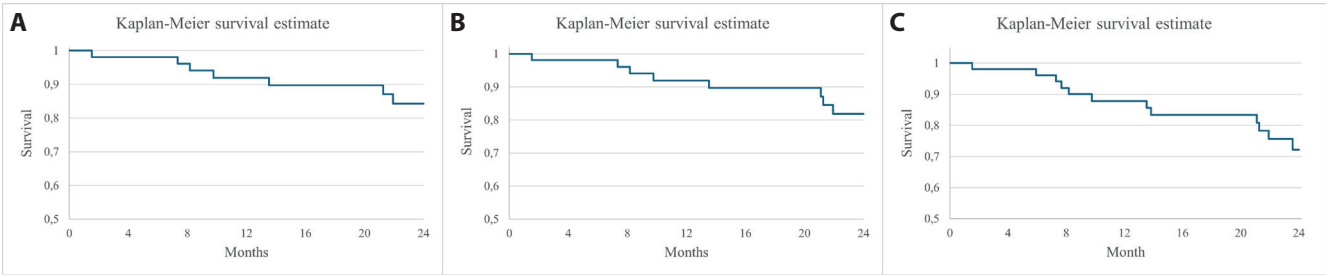

Figure 4. Results of Kaplan-Meier survival analysis at 24 months of follow-up, based on intraocular pressure (IOP) reduction ≥ 20% or ≥ 1 medication reduction and 3 different IOP thresholds: (**A**) ≤ 21 mmHg, (**B**) ≤ 18 mmHg, or (**C**) ≤ 15 mmHg

month following surgery, necessitated by a persistent IOP spike. Survival rates at alternative, more stringent IOP thresholds of ≤ 18 mmHg and ≤ 15 mmHg at 24 months were 81.8% and 72.1%, respectively. Kaplan-Meier plots illustrating the results for each target IOP level are presented in Figure 4.

Survival rates at 24 months were 82.6% for the POAG group and 90% for the OHT group, a difference that was not statistically significant ($P = 0.66$).

Table 3 evaluates the risk factors for failure at 24 months. Cox regression analysis identified age ≤ 65 years (HR 7.06; 95% CI 1.57–31.62; $P = 0.011$) and male sex (HR 11.12; 95% CI 1.33–92.50; $P = 0.026$) as the only factors significantly associated with an increased risk of failure. Other baseline and postoperative variables, including glaucoma diagnosis, preoperative NGM, and the occurrence of hyphema, IOP spikes, or PAS, did not show a statistically significant association with surgical success (all $P > 0.05$).

Visual Acuity

Mean BCVA improved from 0.51 ±0.2 logMAR preoperatively to 0.10 ±0.1 logMAR at 24 months postoperatively, representing a 0.41 ±0.22 logMAR improvement ($P < 0.001$). No reduction of ≥ 2 lines in visual acuity was observed in any patient when compared to the preoperative analysis.

Postoperative Complications

Postoperative complications are shown in Table 4. The most common adverse event was the presence of PAS, occurring in 30 (56.6%) eyes. Typically confined to a single quadrant, these PAS exhibited extensions of no more than 2 clock hours. Hyphema was observed in 27 (50.9%) eyes and usually resolved spontaneously within the first 2 weeks postoperatively. Fifteen (28.3%) eyes experienced an IOP spike and one of these eyes required reoperation for IOP control. Less common adverse events included late-onset microhyphema, intracapsular hemorrhage, cystoid macular edema, and intraoperative Descemet's detachment. Among the two cases experiencing intracapsular hemorrhage, BCVA demonstrated an improvement of ≥ 0.10 logMAR after YAG laser capsulotomy.

Table 4. Intraoperative and postoperative adverse events

Adverse event	Number of eyes (*N* = 53)	Incidence rate (%)
Peripheral anterior synechiae	30	56.6
Hyphema	27	50.9
IOP spikes	15	28.3
Late-onset mycrohyphema	3	5.6
Intracapsular hemorrhage	2	3.7
Tear in Descemet´s	1	1.8
Cystoid macular edema	1	1.8

IOP – intraocular pressure

DISCUSSION

In this study, we assessed the mid-term data regarding the safety and efficacy of GATT combined with CE in patients with POAG and OHT. Overall, our results showed

a significant reduction in IOP and NGM from the first month through the 24-month follow-up. Notably, at the final follow-up, 62.7% of eyes were free of IOP-lowering medications. Postoperatively, no significant differences were found between the OHT and POAG groups regarding IOP reduction, NGM change, and surgical success, except for the first postoperative week, where a higher NGM was observed in the POAG cohort.

Despite MIGS having been described in OHT patients, their outcomes have often been mixed within a broader cohort of open-angle glaucoma patients, rather than being distinctly delineated [6–9]. Furthermore, OHT frequently constitutes a small amount of the total sample of eyes in these studies. For example, Salimi et al. evaluated one-year outcomes of GATT in a young cohort of patients with OHT and open-angle glaucomas, describing an IOP reduction of 49%. However, the OHT subgroup only represented 9% of the overall study population [10]. In our study, at 24-months postoperatively, OHT patients' IOP was reduced from a mean of 19.0 ±4.1 mmHg on 1.7 ±1.4 medications to a mean of 15.1 ±2.7 mmHg on 0.4 ±1.1 medications. This reduction in IOP not only improves disease control, but also mitigates the challenges associated with pharmacotherapy, such as adherence, adverse effects, and costs.

Throughout this investigation, overall success at 24 months was 84.2%. Moreover, when we analyzed success based on alternative lower IOP limits of ≤ 18 and ≤ 15 mmHg, success rates were 81.8% and 72.1%, respectively. These findings are in line with previously reported data of GATT combined with CE. Wan et al. found a success rate of 86.1%, using an IOP threshold of 18 mmHg in POAG patients, 24 months after combined surgery [5]. Using a more stringent IOP limit of 15 mmHg, Sato et al. reported a success rate of 77.8% at 24 months in the combined GATT and CE group. In addition, they assessed success using an IOP threshold of 12 mmHg and found a success rate of 46.7% [3]. Surgical success has traditionally been defined with an IOP limit of 21 mmHg, according to the guidelines of the World Glaucoma Association for reporting surgical trials [11]. Nevertheless, in clinical practice, maintaining an IOP of over 15 or 18 mmHg may not be optimal for patients diagnosed with POAG. The observed surgical success in these studies suggests that this procedure could be a viable option for a significant proportion of individuals with POAG.

Age has been identified as a potential determinant of GATT outcomes in prior studies, although the direction of this association has not been consistent across investigations. Salimi et al. evaluated GATT outcomes in a young cohort of patients with OHT and primary or secondary open-angle glaucoma, and reported that patients younger than 40 years were less likely to experience failure compared with those aged 40–65 years [10]. Similarly, Faria et al. found that individuals older than 60 years had a significantly higher risk of failure than younger patients (HR = 10.96; $P = 0.026$) [12]. In contrast, our results demonstrated that age ≤ 65 years was associated with an increased risk of GATT failure, suggesting comparatively better outcomes in older patients. One possible explanation for this finding is that patients in the 40–65-year age range may exhibit a more robust wound-healing response, potentially predisposing them to increased postoperative fibrosis, canal re-occlusion, or distal outflow resistance following GATT.

Several studies have identified potential factors associated with the failure of GATT, including advanced disease, [4] incomplete trabeculotomy, [13] IOP spikes, [14] Black race, [14] and preoperative IOP [14,15]. In addition to age, we observed that male participants exhibited a higher susceptibility to GATT failure. Although this association has not been described with MIGS, this relationship has been observed in pediatric glaucoma after trabeculotomy and goniotomy [16,17]. Furthermore, male sex has been associated with failure in trabeculectomy and tube shunt procedures, due to a higher risk of Tenon cyst formation [18]. There is a likelihood that the increased intraocular inflammation observed in male participants following GATT could contribute to the occlusion of the canal opening or distal collector channels.

Even though PAS are not usually reported as complications in GATT studies, this postoperative finding is frequently observed. In a recent investigation, the prevalence of PAS was notably higher in the nasal (32.3%) and inferior quadrant (25.8%) following GATT. The authors postulate that increased surgical maneuvers in the nasal quadrant and inflammation linked to hyphema in the inferior angle might contribute to this pattern [19]. Likewise, Matsuo et al. investigated the prevalence of PAS formation after 180° trabeculotomy with the Tanito microhook and found that 86% of eyes developed PAS [20]. In our study, PAS was the most common complication postoperatively (56.6%). Nevertheless, in line with prior research, it did not demonstrate a statistically significant association with the overall surgical outcome at 24 months. Although not directly impacting surgical success, the link between PAS and IOP spikes adds another layer of complexity to postoperative management. Rao et al. found a significant correlation between IOP spikes and PAS. In addition, they noted that PAS > 3 quadrants were one of the main causes predicting the need for medication after GATT [21].

Our study bears several limitations that warrant consideration. Firstly, it is retrospective in nature, relying on data gathered through routine clinical protocols, where IOP measurements were obtained with a single reading by a single examiner, as opposed to a more robust research protocol involving multiple readings by a masked examiner. Regarding the postoperative management, while we established and used tiered target IOP thresholds (≤ 21, ≤ 18, ≤ 15 mmHg) as primary benchmarks for defining success, the reintroduction of topical glaucoma medications was subject to the surgeon's clinical discretion. Although this reflects real-world clinical practice, it introduces potential variability in the management of pharmacological intervention, which may influence the

success rates observed. Furthermore, the cohort was composed exclusively of Hispanic/Latino patients from a single center, which limits the generalizability of our findings to other ethnic or demographic populations. Finally, the lack of a control stand-alone GATT group limits our ability to draw definitive conclusions regarding the comparative effectiveness of GATT combined with CE.

CONCLUSION

The 24-month follow-up data presented herein demonstrate that GATT combined with cataract extraction is an effective, safe, and cost-efficient alternative for lowering IOP and NGM in patients with OHT and POAG (mild to severe). With an overall success rate of 84.2% at 24 months and a low complication profile, GATT can be safely used in patients across the spectrum of disease severity. Critically, these findings provide a rationale for selecting GATT in various scenarios: for patients with comorbidities that complicate standard filtering surgery (e.g., extensive scarring or difficulty with follow-up), as a surgical option to delay the need for trabeculectomy, and as a high-value procedure in settings with limited healthcare resources. While our findings identified age ≤ 65 years and male sex as potential risk factors for GATT failure, these associations warrant further investigation in rigorously designed, prospective randomized trials to optimize patient selection.

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