Surgical Science, 2026, 17(8), 299-316
https://www.scirp.org/journal/ss
ISSN Online: 2157-9415
ISSN Print: 2157-9407

Endoscopic Cyclophotocoagulation (ECP) for Glaucoma: Clinical Evidence, Unresolved Challenges, and Future Directions in Minimally Invasive Therapy: A Systematic Review

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How to cite this paper: Lin, B., Li, T.-T., Cai, L.-R., Liang, W., Shi, P. and Li, D.-K. (2026) Endoscopic Cyclophotocoagulation (ECP) for Glaucoma: Clinical Evidence, Unresolved Challenges, and Future Directions in Minimally Invasive Therapy: A Systematic Review. *Surgical Science*, **17**, 299-316.
https://doi.org/10.4236/ss.2026.178029

Received: July 14, 2026
Accepted: August 8, 2026
Published: August 11, 2026

Abstract

Background: Glaucoma is the leading cause of irreversible blindness globally, and reducing intraocular pressure (IOP) is the only evidence-based therapeutic strategy. Minimally invasive glaucoma surgery (MIGS) is a promising alternative to traditional filtering surgeries, with endoscopic cyclophotocoagulation (ECP) as a core modality that reduces aqueous humor production via direct ciliary process photocoagulation. However, uncertainties regarding its standardization and long-term efficacy remain. **Methods:** A systematic search was conducted in PubMed, Web of Science, and Embase for studies published between January 2010 and May 2025, focusing on ECP's efficacy, safety, technical parameters, and clinical applications in glaucoma. After screening, 7 eligible studies (2 retrospective, 5 prospective) involving primary open-angle glaucoma (POAG), primary angle-closure glaucoma (PACG), and refractory glaucoma were analyzed. **Results:** ECP achieved stable IOP reduction across subgroups: standalone ECP yielded 30.8% IOP reduction in refractory glaucoma, phaco-ECP achieved 20% - 27.3% IOP reduction, and phaco-ECP-iStent showed 30.8% IOP reduction, with 82% - 88% of patients reaching target IOP or surgical success. Medication use decreased by 40% - 71.5% across

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groups. Combined phaco-ECP had a 3% 2-year reoperation rate, compared with 15% for standalone ECP. ECP had a lower severe complication rate (<1.4%) than traditional procedures (trabeculectomy, transscleral cyclophotocoagulation), with mild, transient adverse events. Key uncertainties included unstandardized energy parameters, experience-dependent laser distance regulation, and controversial "pop sound" utility. **Conclusion:** ECP is a safe and effective minimally invasive intervention for glaucoma, especially in refractory cases and combined cataract-glaucoma surgery. Future advancements should focus on intelligent parameter optimization, equipment refinement, and long-term data accumulation to promote its transformation from empiricism to precision medicine.

Keywords

Endoscopic Cyclophotocoagulation (ECP), Minimally Invasive Glaucoma Surgery (MIGS), Glaucoma, Intraocular Pressure, Efficacy, Safety

1. Background

Glaucoma, the leading cause of irreversible blindness worldwide, currently affects over 75 million patients globally, with projections indicating that the number will exceed 100 million by 2040 [1]-[3]. Its pathogenesis is closely linked to optic nerve damage induced by pathological intraocular pressure (IOP) elevation and reducing IOP remains the only evidence-based therapeutic strategy validated by clinical research. While traditional filtering surgeries (e.g., trabeculectomy) can effectively control IOP, they are associated with a 3% - 15% risk of intraoperative complications and postoperative issues such as filtering bleb scarring [4] [5]. This clinical dilemma has driven the rapid advancement of minimally invasive glaucoma surgery (MIGS), which reduces aqueous humor production or modifies outflow pathways via internal approaches, featuring minimal tissue trauma, high safety, and rapid recovery [6] [7].

Within the MIGS technology spectrum, endoscopic cyclophotocoagulation (ECP) occupies a unique therapeutic position. Unlike other procedures relying on aqueous humor drainage pathways (e.g., iStent implantation, XEN gel stent implantation) [8] [9], ECP directly reduces aqueous humor production by selectively photocoagulating the ciliary process epithelium under endoscopic visualization [10] [11] (as illustrated in **Figure 1**). This mechanism renders it unaffected by anatomical variations of the Schlemm's canal or fibrosis of drainage pathways, making it particularly suitable for patients with failed prior filtering surgeries or structural abnormalities of the aqueous outflow system. A German multicenter study demonstrated that ECP combined with cataract surgery achieves a 30% - 40% reduction in IOP, with the incidence of severe complications below 1.4% [4]. The Intelligent Research in Sight (IRIS) Registry study reported a mere 3% reoperation rate and a 1% complication rate at 2 years postoperatively when ECP is combined with phacoemulsification, confirming its favorable safety profile [10]. A multivariate logistic regression analysis revealed geographical disparities in the clinical application of glaucoma surgeries across the United States: ECP is significantly more likely to be performed in urban areas than in non-urban regions (OR = 1.46, 95% CI: 1.39 - 1.53), whereas trabecular micro-bypass devices are less frequently utilized in urban settings (OR = 0.49, 95% CI: 0.47 - 0.51) [11], indirectly validating the excellent clinical performance of ECP.

Nevertheless, uncertainties persist in the clinical application of ECP, including the lack of standardized energy parameters, the controversial clinical value of real-time intraoperative feedback indicators, and the need for more evidence to confirm long-term efficacy stability. From a technological perspective, ECP's advantage lies in the unique optical properties of endoscopes, which enable clear visualization of concealed anatomical structures such as the posterior iris, posterior lens, and ciliary body [12]. This visualization advantage endows it with irreplaceable value in complex cases (e.g., pseudophakic eyes, corneal opacity). This systematic review aims to summarize these issues, thereby consolidating ECP's unique position in the stepped treatment of glaucoma.

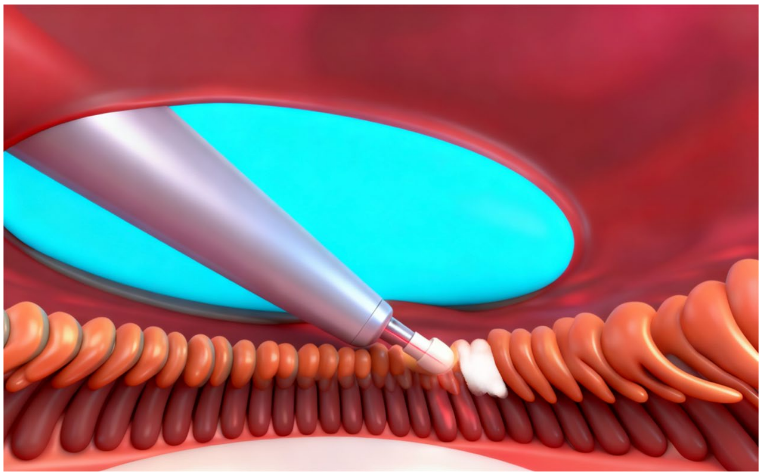

Figure 1. Schematic illustration of the mechanism of ECP. The image is presented from a perspective viewing from the posterior chamber to the anterior chamber of the eye, showing the corresponding ciliary process tissue becoming pale and atrophic under laser irradiation and photocoagulation via the endoscope.

2. Methods

A systematic literature search was performed in PubMed, Web of Science, and Embase to identify relevant studies published between January 2010 and May 2025. The search strategy was designed to capture research on ECP in the context of MIGS, its application in glaucoma treatment, technical characteristics, efficacy, safety, and associated combined surgical approaches, aligning with the core focus of this review. Two reviewers independently extracted data from each included study. Discrepancies were resolved via consensus. No automation tools or additional data confirmation from investigators were used. The specific retrieval strategies for each database and literature inclusion/exclusion criteria are as follows. The detailed literature screening flowchart is presented in **Figure 2**.

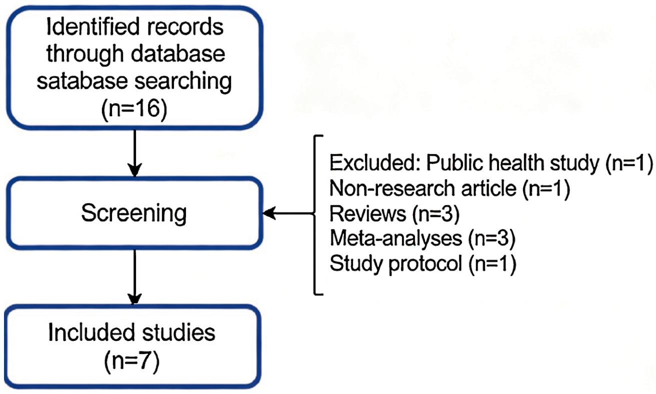

Figure 2. Flow diagram of literature screening process. A preliminary search conducted in accordance with the established retrieval strategy identified 16 relevant studies. Subsequently, 1 study on public health, 1 non-research article, 3 reviews, 3 meta-analyses, and 1 study protocol were excluded. Finally, 7 studies were included in the final analysis.

The final Boolean search strings tailored to each database were constructed as follows:

For Pubmed
("Endoscopic Cyclophotocoagulation" [MeSH Terms] OR "Endoscopic Cyclophotocoagulation" [All Fields] OR "ECP" [All Fields] OR "Endocyclophotocoagulation" [All Fields] OR "Endoscopic Ciliary Photocoagulation" [All Fields])
AND
("Minimally Invasive Glaucoma Surgery" [MeSH Terms] OR "Minimally Invasive Glaucoma Surgery" [All Fields] OR "MIGS" [All Fields] OR "Minimally Invasive Glaucoma Procedures" [All Fields])
OR
("Glaucoma" [MeSH Terms] OR "Glaucoma" [All Fields] OR "Open-Angle Glaucoma" [All Fields] OR "Primary Angle-Closure Glaucoma" [All Fields] OR "Refractory Glaucoma" [All Fields])
OR
("Cyclophotocoagulation" [MeSH Terms] OR "Cyclophotocoagulation" [All Fields] OR "Transscleral Cyclophotocoagulation" [All Fields] OR "TCP" [All Fields] OR "Ciliary Photocoagulation" [All Fields])
OR
("Combined Surgery" [All Fields] OR "Phacoemulsification-ECP" [All Fields] OR "ECP-Phaco" [All Fields] OR "Cataract-Glaucoma Combined Surgery" [All Fields])
AND
("Clinical Study" [pt] OR "Randomized Controlled Trial" [pt] OR "Cohort Study" [pt] OR "Case-Control Study" [pt] OR "Systematic Review" [pt] OR "Meta-Analysis" [pt])

AND
("2010/01/01" [PDAT]: "2025/05/31" [PDAT])

For Web of Science
#1 Topic: ("Endoscopic Cyclophotocoagulation" OR "ECP" OR "Endocyclophotocoagulation" OR "Endoscopic Ciliary Photocoagulation")
#2 Topic: ("Minimally Invasive Glaucoma Surgery" OR "MIGS" OR "Minimally Invasive Glaucoma Procedures")
#3 Topic: ("Glaucoma" OR "Open-Angle Glaucoma" OR "Primary Angle-Closure Glaucoma" OR "Refractory Glaucoma")
#4 Topic: ("Cyclophotocoagulation" OR "Transscleral Cyclophotocoagulation" OR "TCP" OR "Ciliary Photocoagulation")
#5 Topic: ("Combined Surgery" OR "Phacoemulsification-ECP" OR "ECP-Phaco" OR "Cataract-Glaucoma Combined Surgery")
#6 #1 AND (#2 OR #3 OR #4 OR #5)
#7 Document Type: (Clinical Trial OR Randomized Controlled Trial OR Cohort Study OR Case-Control Study OR Systematic Review OR Meta-Analysis)
#8 Publication Date: 2010-01-01 to 2025-05-31
#9 #6 AND #7 AND #8

For Embase
1. exp "endoscopic cyclophotocoagulation"/ or "endoscopic cyclophotocoagulation".ti,ab. or "ecp".ti,ab. or "endocyclophotocoagulation".ti,ab. or "endoscopic ciliary photocoagulation".ti,ab.
2. exp "minimally invasive glaucoma surgery"/ or "minimally invasive glaucoma surgery".ti,ab. or "migs".ti,ab. or "minimally invasive glaucoma procedures".ti,ab.
3. exp "glaucoma"/ or "glaucoma".ti,ab. or "open-angle glaucoma".ti,ab. or "primary angle-closure glaucoma".ti,ab. or "refractory glaucoma".ti,ab.
4. exp "cyclophotocoagulation"/ or "cyclophotocoagulation".ti,ab. or "transscleral cyclophotocoagulation".ti,ab. or "tcp".ti,ab. or "ciliary photocoagulation".ti,ab.
5. "combined surgery".ti,ab. or "phacoemulsification-ecp".ti,ab. or "ecp-phaco".ti,ab. or "cataract-glaucoma combined surgery".ti,ab.
6. 1 and (2 or 3 or 4 or 5)
7. exp "clinical trial"/ or exp "randomized controlled trial"/ or exp "cohort study"/ or exp "case-control study"/ or exp "systematic review"/ or exp "meta-analysis"/
8. publication date 2010-01-01 to 2025-05-31
9. 6 and 7 and 8

2.1. Inclusion Criteria

Study type: Original research including randomized controlled trials, cohort studies, case-control studies, retrospective observational studies, and well-designed single-arm clinical studies with predefined baseline and outcome measures, as well as preclinical studies (animal/*in vitro*) on ECP for glaucoma. Although preclinical studies were eligible per protocol, none meeting the full inclusion criteria were identified. Content: Studies on ECP's efficacy (intraocular pressure reduction, reoperation rate), safety (complications), mechanisms (aqueous humor production, ciliary histopathology), comparisons with other glaucoma surgeries (traditional transscleral cyclophotocoagulation, trabeculectomy, MIGS devices), technical parameters (energy, photocoagulation range), combined approaches (ECP-phacoemulsification), or ECP application epidemiology. Data availability: Studies with extractable clinical/technical/mechanistic data (postoperative intraocular pressure, laser power, ciliary cell apoptosis rate).

2.2. Exclusion Criteria

Studies on glaucoma without mentioning ECP (e.g., only medications, traditional filtration surgery).

Case reports, narrative reviews, conference abstracts, editorials, systematic reviews, meta-analyses lacking original data/full text.

Preclinical studies irrelevant to ECP's mechanism (e.g., glaucoma neuroprotection without ciliary/aqueous humor endpoints).

Duplicate publications (prioritize recent/large-sample/comprehensive studies).

Non-English articles, studies with unextractable key data, or severe methodological flaws (including undefined inclusion/exclusion criteria, absence of baseline outcome measurements, or lack of systematic follow-up; absence of a parallel control group alone was not an exclusion criterion).

2.3. Outcomes and Data Collection Criteria

Outcomes defined: 1) Efficacy: IOP reduction rate, target IOP achievement rate, surgical success rate, reoperation rate, and antiglaucoma medication reduction; 2) Safety: Severe complication incidence, mild transient adverse events; 3) Technical parameters: Laser power, exposure time, and photocoagulation range.

All compatible results (all measures, time points, and analyses) for each outcome domain were extracted from eligible studies.

2.4. Risk of Bias Assessment

Risk of bias was evaluated using the ROBINS-I tool (for non-randomized studies) and the RoB 2 tool (for randomized controlled trials). Two reviewers assessed each study independently, with discrepancies resolved via consensus. No automation tools were utilized. Overall, the 5 prospective studies were rated as having "some concerns" (RoB 2), and the 2 retrospective studies were rated as "moderate risk" (ROBINS-I), primarily due to a lack of blinding and incomplete reporting of outcome data.

2.5. Effect Measures for Outcomes

Efficacy: Mean difference for IOP reduction and medication count change; proportion for target IOP achievement rate, surgical success rate, and reoperation rate.

Safety: Proportion for severe complication incidence and mild adverse events.

Technical parameters: Range and median for laser power, exposure time, and photocoagulation range.

2.6. Eligibility Determination for Synthesis

Eligibility for synthesis was decided by tabulating key study characteristics (intervention type, glaucoma subtype, follow-up duration, outcome data completeness) and aligning with preplanned synthesis groups (ECP monotherapy, ECP + phacoemulsification, ECP + phacoemulsification + iStent). Only studies with complete outcome data for the respective groups were included.

2.7. Data Preparation for Presentation and Synthesis

Missing summary statistics were imputed from graphs/tables via contextual interpolation. Continuous data (e.g., IOP) were standardized to mean ± SD; categorical data (e.g., complication rate) were converted to proportions for consistent presentation.

2.8. Synthesis of Results

Results were synthesized narratively for the seven included clinical studies due to heterogeneous study designs (prospective/retrospective, including one single-arm prospective study) and limited sample sizes (n = 20 - 109 eyes), precluding meta-analysis. For the single-arm study, outcomes were evaluated against predefined baseline values rather than a comparator group. Heterogeneity was qualitatively assessed via comparison of intervention details, outcome definitions, and follow-up durations.

2.9. Risk of Bias Due to Missing Results

Reporting biases were assessed by comparing pre-specified outcomes (in 2.3) with reported results in each study. Funnel plot visualization was not feasible due to the limited study quantity; potential biases were illustrated in the Discussion section.

2.10. Certainty Assessment of Evidence

The GRADE (Grading of Recommendations Assessment, Development and Evaluation) system was used to assess the certainty of the evidence for key outcomes. The certainty of evidence was rated as follows: moderate for short-term IOP reduction (limited by risk of bias and indirectness); moderate for surgical success rate (limited by inconsistent definitions across studies and small sample sizes); moderate for severe complication incidence (limited by underreporting of rare events); and very low for long-term efficacy beyond 2 years (limited by paucity of data). Certainty was categorized as "high", "moderate", "low", or "very low" based on study design limitations, inconsistency, imprecision, indirectness, and publication bias.

3. Technical Principles of ECP

The technical principle of ECP is based on an integrated microendoscopic system, which integrates xenon lamp illumination, a camera, and an 810 nm diode laser module. Its core device is a probe with a diameter of approximately 20 G, which realizes image transmission, light guidance, and laser delivery simultaneously through optical fibers. This allows direct visualization of the ciliary body structure and precise photocoagulation without relying on the refractive media of the cornea or lens. Compared with traditional transscleral cyclophotocoagulation (TCP), the technical advantages of ECP are reflected in two aspects: 1) Direct visualization during operation avoids energy attenuation and destroys other organizations. In clinical practice, the 810 nm laser only requires low energy of 200 - 800 mW to selectively destroy the non-pigmented epithelial cells of the ciliary processes while preserving the pigmented epithelial layer and stromal structure; 2) The photocoagulation range can be adjusted in real-time through the endoscopic imaging system (usually covering 270˚, with a larger limit range), reducing thermal damage to surrounding tissues [12].

From the perspective of histopathological mechanisms, there are significant differences between ECP and TCP. Since ECP can directly target the ciliary processes, lower laser energy can be used to inhibit aqueous humor secretion and reduce intraocular pressure. Pathological studies have shown that ECP induces only mild inflammatory responses, causing local cell apoptosis without extensive necrosis [13] [14]. In contrast, TCP requires penetration through the sclera (with energy attenuation reaching 30% - 50%), thus usually requiring a high energy setting of more than 2000 mW. This not only damages both the pigmented and non-pigmented epithelial layers but also triggers coagulative necrosis of the ciliary body stroma, leading to more severe inflammatory reactions and fibrosis after surgery.

The limbal incision is the conventional approach for ECP, suitable for most cases, especially when combined with cataract surgery, as it provides sufficient operating space. Notably, endoscopic technology can also be performed through a pars plana incision, which is generally indicated for aphakic eyes, pseudophakic eyes, or patients requiring concurrent vitrectomy.

4. Clinical Applications and Efficacy Analysis of ECP

4.1. Overview of Included Studies on ECP

Seven studies focusing on ECP efficacy in glaucoma management were included, spanning 2011-2025 with diverse designs: 2 retrospective (Fernandez-Alcalde *et al.*, 2025 [15]; Moghimi *et al.*, 2018 [16]) and 5 prospective (Razali *et al.*, 2023 [17]; Lima *et al.*, 2023 [18]; Lai *et al.*, 2021 [19]; Francis *et al.*, 2011 [20], 2014 [21]). Sample sizes ranged from 20 to 109 eyes, with follow-up durations of 6 weeks to 3 years, encompassing primary open-angle glaucoma (POAG), primary angle-closure glaucoma (PACG), and refractory glaucoma. Interventions investigated in the included studies fell into two main categories: ECP monotherapy (*i.e.*, standalone

ECP treatment), which was evaluated in one study (Francis *et al.*, 2011 [20]) involving patients with refractory glaucoma who had previously undergone aqueous tube shunt implantation; and combined ECP procedures, which were assessed in the remaining six studies. These combined approaches primarily paired ECP with phacoemulsification, with three of these six studies further incorporating iStent implantation into the ECP-phacoemulsification regimen. Efficacy varied by procedural subgroup: standalone ECP yielded a 30.8% IOP reduction in refractory glaucoma, phaco-ECP achieved 20% - 27.3% IOP reduction, and phaco-ECP-iStent showed 30.8% IOP reduction [18]. Notably, the comparative study by Lima *et al.* demonstrated that this enhanced IOP lowering, relative to phaco-ECP alone, is attributable to the additive effect of the iStent rather than the ECP component. Razali *et al.* (2023) [17] noted that phaco-ECP stabilized IOP but increased fluctuations in POAG. Complications were uniformly mild, confirming ECP's safety. Details can be found in **Table 1**.

Table 1. Summary of clinical studies evaluating the efficacy of ECP in glaucoma management.

Author (Year of Publication)	Study Design	Study Population	Intervention	Core Efficacy Indicators	Core Conclusions on ECP Efficacy
Celia Fernandez-Alcalde *et al.* (2025)	Retrospective Observational Cross-Sectional Study	82 eyes of 82 treatment-naive glaucoma patients with cataract, including preperimetric glaucoma (18.29%), mild glaucoma (32.92%), moderate glaucoma (35.37%), and advanced glaucoma (13.41%).	Phacoemulsification + ECP + iStent Implantation	3-year IOP: 19.5 ± 4.5 mmHg → 14.4 ± 3.2 mmHg (26.2% reduction, $p \leq 0.001$); Medications: 2 types → 1.3 ± 1.1 types, 23.2% of patients were medication-free.	The combined ECP procedure exhibits stable long-term efficacy, with a significant 3-year IOP reduction. 82% of patients achieved target IOP control (≤18 mmHg), and the burden of glaucoma medications was continuously reduced.
Amirah Mohammad Razali *et al.* (2023)	Prospective Observational Study	20 eyes of 17 primary open-angle glaucoma (POAG) patients on topical antiglaucoma medications.	Phacoemulsification Combined with ECP (Phaco-ECP)	6-week postoperative mean IOP: No significant change (14.7 ± 2.7 mmHg vs. 14.8 ± 3.4 mmHg, $p=0.90$); Medications: 2.2 ± 1.15 types → 0.35 ± 0.93 types ($p < 0.001$).	While ECP maintains stable IOP in POAG patients, it significantly reduces the usage of antiglaucoma medications. However, its efficacy in controlling IOP fluctuations is suboptimal.
Francisco E Lima *et al.* (2022)	Multicenter Prospective Comparative Study	Brazilian patients with open-angle glaucoma (OAG) and cataract, randomized into two groups.	Group 1: Phacoemulsification + ECP; Group 2: Phacoemulsification + ECP + iStent Inject Implantation.	12-month IOP reduction: Group 1 (24.2%) vs. Group 2 (43.6%) ($p < 0.001$); Medication reduction: Group 1 (50.2%) vs. Group 2 (71.5%).	ECP combined with phacoemulsification effectively reduces IOP and medication usage. The addition of iStent implantation further enhances the IOP-lowering and medication-reducing efficacy of ECP.

Continued

Isabel S W Lai *et al.* (2021)	Prospective Randomized Controlled Trial (Pilot)	48 eyes of 48 primary angle-closure glaucoma (PACG) patients with cataract, randomized into two groups.	Group 1: Phacoemulsification + ECP; Group 2: Phacoemulsification Alone.	2-year IOP: The group 1 had lower IOP at all time points than the group 2, with significant differences at 1, 12, and 24 months postoperatively; Medication usage: The group 1 had lower usage throughout the study (no statistical significance).	Phacoemulsification combined with ECP demonstrates superior IOP-lowering efficacy in PACG patients compared to phacoemulsification alone, and maintains better long-term (2-year) IOP control.
Sasan Moghimi *et al.* (2018)	Retrospective Case Series	109 eyes of 109 OAG patients with cataract, divided into three groups.	Group 2: Phacoemulsification + ECP; Other Groups: Non-ECP Combined Surgeries	17.2-month IOP: Group 2 decreased from baseline to 16.4 ± 3.9 mmHg (20% reduction); Medication reduction: 40%.	Phacoemulsification combined with ECP achieves effective IOP reduction (20%) and medication reduction (40%). Although its efficacy is lower than viscocanalostomy, it remains a safe and effective option in this study.
Brian A Francis *et al.* (2014)	Prospective Non-Randomized Matched-Control Study	160 eyes of 160 OAG patients with well-controlled glaucoma (on medications) and cataract, matched by age and baseline IOP into two groups.	Group 1: Phacoemulsification + ECP; Group 2: Phacoemulsification Alone.	2-year IOP: The group 1 (16.0 ± 3.3 mmHg) was significantly lower than the group 2 (17.3 ± 3.2 mmHg); Medications: The group 1 reduced from 1.5 ± 0.8 types to 0.4 ± 0.7 types, while the group 2 had minimal reduction.	For OAG patients with well-controlled glaucoma on medications, phacoemulsification combined with ECP further reduces IOP and significantly decreases medication usage, with superior efficacy compared to phacoemulsification alone.
Brian Alan Francis *et al.* (2011)	Prospective Non-Randomized Interventional Clinical Trial	25 eyes of 25 patients with refractory glaucoma (uncontrolled IOP despite prior aqueous tube shunt implantation).	360˚ ECP Monotherapy	2-year IOP: 24.02 mmHg → 15.36 mmHg (30.8% reduction); Medications: 3.2 types → 1.5 types ($p < 0.001$); Success rate: 88% at 12 - 24 months.	ECP monotherapy shows significant efficacy in refractory glaucoma (failed tube shunt implantation), with an IOP reduction of over 30% and a high, stable long-term success rate.

ECP: Endoscopic Cyclophotocoagulation; IOP: Intraocular Pressure; OAG: Open-Angle Glaucoma; PACG: Primary Angle-Closure Glaucoma; Phaco-ECP: Phacoemulsification Combined with Endoscopic Cyclophotocoagulation; p: p-value.

4.2. Expansion of Indications

Refractory Glaucoma

ECP enables significant IOP reduction through endoscopically guided precise photocoagulation of the ciliary processes. A U.S.-based study demonstrated that among 25 glaucoma patients with uncontrolled IOP despite prior aqueous tube shunt implantation, ECP treatment resulted in a 30.8% reduction in mean IOP (from 24.02 mmHg to 15.36 mmHg) and a decrease in the number of antiglaucoma medications (from 3.2 to 1.5 types) at 12-month follow-up [20]. The success rate was 88% and remained stable over 2 years of follow-up, with no serious complications reported. Additionally, a multicenter study indicated that when used as a standalone procedure, ECP had a cumulative 2-year reoperation rate of 15%, which was lower than that of XEN gel stent implantation (24%) and goniotomy/Schlemm's canaloplasty (24%) [10]. For cases refractory to medical or laser therapy, ECP can reduce patients' dependence on IOP-lowering medications [22].

Combined Surgery (Phaco-ECP)

In glaucoma patients with concurrent cataracts, the combined procedure of ECP and phacoemulsification (Phaco-ECP) exhibits synergistic therapeutic advantages [15] [19] [21]. Study data showed that the reoperation rate of the combined surgery group (3%) was significantly lower than that of standalone ECP (15%), with more stable postoperative IOP control [10].

4.3. Comparative Efficacy Studies

Note: All comparisons in this section are based on indirect evidence from separate studies rather than head-to-head trials; differences in study populations, follow-up durations, and outcome definitions limit the interpretability of these cross-study estimates.

Comparison with Cyclocryotherapy/Transscleral Cyclophotocoagulation

The anatomical localization advantage of ECP results in a significantly lower complication risk compared to TCP. Literature reports indicate that the incidence of postoperative hypotony and phthisis bulbi following ECP is lower than that of TCP [22].

Comparison with Glaucoma Drainage Device Implantation

ECP is less invasive, but its long-term IOP-lowering effect may be relatively weaker. Studies have shown that ECP combined with cataract surgery can effectively reduce IOP [23]; however, these ECP cohorts predominantly included milder glaucoma cases, whereas GDD studies often enrolled refractory patients. In contrast, modified Ahmed valves significantly reduce scar formation through sustained-release mitomycin, achieving more durable IOP control [24]. The choice between the two procedures should be based on the severity of the disease and surgical goals [25].

Comparison with Trabeculectomy

ECP demonstrates similar efficacy to trabeculectomy in reducing IOP and alleviating medication burden in comparative cohorts but offers the advantages of minimal invasiveness and fewer complications [22] [25]. Cross-study data suggest that the 2-year reoperation rate of phaco-ECP (3%) is lower than the 15% - 24% rate reported for standalone trabeculectomy [10]; however, this comparison is confounded by indication, as trabeculectomy cohorts often include advanced refractory cases with a higher baseline risk of failure. Notably, ECP does not compromise the feasibility of subsequent trabeculectomy or drainage tube implantation [23].

4.4. Safety and Complications

The overall reoperation rate reported for ECP across the included studies is 1%, lower than the 8% rate reported for trabeculectomy in a separate registry analysis [10]; this difference may reflect that ECP cohorts predominantly comprised mild-to-moderate glaucoma cases, whereas trabeculectomy cohorts included more advanced disease. Severe complications are rare with ECP, and vision-threatening events requiring reoperation are seldom reported, in contrast to the 3% - 15% incidence reported in separate trabeculectomy cohorts [4]. Among MIGS modalities, ECP's complication risk appears comparable to XEN gel stent implantation (1%) and lower than goniotomy/canaloplasty (2%) in cross-registry comparisons [10]; these estimates derive from non-head-to-head analyses of heterogeneous populations. Potential intraoperative complications of ECP include transient hemorrhage (1.1%) and corneal burns (0.9%), but there are no reports of long-term hypotony caused by ciliary body destruction. The 19% rate of early postoperative complications with ECP is reported as significantly lower than the 34% rate in the trabeculectomy group (34%) in a separate comparative cohort [26]. These data demonstrate that ECP exhibits a favorable safety profile while maintaining effective IOP-lowering efficacy [1] [6].

5. Uncertainties in ECP Technology

5.1. Uncertainty 1: Is Pursuit of "Pop Sounds" Necessary for ECP?

TCP relies on "pop sounds" as auditory feedback to confirm energy penetration through the sclera. In contrast, ECP adopts visual criteria for effective photocoagulation—specifically, the observation of ciliary process blanching and shrinkage under direct endoscopic visualization (see Video 1). Unlike TCP, deliberate pursuit of pop sounds is unnecessary in ECP, as such sounds may indicate excessive energy delivery, which can lead to tissue vaporization and increase the risks of inflammatory reactions and iatrogenic damage. Visual feedback is more reliable, and gradual atrophy and blanching of the ciliary processes are sufficient to confirm effective photocoagulation.

5.2. Uncertainty 2: Dilemma of Standardizing Energy Parameter Settings

Currently, there is no unified standard for ECP energy parameters. Clinical practice is characterized by variations in laser power (200 - 800 mW), exposure time

(0.5 - 2 seconds), and photocoagulation range (120˚ - 270˚), with exposure time typically controlled via a foot pedal in "continuous" mode. Key factors influencing energy efficacy include:

Glaucoma subtype: Ciliary bodies in patients with long-standing chronic glaucoma may exhibit reduced energy absorption due to atrophy and depigmentation.

Individual variability: The morphology, size, and pigmentation of ciliary processes differ among individuals, necessitating personalized energy adjustments.

Photocoagulation range: Theoretically, a larger photocoagulation range correlates with improved surgical success, *i.e.*, more pronounced IOP-lowering effects. However, an expanded range may concomitantly increase the risk of postoperative inflammation.

5.3. Uncertainty 3: Precise Regulation of Laser Distance

The distance between the laser diode and the ciliary processes directly affects laser energy density:

Excessively close: May cause overtissue damage; additionally, pigment deposition on the laser diode tip can impede energy emission.

Excessively distant: Results in energy attenuation and compromised photocoagulation focusing.

Currently, there is a lack of standardized methods for distance regulation, and adjustments primarily depend on the surgeon's clinical experience based on real-time endoscopic imaging.

5.4. Epidemiological Data

According to a multicenter retrospective study from the IRIS® Registry (2013-2019), ECP, as a type of MIGS, has demonstrated validated safety and efficacy. Nevertheless, further research is required to standardize energy parameters and operational techniques [10]. Furthermore, advancements in endoscopic technology have enhanced the visualization precision of ECP, but large-scale clinical data are still needed to corroborate its long-term efficacy and complication profiles.

6. Future Outlook: From Empiricism to Precision

6.1. Individualization of Energy Parameters and Intelligent Decision-Making Systems

Currently, the setting of ECP energy parameters primarily relies on surgeons' experience, lacking quantitative standards. In the future, an intelligent recommendation model can be constructed through the integration of multimodal data: 1) Leveraging large-scale databases such as the IRIS® Registry (covering ECP surgical cases from 2013 to 2019) [10], incorporating variables including glaucoma subtype (e.g., open-angle/angle-closure), ciliary process morphology (ultrasound biomicroscopy data), and pigmentation grading (gonioscopic scores); 2) Integrating real-time feedback technologies, such as intraoperative OCT for more precise monitoring of ciliary process coagulation volume, to replace traditional visual feedback.

6.2. Minimally Invasive Equipment Advancement and Energy Transmission Optimization

Existing ECP technology offers two key areas for improvement: 1) Laser transmission efficiency: The 810 nm diode laser can adopt a "matrix spot" mode mimicking retinal photocoagulation, developing triple, quadruple, or more consecutive photocoagulation spots to achieve faster and more uniform ciliary process coverage, reducing repeated photocoagulation and surgical duration; 2) Endoscopic intelligence: Drawing on ultra-fine fiber endoscope design [27], integrating self-cleaning channels and temperature sensing modules to clear opaque intraocular fluids and avoid intraoperative visual field blurring, while enhancing the controllability of intraocular temperature during photocoagulation.

6.3. Combined Therapy and Expansion of Indications Further

The minimally invasive nature of ECP endows it with unique advantages in special populations: For high-risk patients (e.g., those with coagulation disorders), ECP can serve as a first-line intervention, as it carries a lower bleeding risk compared to trabeculectomy or other drainage device implantations [22] [28]. Future research should explore the synergistic mechanisms between ECP and novel drainage devices, extending therapeutic efficacy through the dual effects of "aqueous humor drainage + secretion inhibition" [18], given that studies have indicated that IOP stability may be insufficient in some patients with extremely severe conditions following ECP [16] [17].

6.4. Long-Term Efficacy and Complication Management

Current evidence for ECP is mostly limited to moderate certainty [1], requiring improvements in the following study designs: 1) Prospective cohorts: Distinguishing the efficacy differences between standalone ECP and combined surgeries (e.g., ECP + cataract surgery). IRIS® data show that combined surgeries account for 81% [10], which may overestimate the efficacy of standalone ECP; 2) Complication registration: Establishing a standardized reporting system, with a focus on monitoring delayed ciliary body atrophy and macular edema correlation. Additionally, referring to other disciplines, formulating ECP operational consensus can mitigate the impact of the learning curve.

7. Conclusion

As a pivotal MIGS modality, ECP demonstrates significant advantages in the management of refractory glaucoma and combined cataract-glaucoma cases, leveraging its unique mechanism of precise photocoagulation of ciliary processes under direct visualization to reduce aqueous humor production. Potential reporting biases were qualitatively evaluated: All included studies reported core efficacy (IOP reduction, success rate) and safety (complication) outcomes pre-specified in our review, but three studies lacked detailed data on technical parameters. This may slightly limit the generalizability of technical recommendations but does not compromise the main conclusions on ECP's safety and efficacy. It achieves stable IOP-lowering effects with an incidence of severe complications below 1.4%. Its core strengths lie in minimal tissue trauma, independence from aqueous outflow system abnormalities, and a visualized operation that is well-suited for complex cases. However, ECP currently faces several challenges, including the lack of unified standards for energy parameters, experience-dependent regulation of laser distance, and the controversial clinical value of "pop sounds". In the future, efforts should be directed toward constructing intelligent decision-making systems, optimizing equipment and energy transmission, expanding combined treatment regimens, and accumulating long-term clinical data. These advancements will promote the transformation of ECP from empiricism to precision medicine, further consolidating its important position in the stepped treatment of glaucoma. Per GRADE assessment, evidence certainty for ECP's short-term safety and efficacy is moderate, while long-term efficacy evidence remains low due to limited follow-up data.

Consent for Publication

All authors agree to publish their findings in this journal.

Availability of Data and Materials

Template data collection forms, extracted data, analytic code, and other review materials are not publicly available due to institutional data management policies.

Author Contributions

Bin Lin: Conceptualized the review on ECP in glaucoma management, designed the literature retrieval strategy, curated and analyzed data, drafted the original manuscript, and oversaw project progress.

Ting-Ting Li & Li-Rong Cai: Co-conceptualized the review, collated literature on ECP's comparative efficacy and combined surgeries, analyzed its indication expansion, and revised the manuscript.

Wei Liang: Assisted in data collation, supported analysis of ECP's technical principles, and edited sections on safety and technical uncertainties.

Peng Shi: Conducted systematic literature retrieval and screening, extracted data from eligible studies, contributed to the "Future Outlook" section, and participated in manuscript revision.

Dong-Kan Li: Supervised the research, provided critical insights on ECP's clinical positioning, revised the manuscript for academic rigor, and validated data analysis consistency.

Acknowledgements

Thanks to Jing Tang for her help in data collection in this study.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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