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Three-year outcomes of gonioscopy-assisted transluminal trabeculotomy for juvenile-onset primary open-angle glaucoma: a retrospective study

Baiyu Hu[1], Suju Liu[2], Hanying Fan[1] and Liuzhi Zeng[1*]

Abstract

Objectives This retrospective study evaluates the three-year efficacy and safety of gonioscopy-assisted transluminal trabeculotomy (GATT) in patients with juvenile-onset primary open-angle glaucoma (JOAG).

Methods A total of 26 patients (35 eyes) with juvenile-onset primary open-angle glaucoma (JOAG) were included in this single-center, retrospective study. Clinical records of patients who underwent gonioscopy-assisted transluminal trabeculotomy (GATT) were analyzed to assess intraocular pressure (IOP), the number of glaucoma medications, and complications, while anterior chamber angle changes were observed by gonioscopy. The follow-up period was up to 36 months.

Results At the time of surgery, the median age of the cohort was 26 years (range: 4–35 years), with a mean visual field deviation (MD) of -17.03 ± 8.67 dB. The mean intraocular pressure (IOP) was reduced from 29.89 ± 9.43 mmHg preoperatively (on 2.7 ± 0.7 glaucoma medications) to 15.70 ± 4.39 mmHg at 12 months (on 0.4 ± 0.9 medications), 15.27 ± 3.24 mmHg at 24 months (on 0.3 ± 0.6 medications), and 17.33 ± 3.37 mmHg at 36 months (on 0.5 ± 0.7 medications). Gonioscopic examinations indicated that peripheral anterior synechiae (PAS) primarily formed within the first 1–3 months and were fully established by 6 months, after which the extent of peripheral anterior synechiae (PAS) remained relatively stable. Kaplan–Meier survival analysis revealed complete and qualified success rates of 73.7% and 82.6% at 12 months, 73.7% and 76.7% at 24 months, 60.3% and 69.1% at 30 months, and 51.7% and 69.1% at 36 months, respectively. The cumulative total success proportion were 90.6% at 12 months, 96.7% at 18 months, 92.3% at 24 months, 86.4% at 30 months and 73.3% at 36 months.

Conclusions GATT is a safe and effective surgical option for JOAG, achieving sustained IOP reduction and favorable long-term success rates.

Keywords Glaucoma, Gonioscopy-assisted transluminal trabeculotomy (GATT), Juvenile-onset primary open-angle glaucoma (JOAG), Minimally invasive glaucoma surgery (MIGS)

*Correspondence:
Liuzhi Zeng
676681961@qq.com
Full list of author information is available at the end of the article

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Introduction

Juvenile-onset primary Open-Angle Glaucoma (JOAG) is a subtype of primary open-angle glaucoma that occurs in younger individuals, typically between the ages of 4 and 35 years [1]. The gonial histological feature of JOAG is goniodysgenesis, characterized by the anomalous persistence of the fetal endothelial membrane, which covers the trabecular meshwork at the iridocorneal angle and impairs aqueous drainage [2]. Persistent intraocular pressure(IOP) elevation results in severe optic nerve damage and progressive visual field loss, underscoring the need for early intervention in affected patients [3]. While medical therapy and laser surgery are commonly employed as first-line treatments, they are not definitive solutions for these patients and are typically only used for a short period while awaiting definitive surgical intervention. Their long-term effectiveness in sustaining IOP control remains limited. Consequently, when pharmacologic management fails, children and young adults with JOAG often require more invasive surgical interventions, including angle surgeries, filtering procedures, glaucoma drainage device implantation, or cyclodestructive procedures [4]. Trabeculectomy remains one of the most frequently performed glaucoma surgeries in China; however, its long-term success is often compromised by filtering bleb failure, primarily due to episcleral fibrosis, inflammation, and subconjunctival scarring [5]. Moreover, complications such as anterior chamber shallowing or flattening, cataract formation or progression and choroidal detachment further restrict its clinical applicability [6]. Given these limitations, there is a need for alternative surgical approaches that enhance aqueous outflow without dependence on a filtering bleb. Gonioscopy-assisted transluminal trabeculotomy (GATT) is a minimally invasive glaucoma surgery (MIGS) that circumferentially incises the trabecular meshwork and the inner wall of Schlemm's canal, creating a direct pathway between the aqueous humor and collector channels to facilitate enhanced aqueous outflow [5]. As a bleb-independent and conjunctiva-sparing procedure, GATT offers a favorable safety profile and achieves moderate IOP reduction with fewer complications, making it a viable option for the long-term management of younger patients, including adolescents [6, 7]. This study aims to assess the long-term safety and efficacy of GATT in adolescent patients with JOAG. While its effectiveness has been demonstrated in previous studies [8, 9], data on its long-term outcomes in this population remain scarce. By evaluating clinical outcomes over a 36-month follow-up, this study seeks to provide further evidence on the durability and sustained efficacy of GATT in JOAG management.

Methods

Study design

This study is a retrospective consecutive case series of JOAG patients who underwent microcatheter-assisted GATT at Chengdu First People's Hospital between June 2019 and September 2024 (36 months). The study was approved by the Ethics Committee of Chengdu First People's Hospital and conducted in accordance with the principles of the Declaration of Helsinki. Written informed consent was obtained from all patients prior to surgery.

Data collection and outcome measures

Data were collected preoperatively and during postoperative visits at 1 week; 1, 3, 6, 12, 24, 30, and 36 months. Outcome measures included IOP, the number of glaucoma medications, success rates, and the frequency of complications. Surgical success was defined as postoperative IOP between 6 and 18 mmHg (including 6 mmHg and 18 mmHg) with at least a 20% reduction from preoperative IOP, achieved either with (qualified success) or without (complete success) the use of glaucoma medications. Qualified success was defined as achieving the target IOP with one or two glaucoma medications, whereas complete success required maintaining the target IOP without any glaucoma medications. The severity of glaucoma was classified based on the mean deviation (MD) of the Humphrey 24–2 SITA Standard test, with mild-to-moderate JOAG defined as $MD \geq -12$ dB and severe JOAG defined as $MD < -12$ dB [8]. Complications were defined as follows: (1) IOP spike was defined as $IOP \geq 30$ mmHg within the first postoperative month [8]; (2) hyphema was categorized as microhyphema (< 1 mm anterior chamber bleeding) or macrohyphema (≥ 1 mm anterior chamber bleeding) [10]. Data on IOP, the number of glaucoma medications, adverse events, and history of prior glaucoma surgeries were collected during preoperative and postoperative visits, and the success rates were calculated based on these measurements.

Inclusion criteria

Patients diagnosed with JOAG who met the following criteria were included: (1) age between 4 and 35 years; (2) preoperative $IOP \geq 18$ mmHg with progressive visual field (VF) deterioration despite maximum tolerated medical therapy; or (3) intolerance to medical therapy and/or failure of previous surgery to achieve target IOP; (4) open anterior chamber angle with identifiable trabecular meshwork (TM) on gonioscopy. All JOAG patients exhibited open angles on preoperative gonioscopy (Spaeth classification: ≥ 25° angle width in all quadrants) without peripheral anterior synechiae (PAS).

Exclusion criteria

Patients were excluded if they (1) were diagnosed with other types of glaucoma, had a history of ocular trauma, or underwent intraocular surgery surgeries other than glaucoma surgery; (2) had unidentifiable trabecular meshwork or corneal abnormalities precluding gonioscopic observation of the angle; or (3) had a bleeding tendency or were receiving anticoagulant therapy.

Surgical technique

All surgical procedures were independently performed by the same surgeon (Liuzhi Zeng). The surgeon was positioned temporally to the patient and created two corneal incisions at the clear corneal limbus: a 1.8 mm main incision in the superotemporal quadrant and a secondary incision in the supernasal quadrant for the left eye or the inferotemporal quadrant for the right eye. The patient's head was positioned slightly nasoinferiorly, and the microscope was tilted at an angle between 30° and 45° to optimize visualization of the anterior chamber angle through the surgical gonioscope. The anterior chamber was filled with a viscoelastic agent to maintain stability and make the IOP reach about 30 mmHg. Under direct visualization using a Volk goniosurgical gonio lens (Volk Gonio Lens), a 1–2 mm incision was made in the nasal trabecular meshwork and the inner wall of Schlemm's canal. A microcatheter (iTrack 250 A; Ellex iScience Inc., Fremont, CA) was inserted through this incision and advanced 360° counterclockwise within Schlemm's canal. Once the catheter completed the loop, both ends were simultaneously pulled to perform a circumferential trabeculotomy of the trabecular meshwork and the inner wall of Schlemm's canal. The anterior chamber was then irrigated to remove the viscoelastic agent and any residual blood reflux. The corneal incisions were hydrated to ensure watertight closure, and clean air was injected into the anterior chamber to slightly elevate the intraocular pressure.

Postoperative treatment and follow-up

Postoperatively, patients received topical antibiotics for 3–4 weeks and corticosteroids for 1–2 weeks, including tobramycin-dexamethasone (TobraDex, Alcon, Rijksweg, Belgium). Diclofenac sodium eye drops were administered for 3 months to mitigate the inflammatory response. The steroids regimen was gradually tapered at the surgeon's discretion to control inflammation while minimizing the risk of steroid-induced IOP elevation. Pilocarpine 0.5% eye drops (Shandong Bausch & Lomb Freda Pharmaceutical Co., Ltd., Jinan, Shandong, China) were initiated 1 week postoperatively and administered two to three times daily for 3 months to prevent peripheral anterior synechiae, irrespective of IOP control. In patients with significantly dilated pupils, the frequency was increased to four times daily. For those with high myopia, pilocarpine was applied one to three times before bedtime, depending on pupil size, to prevent excessive dilation that could exacerbate myopic progression or impair visual function. Pilocarpine was not included in the count of glaucoma medications.

Statistical analysis

All statistical analyses were performed using SPSS (version 27.0, IBM Corp.), and data visualization was conducted with GraphPad Prism (version 9.5.1). Statistical significance was set at $P<0.05$ (two-tailed). Non-parametric tests (e.g., Wilcoxon signed-rank test) were used for non-normally distributed variables. Kaplan–Meier survival analysis, with log-rank and Breslow-Wilcoxon tests for comparison, was used to assess cumulative success rates. The Cox proportional hazards model identified risk factors for surgical failure. A mixed-effects model was used to compare IOP and medication changes between groups, while the Friedman test and mixed-effects model analyzed anterior chamber angle changes. Multivariable logistic regression assessed the impact of visual field severity on surgical outcomes.

Results

Baseline demographic and ocular characteristics

Details of the demographics and ocular characteristics are summarized in Table 1. The data for this analysis were derived from 35 eyes of 26 JOAG patients (18

Table 1 Baseline demographics and ocular characteristics

Variables	Data Values	Total
Number of eyes(patients)	35(26)	35
Age at surgery,y	26(20–31)	35
Sex (Male, %)	69.23%	18
Diagnosed Age	24(17–29)	35
Preoperative IOP (mmHg), mean ± SD	29.89 ± 9.43	35
Preoperative medications, mean ± SD	2.71 ± 0.79	35
Cup-to-disc ratio	0.9(0.8–1.0)	35
Axial length(mm, mean ± SD)	25.78 ± 1.86	34
corneal thickness (CCT)	552.53 ± 58.85	30
Maximum intraocular pressure	38.91 ± 10.07	35
White to white distance	11.87 ± 0.46	33
MD (dB, IQR)	−17.03 ± 8.67	31
BCVA baseline LogMar(IQR)	0.22(0.0–1.0)	35
Number of prior surgeries (%)	20%	7
Bilateral GATT (%)	34.62%	9
Follow-up duration (months)	30 (18,36)	35

males and 8 females). The median age at the time of surgery was 26 years (IQR: 20–31), and the median age at diagnosis was 24 years (IQR: 17–29). The mean preoperative IOP was 29.89 ± 9.43 mmHg, with a recorded peak IOP of 38.91 ± 10.07 mmHg. The mean number of preoperative glaucoma medications was 2.71 ± 0.79. Ocular biometric characteristics were also collected, including a median cup-to-disc ratio of 0.9 (IQR: 0.8–1.0), mean axial length of 25.78 ± 1.86 mm, mean corneal thickness of 552.53 ± 58.85 µm, white-to-white distance of 11.87 ± 0.46 mm, visual field mean deviation (MD) of −17.03 ± 8.67 dB, and baseline best-corrected visual acuity (BCVA) in LogMAR units of 0.22 (IQR: 0.0–1.0). Of the 35 eyes, a total of 18 eyes from 9 patients underwent bilateral GATT. Seven eyes from the cohort of 35 had a history of prior glaucoma surgery, all of which underwent unilateral trabeculectomy. Among them, one patient initially underwent trabeculectomy in one eye, followed by drainage valve implantation in the same eye at a later stage. The mean follow-up duration was 30 months (IQR: 18–36). Gonioscopy examination before surgery confirmed that all eyes had open anterior chamber angles.

Assessment of surgical effectiveness

As summarized in Table 2, significant reductions in IOP were observed at all postoperative time points (1 week and 1, 3, 6, 9, 12, 18, 24, and 36 months), with all $p < 0.05$ except at 1 week. Notably, there was a consistent and significant reduction in the number of medications at every postoperative time point, with decreases of ≥ 60% at all follow-ups. A significant reduction in IOP was observed at most time points. ($p < 0.05$) (Table 2). The mean IOP decreased from a preoperative value of 29.89 ± 9.43 mmHg (with 2.7 ± 0.7 medications) to 15.70 ± 4.39 mmHg at 12 months (with 0.4 ± 0.9 medications), 15.43 ± 2.60 mmHg at 18 months (with 0.4 ± 0.8 medications), 15.27 ± 3.24 mmHg at 24 months (with 0.3 ± 0.6 medications), 16.00 ± 4.07 mmHg at 30 months (with 0.5 ± 0.8 medications) and 17.33 ± 3.37 mmHg at 36 months (with 0.5 ± 0.7 medications). Figure 1 illustrates the changes in IOP (Fig. 1a) and the number of glaucoma medications (Fig. 1b) over time. Of the 35 eyes, 21 of 35 eyes (60%) required three or more glaucoma medications preoperatively. At 12 months postoperatively, 25 of 32 eyes (78.12%) had discontinued all glaucoma medications, with 22 of 30 eyes (73.33%) at

Table 2 Intraocular Pressure Reduction and Medication Usage During Follow-up Periods

Time	n	Preoperative IOP(Mean,95%CI)		Postoperative (Mean,95%CI)	Reduction (%)		*P* value	
		Highest	Last		Highest	Last	Highest	Last
1w	35	38.91 (35.45–42.37)	29.89 (26.65–33.12)	24.16 (19.41–28.90)	14.76 (9.23–20.28) (35)	5.73 (−0.14–11.60) (10)	< 0.001[§]	> 0.05[§]
1 m	35	38.91 (35.45–42.37)	29.89 (26.65–33.12)	16.54 (14.27–18.82)	22.37 (18.28–26.47) (55)	13.34 (9.43–17.26) (39)	< 0.001[§]	< 0.001[§]
3 m	35	38.91 (35.45–42.37)	29.89 (26.65–33.12)	15.29 (13.91–16.67)	23.63 (19.93–27.32) (58)	14.60 (10.87–18.33) (43)	< 0.001[§]	< 0.001[§]
6 m	33	38.64 (35.12–42.15)	29.36 (26.35–32.38)	15.15(14.43–15.88)	23.48 (20.17–26.80) (58)	14.21 (11.44–16.99) (45)	< 0.001[§]	< 0.001[§]
12 m	32	38.63 (35.00–42.25)	29.34 (26.23–32.46)	15.70 (14.12–17.28)	22.93 (19.00–26.85) (57)	13.65 (9.84–17.45) (40)	< 0.001[§]	< 0.001[§]
18 m	30	38.30 (34.45–42.15)	28.70 (25.53–31.87)	15.43 (14.46–16.40)	22.87 (19.14–26.59) (57)	13.27 (10.21–16.32) (42)	< 0.001[§]	< 0.001[§]
24 m	26	38.46 (34.15–42.77)	28.85 (25.34–32.35)	15.27 (13.96–16.58)	23.19 (18.95–27.43) (57)	13.58 (10.08–17.07) (43)	< 0.001[§]	< 0.001[§]
30 m	22	37.68 (32.76–42.61)	27.41 (23.66–31.16)	16.00 (14.20–17.80)	21.68 (17.13–26.23) (55)	11.41 (7.86–14.96) (38)	< 0.001[#]	< 0.001[#]
36 m	15	38.47 (31.64–45.29)	28.27 (23.04–33.49)	17.33 (15.47–19.20)	21.13 (14.31–27.96) (51)	10.93 (5.44–16.43) (33)	< 0.001[#]	< 0.01[#]
Time	**n**	**Preoperative medication count (Mean,95%CI)**	**Postoperative medication count (Mean,95%CI)**	**Reduction(%)**	***P* value**			
1w	35	2.7(2.4–3.0)	0.5(0.2–0.8)	2.2(1.8–2.6) (77)	< 0.001[§]			
1 m	35	2.7(2.4–3.0)	0.8(0.5–1.1)	1.9(1.4–2.4) (64)	< 0.001[§]			
3 m	35	2.7(2.4–3.0)	0.3(0.1–0.6)	2.3(2.0–2.7) (85)	< 0.001[§]			
6 m	33	2.7(2.4–3.0)	0.4(0.1–0.7)	2.3(1.9–2.7) (84)	< 0.001[§]			
12 m	32	2.8(2.5–3.0)	0.4(0.1–0.7)	2.3(1.9–2.8) (85)	< 0.001[§]			
18 m	30	2.7(2.4–3.0)	0.4(0.1–0.7)	2.3(1.8–2.7) (81)	< 0.001[§]			
24 m	26	2.7(2.4–3.0)	0.3(0.1–0.6)	2.3(1.9–2.7) (83)	< 0.001[§]			
30 m	22	2.6(2.3–3.0)	0.5(0.1–0.9)	2.1(1.5–2.7) (74)	< 0.001[§]			
36 m	15	2.7(2.2–3.1)	0.5(0.1–0.9)	2.2(1.4–3.0) (74)	< 0.01[§]			

CI confidence interval, *n* number of patients

[#] Paired Student's t-test

[§] Paired Wilcoxon signed-ranks test

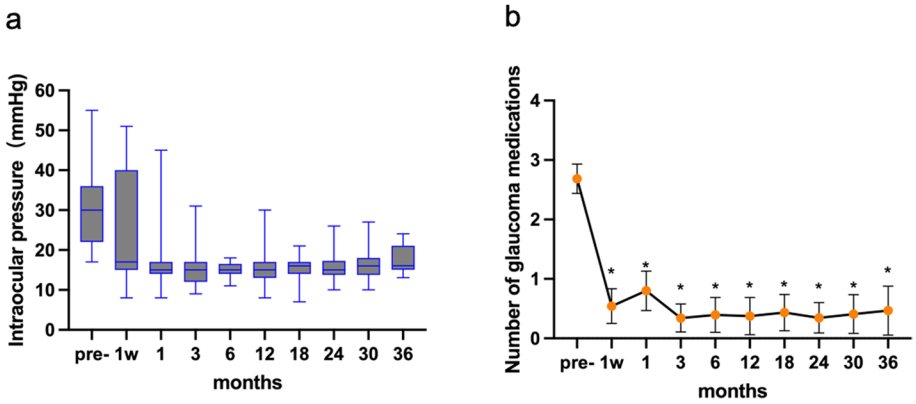

Fig. 1 **a** Box-and-whisker plot showing the distribution of intraocular pressure (IOP) at different time points preoperatively and postoperatively. The boxes represent the interquartile range (IQR), with the horizontal line inside each box indicating the median IOP. Whiskers extend to the minimum and maximum values within 1.5 times the IQR. **b** Line plot illustrating the mean number of glaucoma medications used at each time point. Error bars represent the 95% confidence intervals. Asterisks (*) indicate statistically significant reductions compared to the preoperative period ($p < 0.05$)

18 months, 19 of 26 eyes (73.07%) at 24 months, and 10 of 15 eyes (66.67%) at 36 months. At the final follow-up, 11 of 15 eyes (73.33%) achieved effective IOP control (IOP ≤ 18 mmHg), and 10 eyes (66.67%) required no topical medications. The complete and qualified success rates were 73.7% and 82.6% at 12 months, 73.7% and 76.7% at 24 months, 60.3% and 69.1% at 30 months, and 51.7% and 69.1% at 36 months, respectively (Fig. 2 I, II).

Kaplan–Meier survival curves for complete and qualified success were analyzed using log-rank and Breslow-Wilcoxon tests, stratified by surgical history (Fig. 2 III, IV, V), incidence of postoperative intraocular pressure spike (IOP spike) (Fig. 2 VI, VII), and severity of glaucoma status (mild-to-moderate and severe) (Fig. 2 VIII, IX). Kaplan–Meier survival analysis revealed a significant association between prior surgical history and the likelihood of maintaining complete success, with patients without a history of glaucoma surgery showing a higher probability of achieving complete success compared to those with a prior surgical history (log-rank $p < 0.05$). However, this association was not statistically significant in the multivariate Cox regression analysis within the complete success group. Furthermore, no significant differences were observed in the survival distributions of complete, qualified, and total success between patients with and without postoperative IOP spikes, nor between those with mild-to-moderate and severe glaucoma status (log-rank and Breslow-Wilcoxon tests, $p > 0.05$), suggesting that these factors had no statistically discernible impact on long-term surgical outcomes.

Figure 3 illustrates the changes in intraocular pressure (IOP) and the number of glaucoma medications in patients with and without a history of prior glaucoma surgery. Both groups exhibited a sharp decline in IOP and medication usage shortly after surgery, followed by a gradual stabilization over time. The initial postoperative reduction in IOP was more pronounced, with a subsequent slight upward trend in later follow-ups.

Postoperative complications and reinterventions

Among the 35 eyes that underwent surgery, 13 developed postoperative microhyphema, while macrohyphema occurred in 17 eyes. All cases of hyphema resolved spontaneously within 1–2 weeks. Anterior chamber flare was observed in 15 eyes (42.86%) on the first postoperative day, all of which resolved within 1 week. IOP spikes occurred in 21 of 35 eyes (60%), with 16 cases (76.2%) decreasing to below 30 mmHg within one week. The median duration of IOP spikes was 2 days (range: 2–21 days). IOP spikes were successfully managed in 21 eyes with glaucoma medications, while 14 eyes underwent anterior chamber paracentesis to release aqueous humor, effectively controlling the pressure elevation. At the end of the 36-month follow-up, no permanent vision-threatening complications were recorded. Excluding postoperative hyphema, IOP spikes, and anterior chamber flare, with only one case of ciliary body detachment. No other significant complications were observed, and most patients required no additional interventions beyond adjustments to glaucoma medications. Two eyes with uncontrolled IOP following GATT underwent repeat surgery, specifically transscleral cyclophotocoagulation. One eye in a highly myopic patient developed ciliary body detachment, which was later complicated by cataract formation.

Analysis of factors influencing surgical success

To assess potential factors influencing cumulative surgical success, Fisher's exact test was conducted to analyze

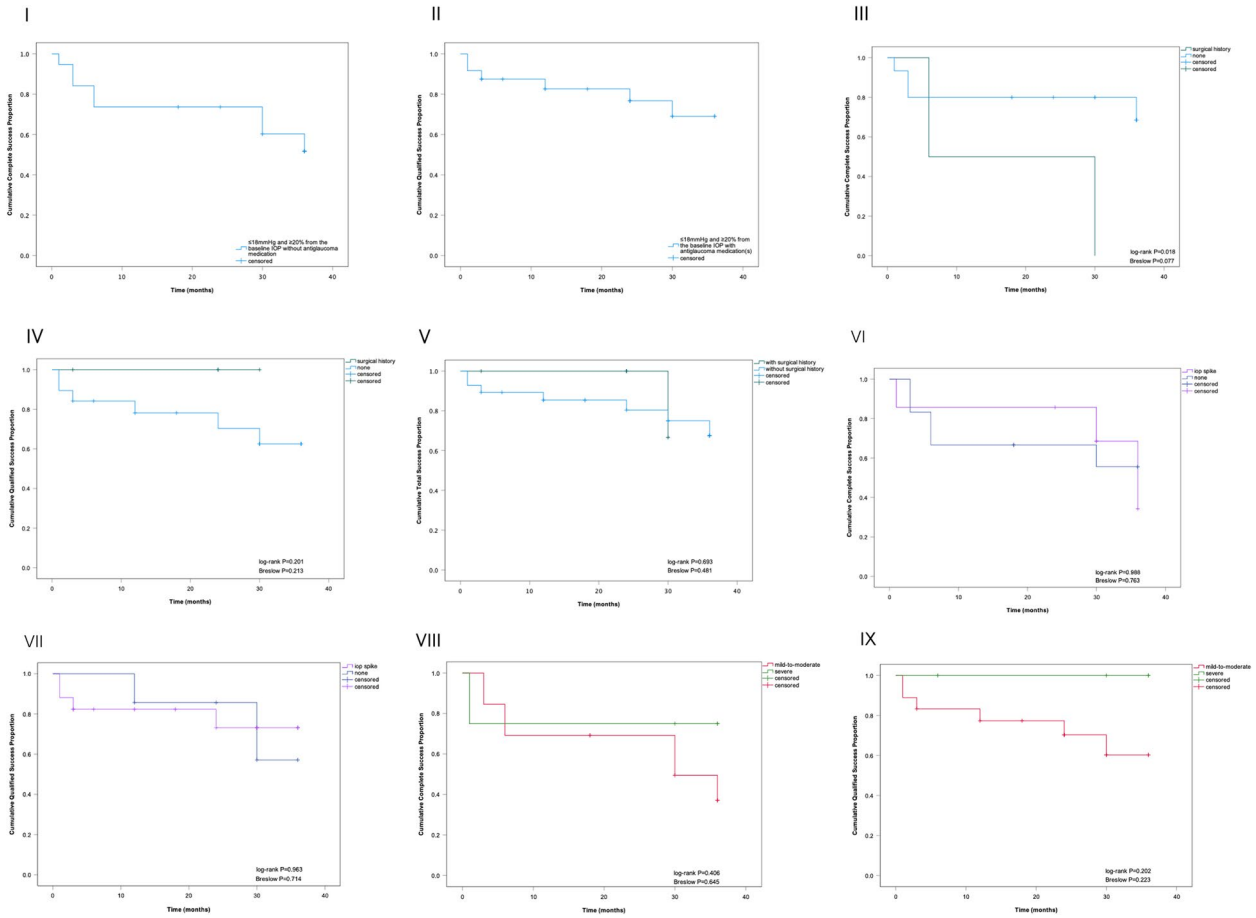

Fig. 2 Kaplan–Meier curve of surgical success in GATT group separated [(I) complete and (II) qualified success], surgical history [(III)complete, (IV) qualified and total(V) success], and IOP spikes [(VI) complete and (VII) qualified success], mild-to-moderate and severe visual field[(VIII) complete and (IX) qualified success]

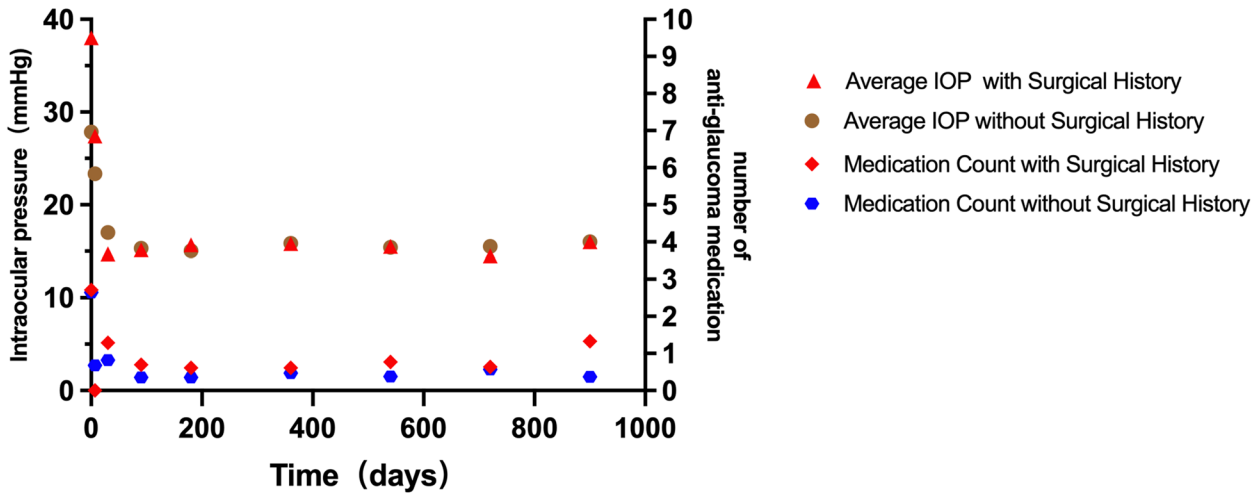

Fig. 3 Postoperative intraocular pressure (IOP) and glaucoma medication administration over time in patients with and without a history of prior glaucoma surgery. (Preoperative IOP based on last recorded IOP)

baseline patient characteristics and postoperative complications. The results demonstrated that surgical failure was not significantly associated with gender, age, history of prior glaucoma surgery, preoperative IOP, number of preoperative medications, severity of visual field impairment (MD), or any postoperative complications, including postoperative IOP spike, hyphema, corneal edema, and anterior chamber flare ($p > 0.05$). Univariate logistic regression analysis was performed to further evaluate the impact of visual field impairment on surgical success or failure. The results indicated no statistically significant association ($p = 0.999$), suggesting that the severity of visual field damage was not a significant predictor of surgical outcomes in this study.

Cox proportional hazards regression analysis was performed to evaluate the impact of preoperative and postoperative factors on surgical failure. The analysis consistently identified IOP spike duration as the only significant predictor of surgical failure (HR = 4.181, 95% CI: 1.275–13.716, $p = 0.018$ for highest preoperative IOP model; HR = 3.449, 95% CI: 1.083–10.981, $p = 0.036$ for last recorded preoperative IOP model), indicating that prolonged postoperative IOP spike was independently associated with an increased risk of surgical failure.

Other variables, including preoperative IOP (HR = 1.581, $p = 0.051$ for highest preoperative IOP model; HR = 1.284, $p = 0.193$ for last recorded preoperative IOP model), preoperative medication (HR = 0.000, $p = 0.067$ for highest preoperative IOP model; HR = 0.002, $p = 0.183$ for last recorded preoperative IOP model),visual field(HR = 0.000, $p = 0.947$ for highest preoperative IOP model; HR = 0.000, $p = 0.918$ for last recorded preoperative IOP model) (mild to moderate: 6 patients, severe: 24 patients), axial length(HR = 7.488, $p = 0.270$ for highest preoperative IOP model; HR = 1.682, $p = 0.665$ for last recorded preoperative IOP model) all did not reach statistical significance.

While a history of prior glaucoma surgery (HR = 11,821,234.157, $p = 0.094$ for baseline IOP model) and younger age (HR = 0.435, $p = 0.094$ for baseline IOP model) suggested a potential protective trend, neither variable reached statistical significance.

Postoperative complications, including IOP spikes (HR = 0.000, $p = 0.192$ for highest preoperative IOP model; HR = 0.000, $p = 0.248$ for last recorded preoperative IOP model), hyphema (HR = 0.004, $p = 0.365$ for highest preoperative IOP model; HR = 0.000, $p = 0.169$ for last recorded preoperative IOP model), corneal edema (HR = 0.000, $p = 0.127$ for highest preoperative IOP model; HR = 0.000, $p = 0.085$ for last recorded preoperative IOP model), and anterior chamber flare (HR = 0.000, $p = 0.355$ for highest preoperative IOP model; HR = 0.000, $p = 0.164$ for last recorded preoperative IOP model) were not significantly associated with surgical failure in multivariable analysis.

Mixed-effects model analysis demonstrated a significant reduction in both postoperative IOP and the number of glaucoma medications across multiple time points. Compared to baseline, both postoperative IOP and medication burden were markedly reduced (mixed-effects model, $p < 0.001$). Throughout the follow-up period, no significant differences were observed in the mean IOP or the number of glaucoma medications between the two groups ($p > 0.05$).

Postoperative gonioscopy observations

Gonioscopy findings were interpreted by two experienced clinicians using the Spaeth classification system (Fig. 4). Preoperative evaluation confirmed open angles (Spaeth grade $\geq 25°$ in all quadrants) in all patients with no signs of PAS, fulfilling the JOAG diagnostic criteria. In patients who were followed up and consented to gonioscopy imaging ($n = 15$), postoperative PAS was observed in all cases, mainly in the nasal quadrant, corresponding to the site of surgical goniotomy. These adhesions usually appeared within the first 3 months after surgery with limited progression (median hours: 1 [IQR: 1,3]. Friedman test showed a statistically significant difference in the incidence of PAS over time ($\chi^2 = 60.588$, $p < 0.001$). The mean grade of PAS (1.46) was significantly lower than IOP (4.75), indicating a temporal association between PAS formation and IOP change. Initially, no PAS was observed at baseline. From 1 to 3 months, PAS gradually formed in 92% of cases, and from 6 months onwards, all patients showed PAS formation. The grade values also showed a gradual increase in the presence of PAS and stabilized after 6 months. However, mixed-effects models did not identify a significant association between PAS presence ($\beta = 0.97$, $p = 0.901$) or clock-hour extent (max $\beta = 5.60$ for CH = 1.0, $p = 0.465$) and IOP. Based on the data we have observed, the extent of PAS has a limited impact on intraocular pressure, with IOP fluctuations remaining minimal across CH categories (changes in IOP staying below 2 mmHg for CH 0–3) (Table 3).

Discussion

Juvenile-onset primary open-angle glaucoma (JOAG) is primarily associated with abnormalities in the anterior chamber angle structure [9, 11]. Gonioscopy-assisted transluminal trabeculotomy (GATT) creates a 360° circumferential incision in the trabecular meshwork and the inner wall of Schlemm's canal, thereby reconstructing the physiological drainage of aqueous humor and enhancing aqueous outflow. Existing studies have demonstrated that GATT is effective in both primary and various secondary types of open-angle glaucoma, including steroid-induced glaucoma, pseudoexfoliation glaucoma, and glaucoma following vitreoretinal surgery [12]. As a targeted,

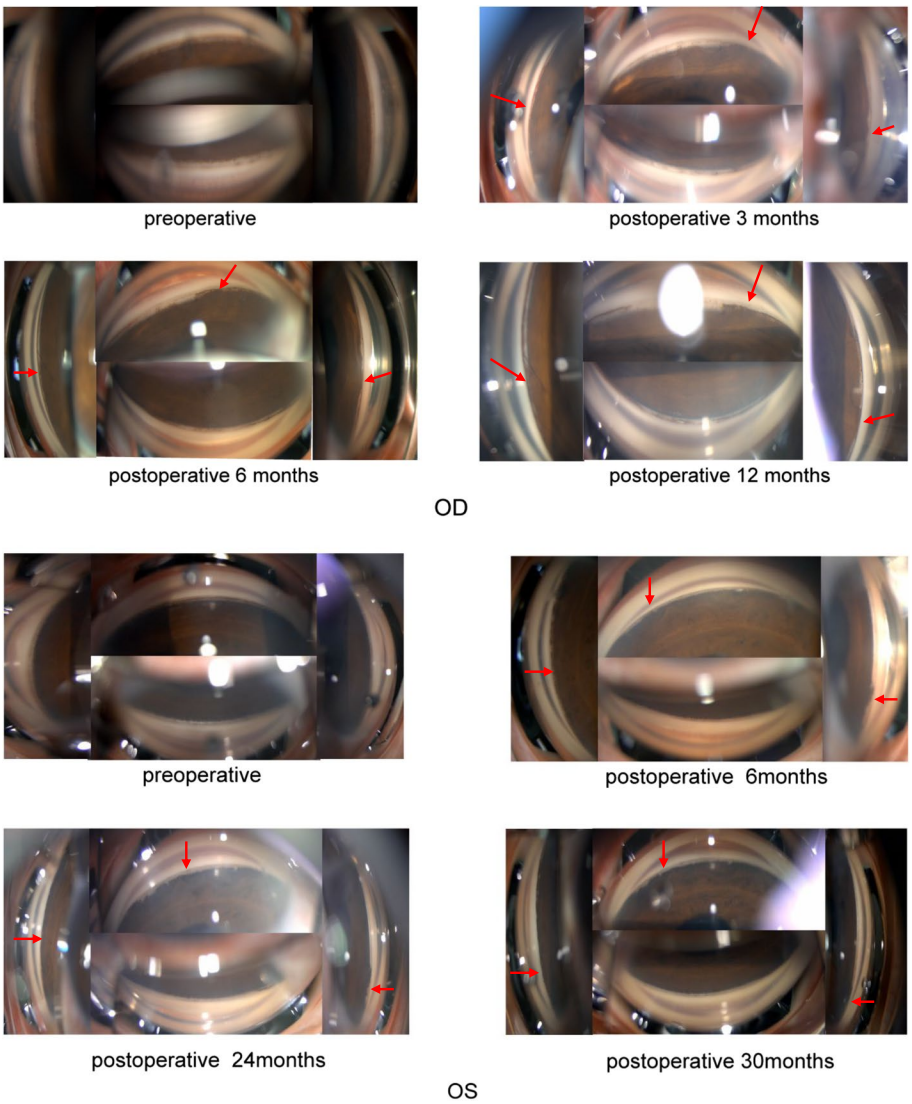

Fig. 4 Follow-up Observations of Postoperative Dynamic Changes in the Anterior Chamber Angle, with Red Arrows Indicating the Formation of Peripheral Anterior Synechiae (PAS)

Table 3 Friedman test of gonioscopy findings across different time points, showing variations in the extent of peripheral anterior synechiae (PAS) (clock hours), pigment and IOP

n	Median(IQR)	Mean rank	*P* value
Time	6.0 (0–12.0)	3.31	0.021
PAS	1.0 (0–1.0)	1.46	0.901
CH	1.0 (0–3.0)	2.04	> 0.05
IOP	15.0 (13–18)	4.75	-
Pigment	6.0 (4–7)	3.44	0.130

bleb-independent surgical technique, GATT offers a viable surgical intervention option for these patients [13, 14]. Furthermore, its conjunctiva-sparing characteristic makes it especially suitable for younger patients.

The results of this study indicate that the efficacy of GATT surgery in JOAG patients is not significantly influenced by traditional risk factors (such as gender, age, preoperative intraocular pressure, medication burden, and degree of visual field damage) or common postoperative complications (such as anterior chamber hemorrhage, corneal edema, anterior chamber flare, and IOP spike). In

this study, the incidence of postoperative IOP spike was 60%, which is higher than the previously reported 48.3% [8]. Among these, 76.2% of patients experienced relief of IOP spike within one week postoperatively, and this did not significantly impact the long-term success rate of the surgery. However, the duration of postoperative IOP spike was significantly correlated with surgical failure. The exact mechanism of postoperative IOP spike after GATT surgery remains unclear, but it may be associated with factors such as steroid sensitivity [15], postoperative inflammatory response, and the deposition of inflammatory cells and blood cells, which can obstruct the aqueous humor outflow pathway. Prolonged IOP spike increases the risk of surgical failure, highlighting the importance of closely monitoring IOP fluctuations postoperatively and implementing timely interventions when necessary. These findings further emphasize the significance of early postoperative IOP monitoring and prompt intervention (such as anterior chamber paracentesis).

In patients with a history of failed filtering surgery, this study demonstrates that GATT achieves long-term success rates comparable to those of treatment-naïve patients (with a 36-month complete success rate of approximately 51.7% and a partial success rate of 69.1%). It is noteworthy that these patients are more likely to transition from complete success to partial success, suggesting an increased dependence on IOP-lowering medications, which may be related to subconjunctival scarring from prior surgery, the tendency for peripheral anterior synechiae, and elevated distal scleral venous pressure. [5, 9, 16, 17]. Therefore, postoperative medication may be necessary to achieve optimal IOP control. Overall, the impact of a previous filtering surgery on GATT outcomes is mainly reflected in the increased dependence on antiglaucoma medications, rather than a significant decrease in the surgery's ability to lower IOP.

Regarding the degree of visual field damage, although previous studies generally suggest that GATT is more effective in mild to moderate glaucoma [9], this study found that even in advanced glaucoma patients (mean MD approximately −17.76 dB), GATT was able to maintain good IOP-lowering effects (with a 36-month IOP of 18.1 ± 3.76 mmHg), with no significant statistical difference compared to the mild to moderate visual field damage group. This may be attributed to the relatively intact distal aqueous humor outflow system in JOAG patients, where GATT surgery relieves the proximal outflow resistance primarily caused by the trabecular meshwork and reconstructs the physiological aqueous humor drainage pathway to lower IOP.

During surgery, EVFW (episcleral venous fluid wave) serves as a real-time indicator of the distal aqueous humor outflow status and is closely associated with postoperative IOP control. Our prior studies indicated that a larger EVFW range is associated with lower postoperative IOP and more significant IOP-lowering effects [18]. Moreover, consistent with the findings of Aktas et al., a significant correlation exists between the EVFW range and postoperative IOP in patients with advanced primary open-angle glaucoma [19]. Our results are comparable to those of Wang NL et al.'s study, with the cumulative rates of complete success and partial success at 36 months being 51.7% and 69.1%, respectively, indicating a high surgical success rate. In contrast, a 30-month follow-up of patients with primary open-angle glaucoma who underwent GATT surgery, as reported by Kamran Rahmatnejad [20], showed an overall success rate of 63.0%. In comparison, our study observed a total success rate of 86.4% in JOAG patients at 30 months post-surgery, suggesting that GATT may offer more durable efficacy in younger patients, which aligns with the pathophysiological characteristics of JOAG patients, where aqueous humor outflow resistance is primarily located in the trabecular meshwork and the inner wall of Schlemm's canal [8, 21].

The postoperative decrease in IOP is highly consistent with the reduction in medication usage, emphasizing that GATT lowers IOP through the reconstruction of physiological aqueous humor outflow rather than relying on medication. Moreover, the period between 1 to 3 months postoperatively is considered a critical time for the formation of PAS (peripheral anterior synechiae), with approximately 92% of cases developing PAS within 3 months, predominantly affecting the inferior nasal quadrant, which is consistent with the findings of Murat Gunay et al. [20] The mechanism may be related to the mechanical tension exerted by the catheter on the trabecular meshwork during surgery, postoperative inflammatory response, and changes in aqueous humor outflow pathways. Notably, all cases developed varying degrees of PAS, and the extent of PAS adhesion showed an increasing trend over time, stabilizing after 3 months. When the median PAS formation time was 1 h [IQR: 1,3], the impact on IOP was limited. PAS appears to reflect localized responses induced by the surgical procedure rather than a marker of disease progression.

This study also compared the effects of preoperative maximum IOP and baseline IOP on postoperative outcomes. The results showed similar effects between the two, further supporting the robust efficacy of GATT in treating high IOP cases in JOAG patients and reinforcing GATT as a first-line surgical option for JOAG, including in patients with elevated IOP. Only one case of ciliary body detachment occurred, indicating that meticulous surgical technique and proper postoperative

management, especially measures to maintain IOP stability during surgery, play a crucial role in reducing severe complications.

This study has some limitations: (1) genetic profiling information was not included; (2) the potential confounding effect of herbal hemostatic agents on anterior chamber hemorrhage; (3) despite the long follow-up period, the sample size was relatively small. Nonetheless, this study provides long-term follow-up data for JOAG patients, supporting GATT as the preferred surgical option. In treatment-naïve patients, GATT achieves a 36-month medication-free rate of approximately 66.7%; for patients with previous failed filtering surgery, GATT offers advantages over repeat filtering surgery (minimally invasive and avoids conjunctival scarring issues). Additionally, the period between 1 to 3 months postoperatively is a high-risk window for PAS formation, and it is recommended to consider timely interventions with pilocarpine and nonsteroidal anti-inflammatory drugs to reduce the occurrence of PAS.

Conclusion

This study demonstrates that GATT is a safe and effective treatment modality, particularly suitable for JOAG patients facing therapeutic challenges, especially those with advanced visual field loss, a history of previous glaucoma filtering surgeries, and preoperative elevated intraocular pressure. Although these patients are typically at a higher risk of surgical failure, the use of GATT effectively reduced postoperative complications and maintained stable intraocular pressure control during long-term follow-up. GATT not only provides a potential treatment option for these more challenging cases but also demonstrates its advantages as a minimally invasive procedure. Additionally, this study highlights the impact of the duration of IOP spike and the degree of PAS on treatment outcomes, offering valuable insights for personalized treatment strategies in JOAG patients in the future.

Abbreviations

JOAG	Juvenile-onset primary open-angle glaucoma
GATT	Gonioscopy-assisted transluminal trabeculotomy
IOP	Intraocular pressure
IOP spike	Intraocular pressure spike

Authors' contributions

Conceptualization: Liuzhi Zeng; Baiyu Hu; Methodology: Liuzhi Zeng; Hanying Fan; Formal analysis: Baiyu Hu; Sujv Liu; Writing—Original Draft: Baiyu Hu, Sujv Liu ; Writing—Review & Editing: Baiyu Hu; Liuzhi Zeng;

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Data availability

Data can be available from the corresponding author upon request.

Declarations

Ethics approval and consent to participate

This study was conducted in accordance with the Declaration of Helsinki. Ethical approval declarations: Ethical approval was granted by the Ethical Committee of the First People's Hospital of Chengdu, with the approval number: 2024 YNYJ-018; The Ethics Committee waived the requirement for written informed consent due to the retrospective nature of the study.

Consent for publication

Not Applicable.

Competing interests

The authors declare no competing interests.

Author details

[1]Department of Ophthalmology, Chengdu First People's Hospital, No.18 Wanxiang North Road, High-Tech Zone, Chengdu, Sichuan Province 610095, China. [2]Eye School of Chengdu University of TCM, Chengdu, Sichuan Province 610000, China.

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