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REVIEW

Microinvasive Glaucoma Surgery: A Review of Schlemm's Canal-Based Procedures

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Abstract: Microinvasive glaucoma surgery has gained popularity over the past decade. It can be performed using three different mechanisms. In the present review, we focused on Schlemm's canal (SC)-based surgery, which increases aqueous humor (AH) outflow into the aqueous veins by either removal of the trabecular meshwork (TM) or an increase in the tension in the TM. In primary open-angle glaucoma (POAG), the TM is the most likely region for increased AH outflow resistance. Theoretically, removal of the TM can improve the AH outflow; hence, glaucoma specialists focus on microsurgical dissection of the TM. In this review, we analyzed the available literature to examine SC-related microsurgical modalities based on the histopathological proofs of the localization of resistance of the AH outflow. First, we considered the role, anatomy, and physiology of the TM and SC. We referred to studies that describe the mechanisms and potential pathways, related to increased intraocular pressure in the POAG, that are targeted using the SC-related microsurgical interventions. Next, we took a closer look at the gonioscopic tools necessary for an ab-interno approach and explored incision canal surgery: ab-interno trabeculectomy using different instrumentation (Trabectome®, Kahook Dual Blade) and variations of the technique. Thereafter, we discussed ab-interno canaloplasty, explaining the technique and reviewing its effectiveness. Finally, we presented the scope for future research in the field. Although the iStent also targets SC by bypassing it, this device has been reviewed extensively elsewhere.

Keywords: microsurgery, trabecular meshwork, canaloplasty, trabeculotomy, Kahook Dual Blade, Schlemm's canal

Introduction

Glaucoma is still the most common cause of blindness worldwide. It is estimated that 13.5–42.0% of glaucoma patients are blind unilaterally, and 4.0–16.0% bilaterally.[1] The only treatment proven to slow progression of glaucoma and the related visual-field loss is the reduction of intraocular pressure (IOP).[2,3] Although trabeculectomy is still considered to be the gold standard in glaucoma surgery, it may cause many short- and long-term side effects.[4] It has an approximate success rate of 80% after 1 year.[5] This success is paired with the burden of a 1%-per-year risk of endophthalmitis and other frequent, sight-threatening adverse events, such as persistent hypotony and choroidal detachments.[6] Glaucoma drainage devices are reported to have a success rate of approximately 50–75% at 5 years, but can also precipitate major complications such as motility disturbances, hypotony, corneal decompensation, and tube erosion,[7–9] to name a few. Such complications often result in the postponement of surgery until visual-field loss is extensive.

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Due to increasing life expectancy, individuals have a higher lifetime risk for glaucoma development and generally live long when they do have glaucoma.[10] Therefore, it has become essential to operate glaucoma at an early stage and lower IOP intensively from the beginning. For over a decade, intensive research has been conducted on the use of microinvasive glaucoma surgery (MIGS), aiming to reduce IOP and the fluctuations thereof, while posing a low risk of side effects that influence the patients' quality of life, and decreasing the burden of medications. There are different types of MIGSs from an anatomical viewpoint. In this review, we focused on procedures based on Schlemm's canal (SC), since the likely underlying mechanism of IOP increase is an amplified resistance to aqueous humor (AH) outflow by the trabecular meshwork (TM).[11–13]

Goniotomy and trabeculotomy are effective in treating glaucoma in children; the incisions made cause the elastic scleral spur to retract posteriorly, stretching and separating the TM. These techniques are improved by removing a strip of the TM in adults; otherwise, the anterior and posterior TM may reapproximate and occlude the collector channel (CC) intakes. Goniotomy and trabeculotomy are categorized as MIGSs when they are modified to perform via an anterior chamber access. The difference between the SC-based MIGSs is in the method of the TM removal or bypass. The TM may be removed using plasma-mediated TM ablation[14] or physical TM removal with or without irrigation and aspiration;[15] the TM may also be bypassed using stents.[16–18]

Trabecular Meshwork Function and Structure

Drainage of the AH from the trabeculum to the CCs takes place via SC. Cells of SC vary depending on their location, as the inner and outer walls can be distinguished in the canal's microanatomy. Each wall is lined with an endothelium: a continuous, single layer of cells that differ in terms of morphology, expression of markers, organelles, and function.[19,20] The TM is a connective tissue without any vessels, which lines the inner SC.[21] The TM has three regions. 1) The anterior chamber borders the uveal meshwork contains a system of fenestrated collagen-elastin fiber lamellae concealed by the TM cells. 2) The corneoscleral meshwork contains the TM, which covers the perforated collagen and elastin plates. This structure borders the sclera and the cornea. 3) The juxtacanalicular connective tissue (JCT) borders the inner wall of SC and consists of loose connective tissue, with the TM cells encircled by an irregular extracellular matrix (ECM).[21] The inner wall is linked to the ciliary muscle with elastin fibers that extend from the terminal part of the longitudinal fibers via the corneoscleral meshwork and the JCT.[22] The above three regions are considered to function as a filter, as they are positioned directly over SC. The terminal part of the TM, the "insert," is considered "non-filtering," as it abuts Schwalbe's line rather than SC.[21,22]

The inner wall is the region most frequently analyzed since it provides major resistance to the drainage of the AH.[23,24] Characteristic features of the inner wall are tight junctions of vascular endothelial-cadherin and giant vacuoles and pores. Together, the JCT and the inner wall structures play important roles in the regulation of the AH outflow.[25]

The spaces between the ECM and the inner wall cells of SC are called "giant vacuoles."[26] These are dynamic and increase in quantity and size as IOP increases.[27–29] Giant vacuoles are mostly found near the CC outlets.[26,30] This indicates the presence of a high aqueous flow resulting in a high-pressure gradient at these sites.[26]

The pores of the inner wall, with sizes of 0.6–3 µm,[31] account for 10% of the AH outflow.[32,33] The AH flow in the inner wall mainly takes place via these pores. Such pores may occur in the walls of giant vacuoles or in other areas.[34] Giant vacuoles form the preferential AH drainage pathways across the endothelium via a one-way valve mechanism. When the pressure increases in the episcleral veins, it also rises in SC; subsequently, the number of vacuoles and pores in the inner wall of SC reduces, preventing reverse blood flow from SC to the anterior chamber.[35] Some medications (ie, glucocorticoids) that stimulate the polymerization of cytoskeleton proteins[36] may hinder vacuole development, thereby increasing the resistance to the AH outflow.[37] Reduced pore density is typical for eyes with glaucoma. This fact reveals that the inner wall plays a critical role in maintaining the AH homeostasis. The AH outflow resistance is amplified markedly by the interaction of the pores and the subendothelium (the basement membrane of SC cells and the JCT ECM).[38]

The second main role of TM cells is to act like biological filters. Interestingly, TM cells exhibit macrophage-like activity.[21] They rapidly phagocytize cellular fragments of pigmented epithelia carried by the AH flow[39] before it reaches the TM, where it may collect and alter the AH outflow.[40] To fulfill this role, the TM cells produce a significant amount of anti-thrombogenic substances, such as heparin or tissue-plasminogen activator.[41] Similar to endothelia, cells of the inner wall of the TM contribute to the antigen presentation and inflammatory reaction by releasing histocompatibility proteins and inflammatory cytokines.[21]

Outflow Resistance

AH is not distributed uniformly throughout the inner wall of SC. As noted in the previous section, aqueous flow takes place mostly near CCs,[26] where double the number of giant vacuoles are found compared to the rest of the inner wall. This shows that the fluid movement through the inner wall depends on the pressure gradient.[42] AH flows through multiple curved veins, from the deep blood vessels known as the deep scleral plexus, through the limbal and intrascleral plexus, to the episcleral veins.[43] SC-based MIGS builds on Grant's study,[44] in which it was observed that the excision of the TM or the external wall of SC in enucleated human eyes lowered the AH outflow resistance by 49% at normal IOP. When IOP was higher than normal, 71% of the outflow resistance was eliminated.[33] Schuman et al[45] also noticed that at normal IOP, TM ablation with an excimer laser allowed for a 35% reduction in the outflow resistance. These studies suggest that up to 50% of the outflow resistance occurs distally to SC, depending on the IOP. The fact that the IOP was reduced after removal of parts of the TM implies that the AH was able to drain through the downstream pathways beyond SC.

This residual outflow resistance beyond SC may reside in the AH pathway from the CCs to the intrascleral venous plexus or aqueous veins.[46] The complete mechanism of the formation of this residual resistance is not fully known. What is known, however, is that the segmental AH outflow,[47] perilimbal tissue biomechanics,[48] and the aqueous veins are factors contributing to this mechanism.[49]

In a healthy eye, the IOP is nearly 16 mmHg, while pressure in the episcleral veins is 7–8 mmHg.[50] The pressure differential across the TM is, therefore, ~8 mmHg. Grant et al[32] managed to maintain an IOP of 25 mmHg in their early ex vivo experiments, which was higher than the mean IOP in a healthy eye. Consequent research revealed that trabeculotomy allowed for the elimination of only ~14% of the resistance under the condition of 5 mmHg IOP ex vivo (which is estimated as 13 mmHg in vivo).[51] The same procedure eliminated up to 27% of resistance at an ex vivo IOP of 10 mmHg (equal to 18 mmHg in vivo), and at an ex vivo IOP in the range of 20–50 mmHg, it eliminated as much as 62–82% of the resistance.[52] Subsequent experiments confirmed these findings[53] as trabeculotomy decreased the resistance by 49% at an IOP of 7 mmHg and by 71% at an IOP of 25 mmHg. The conclusion of these studies is that the removal of TM at a low IOP results in minor improvements.

Visualization

Ab-interno trabeculotomy (AIT) is performed under a goniolens, of which several kinds are commercially available. These lenses are modified versions of the Swan Jacob Lens, and they differ in the field of view, handle length, image magnification, and extent of corneal contact. Some of these goniolenses have been designed specifically to improve eyeball stability. Recently, a two-mirror goniolens with a static 45° field of view, the Ocular Upright 1.3× Surgical Gonioprism (Ocular Instruments, Bellevue, WA, USA), was presented.[54] It redirects the oblique gonioscopy image to the coaxial "cataract-surgery" view, reducing the need for tilting the microscope.

The lens should be docked gently onto the corneal surface to avoid compression on the cornea and forming Descemet's folds, which preclude visualization. To facilitate this, manufacturers provide additional equipment. The Volk Transcend Vold Gonio (TVG) Surgical Lens (Accutome, Malvern, PA, USA) consists of a main handle, a fixation ring, and a balancing lens, which is suspended by a separate pendular handle that endures the compression. The Ocular Hill Surgical Gonioprism (Ocular Instruments) has a marginal lip at the base of the lens for fixating the eyeball. The disposable iPrism Clip view stabilizer (Glaukos Corp., San Clemente, CA, USA) is an accessory made specifically to snap onto the lens base; it possesses atraumatic surface protrusions and an extended base, which are designed to stabilize the globe effectively.

Ab-Externo and Ab-Interno Trabeculotomy

Trabeculotomy, classically performed using an ab-externo approach, can also be performed using a clean corneal approach (AIT), owing to recent developments. AIT was first introduced in 2014 by Grover et al.[55,56] In this method, a 360-degree incision that disrupts the first layer of the TM is made. The procedure is performed ab-interno under gonioscopy and via temporal and superonasal/inferonasal paracentesis with a microcatheter or a suture.[57,58] Better known as gonioscopy-assisted transluminal trabeculotomy (GATT), this method makes performing trabeculotomy possible without the need for conjunctival or scleral incisions. Briefly, a temporal corneal incision is made and the nasal-angle structures are visualized using direct gonioscopy. A goniotomy is performed in the nasal quadrants, and microsurgical forceps are used to introduce a suture or a catheter (ie, iScience Interventional Corp., Menlo Park, CA, USA) into SC. Thereafter, the microcatheter or suture is circumferentially advanced into SC, until the distal end reaches the goniotomy point, following which it is retrieved. Thereby, a 360° trabeculotomy is performed. In two previous studies, the reported success rates of GATT was 68% and 100% in young children and infants with congenital glaucoma.[56] Grover et al[56] reported that in cases of juvenile glaucoma, the IOP dropped from 27.3 to 14.8 mmHg 12 months after GATT, and the medication burden declined from 2.6 to 0.86. In a study of adult patients, Grover et al[57] reported an IOP drop of 11.1 mmHg and 1.1 fewer glaucoma medications administered at 12 months after GATT for primary open-angle glaucoma (POAG). In patients with secondary open-angle glaucoma (SOAG; ie, pseudoexfoliative, pigmentary, uveitic, and steroid-induced glaucoma) in the same study, the average decreases in IOP and glaucoma medications were 19.9 mmHg and 1.9, respectively, at 12 months. Two years after GATT, an IOP drop in patients with POAG of 9.2 mmHg (37.3%) and a decline in medication burden of 1.43 were observed.[57] In patients with SOAG, at 24 months, an IOP decline of 14.1 mmHg (49.8%) was observed and 2.0 fewer medications were administered.[57] Rahmatnejad et al[59] did not observe a difference in the decrease in IOP between patients with POAG and SOAG. In that study, 66 patients were followed up for 11.9 months, on average. The overall success rate (IOP < 21 mmHg) was 63.0%. One year after GATT, the IOP dropped from 26.1 ± 9.9 mmHg to 14.6 ± 4.7 mmHg (44%), and the medication burden lessened from 3.1 ± 1.1 to 1.2 ± 0.9. Baykara et al[58] reported a statistically significant average decrease in IOP from 34.2 ± 10.6 mmHg to 24.3 ± 11.7 mmHg (65.9% ± 10.7%), 6 months after GATT with phacoemulsification for patients with POAG. The medication burden was also reduced from 3.8 ± 0.4 to 0.3 ± 0.7. Aktas et al[60] examined 65 patients with POAG and 39 with SOAG who had undergone GATT over a mean follow-up of 19.4 ± 8.1 (range, 6 to 37) months. The effect of GATT in their study was contrary to that observed by Grover et al,[55–57] in that participants with POAG had a larger decrease in IOP versus patients with SOAG at the 18-month observation period (40.1% vs 27.6%). The medication burden at the end of follow-up did not differ between patients with POAG and SOAG, and overall surgical success (IOP < 21 mmHg) was achieved in 87 of 104 (83.7%) cases. The most frequent postoperative complication in all the above-mentioned studies was hyphema; in Grover et al,[56] the rate of hyphema after the first week was 38%, and after 1 month it was 6%.

Trabectome

The Trabectome® electrosurgical device (MicroSurgical Technology, Redmond, WA, USA) was approved "for use with compatible electrosurgical instruments in low power microsurgical applications for the removal, destruction and coagulation of tissue" by the US Food and Drug Administration in 2004.[61] It can be used for AIT, using a bipolar, 550-kHz electrode to ablate 30–180° of TM, which enables irrigation during dual-blade goniotomy.[62] The trabectome comprises a disposable handpiece attached to a console that provides irrigation, aspiration, and electrocautery. Similar to the modern phacoemulsification machines, a foot pedal is used to control these actions. The trabectome is designed for the permanent ablation and removal of a strip of TM and the inner wall of SC, leaving the rest of the outflow system (the outer wall of SC, CCs, and aqueous veins) intact. It is also designed to minimize the development of anterior synechiae that would result in closure of the cleft. The 19.5-gauge tip is designed to fit through a 1.6-mm-or-larger corneal incision. A footplate, insulated with a proprietary multilayered polymer, is located at the tip of the handpiece, which is designed to prevent thermal and electrical damage to surrounding tissues. The distal tip of the device is pointed to allow for insertion into SC, and the footplate connects the tissues with the bipolar electrodes. An aspiration port near the tip is used to remove the ablated tissue and debris, while the irrigation port is used to maintain the IOP and dissipate heat generated during cauterization.[63] A strip of TM and inner wall of SC, straddling from 80° to 100°, is ablated and aspirated afterwards. During the procedure, the surgeon is seated temporally to the operated eye and the ablation is initiated at 0.8 mW. Up to 90° of tissue can be ablated in both sides. Following removal of the tissue, a viscoadaptive substance can be injected into the anterior chamber to minimize blood reflux from SC. Studies that compared the relationship between the area of ablation and postoperative IOP decrease did not reveal any statistically significant differences.[64] Intraoperative hyphema is desired during AIT and confirms the successful "unroofing" of SC. In traditional goniotomy or trabeculotomy, particles of the ruptured tissue remain after the procedure. Using the trabectome, tissue debris is simultaneously removed, which reduces the risk of inflammation and scarring.

The overall average success rate (defined as IOP < 21 mmHg, a 20% decrease, and no reoperation needed) in a study by Khan et al[67] was 61 ± 17% at 1 year, and 46 ± 34% at 2 years. According to the authors of a review and meta-analysis,[15] combining phacoemulsification with AIT using the trabectome yielded a surgical success rate of 85 ± 17% after 1 year (n=6) and 85 ± 7% after 2 years (n=2). They found a 27% drop in the IOP postoperatively (21 ± 1.31 mmHg), and an even larger drop to the final follow-up (6.24 ± 1.98 mmHg); 0.76 ± 0.35 fewer medications were required, on average, following the surgery. After AIT with the trabectome, IOP was lower by an average of 31%, for a postoperative IOP of 15 mmHg. This allowed for a reduction in the number of IOP-lowering medications required to less than 1. After 2 years of follow-up, the average success rate was 66%.[15]

In previous studies, AIT with the trabectome was compared to the conventional filtration surgery (trabeculectomy with mitomycin C); the IOP decreased 52–76% in the latter, but only 30–35% in the former.[65,66] In another study, combined phacoemulsification and AIT was compared with phacoemulsification and the insertion of two iStents; after 12 months, the IOP dropped to less than 18 mmHg in 14% of patients following the former procedure and in 39% following the latter.[67]

Finally, the rate of vision-threatening complications using the trabectome is < 1%.[66,68] To date, there have been no randomized controlled trials involving the trabectome, and the largest available data set is from a study that was sponsored by the device manufacturer.[69] In summary, AIT using the trabectome is estimated to decrease the IOP by approximately 36% to a final average of around 16 mmHg and enables a decrease in the medication burden to less than 1.

Ab-Interno Canaloplasty

The safety and efficacy of ab-interno canaloplasty (ABiC) was studied by Gallardo et al in 2018.[70] Ab-externo canaloplasty was modified to provide an ab-interno approach to SC through a 1.8-mm clear corneal incision. ABiC enables access, catheterization, and viscodilation of all aspects of the outflow resistance—the TM, SC, and the distal outflow system, beginning with the CCs (Video 1). The main modification is the lack of a tensioning suture, which is inserted into SC in classic canaloplasty, and the conjunctiva is preserved for subsequent surgery, if needed.[71,72] Injection of viscoelastic (Healon® or Healon GV®, Johnson & Johnson Surgical Vision, Inc., Santa Ana, CA, USA) during insertion of the iTrack™ 250A canaloplasty microcatheter (Ellex Medical Lasers Ltd., Adelaide, Australia) allows compressed and herniated tissue of the TM to separately withdraw from CCs. The indication for ABiC is mild-to-moderate glaucoma, and contraindications include neovascular glaucoma, a closed- or a narrow-angle, peripheral anterior synechiae, and narrow-angle glaucoma. ABiC can also be performed in conjunction with phacoemulsification.[73] Davids et al[74] observed statistically significant reductions in IOP at all follow-ups over a 12-month period and there were no major perioperative complications to report; however, the number of glaucoma medications required at 12 months did not differ from the preoperative number. Thus, this technique does not seem to reduce dependence on glaucoma therapy, which should be considered.

Kahook Dual Blade Device

The Kahook Dual Blade® (KDB; New World Medical, Inc., Rancho Cucamonga, CA, USA) is designed for the removal of the TM while minimizing collateral damage. It consists of a sharp blade allowing for smooth access into SC. Once inserted into the canal, the device is capable of removing the TM with minimal damage.[75] The KDB is introduced into the anterior chamber via an ab-interno approach. Incision of the TM may be conducted using several techniques: mark-and-meet, outside-in, or inside-out, the first of which is outlined below (Video 2).

Under gonioscopic visualization, the tip is used to engage the TM at a 10° angle to SC, to mark the excision endpoint. Thereafter, the KDB is disengaged, rotated 180°, and re-engaged at 3 to 4 clock hours from the initial incision site, again with the tip at a 10° angle to SC. Thereafter, the footplate is seated and the dual blades are advanced through the planned excision points to reach the initial mark point. The ramp at the distal end of the KDB elevates the TM tissue and guides it toward the blades on either side of the device for clean incision, easy removal, and minimal damage to adjacent structures. This is possible thanks to the design of the angle of the distal cutting surface and shaft size of the device.

Sieck et al[76] studied the IOP-lowering effect of KDB goniotomy alone or combined with phacoemulsification in glaucoma patients. At 12 months, the success rate was 71.8% versus 68.8% for the phaco-KDB group and KDB-alone group, respectively. In the phaco-KDB group, at 12 months, the IOP dropped from 16.7 ± 0.4 mmHg on 1.9 ± 0.1 medications to 13.8 ± 0.4 mmHg on 1.5 ± 0.1 medications. In the KDB-alone group, at 12 months, the IOP declined from 20.4 ± 1.3 mmHg to 14.1 ± 0.9 mmHg. The number of IOP medications dropped from 3.1 ± 0.2 to 2.3 ± 0.4 at the end of follow-up. In a study by Dorairaj et al,[77] the effect of phaco-KDB was investigated in angle-closure glaucoma participants. The mean IOP was 25.5 ± 0.7 mmHg, preoperatively, and reduced by 12.3 ± 0.73 mmHg at month 6 of follow-up. Preoperatively, the medication burden was 2.3 ± 0.1, which dropped at month 6 by 2.2 ± 0.12. At month 6, 92.9% of eyes exhibited an IOP ≤ 18 mmHg and 100% exhibited an IOP reduction of ≥20%.

ElMallah et al[78] studied the efficacy of KDB in a multicenter study with a 12-month follow-up in patients, most (86%) of whom had mild-to-severe POAG. In their study, the preoperative IOP was 21.6 ± 0.8 mmHg, and the mean medication burden at baseline was 2.6 ± 0.2. After 12 months, the IOP dropped by 3.9 mmHg (19.3%) and the mean reduction in medication burden was 0.3 (12.5%). In six cases (14.3%), additional glaucoma surgery was required within the 12-month follow-up period.

Combined Gonioscopy-Assisted Transluminal Trabeculotomy with Ab-Interno Canaloplasty

Recently, Al Habash et al[79] reported 12-month results of GATT combined with ABiC. The first step in GATT-ABiC is the creation of a portside incision directed toward the nasal angle. After adjustment of the patient's head, a Volk TVG Surgical Lens of the surgical microscope is used to identify the nasal-angle landmarks. A small (2 mm in width), localized goniotomy is performed horizontally in the nasal angle to gain access to SC. Thereafter, an iTrack™ microcatheter with an illuminated tip is inserted into SC and is catheterized 360° circumferentially using microsurgical forceps, with injection of Healon®/Healon GV®. After cannulation of the entire canal, the microcatheter's distal end is removed through the main corneal incision. The proximal part is introduced into the anterior chamber and 360° GATT is performed. The viscoelastic is aspirated with the irrigation/aspiration probe; however, a small amount may be left to prevent blood outflow from SC. In their study of 19 patients (20 eyes),[79] the success rate was 100%. The preoperative IOP was 19.75 ± 4.68 mmHg; thereafter, it declined to 13.30 ± 1.30 mmHg (a 32.7% reduction) at 12 months postoperatively. The medication burden before surgery was 3.4; after 12 months, it dropped to 1.1. None of the operated participants required additional glaucoma surgery. Hyphema was present in six cases in the first postoperative week. Also, three eyes exhibited IOP spikes that normalized by the end of the first postoperative month.

Discussion

MIGS devices and instrumentation are developed to lower the IOP and are considered safer and more effective methods compared to the traditional, full-thickness filtration surgeries. SC-based procedures are effective in lowering the IOP in eyes with different types of glaucoma. Similar to most other MIGS procedures, canal-based procedures require a clear corneal incision that can be combined with phacoemulsification. One of its main advantages is the lack of bleb formation, reducing the risk of fibrosis and endophthalmitis. When the hypotensive effect is not as expected, the eye remains naive to classic glaucoma procedures, and bleb-based filtration surgery remains an option. However, SC-based MIGS procedures are not without drawbacks. It is worth mentioning that GATT can only be used for trabeculotomy; the TM tissue is not removed during this procedure. Transient efficacy of GATT in adults is most probably due to postoperative regeneration, scarring, and formation of anterior synechiae.[59] Post-surgical repairing of residual TM may indicate the regeneration of TM and subsequently may increase the AH outflow. Some authors reported that the goniotomy area was covered with granular tissue within 4 months of surgery.[80]

Theoretically, using the trabectome, successful tissue removal, and ablation of the edges of the incision helps prevent the closure of the surgical cleft, postoperative fibrosis, and inflammation caused by residual tissue fragments in the anterior chamber angle. However, with the trabectome system, an electrocautery unit and disposable handpieces are required. Therefore, its operating cost may limit its utility in resource-poor areas. In this respect, the KDB is more economical for the treatment of glaucoma.

The trabectome can also cause thermal damage to the adjacent tissues, and removal of the TM using the manual "gonioscraper" also causes injury to the adjacent tissues, including the splitting of the posterior wall of SC.

Seibold et al,[75] in their research on corneoscleral rims from human donors, used the KDB for incision of the TM. Thereafter, specimens were examined histologically and compared to those obtained using goniotomy with a microvitreoretinal (MVR) blade and cautery with the trabectome. They observed a full-thickness incision through the TM caused by the MVR blade. The amount of removed tissue was minimal with large residuals of TM on either side of the incision. In addition, the procedure resulted in damage to the adjacent sclera. The trabectome produced a similar opening in the TM, but also resulted in residual TM tissue, as well as thermal damage to the residual TM leaflets. Specimens treated with the KDB exhibited complete TM-tissue removal and no substantial damage to adjacent tissues. Use of the KDB, MVR blade, and trabectome all result in a similar reduction in IOP. The number of degrees treated did not correlate with the level of decrease in IOP for any of the devices.[73]

Wang et al[81] used anterior segment optical coherence tomography (AS-OCT) to compare the intraoperative angle stability and postoperative outflow yielded by two AIT devices, with or without active aspiration and irrigation, in enucleated porcine eyes. Angle stability was determined by measuring the degree of the nasal angle and the anterior chamber depth (ACD). For this, a passive dual blade goniectome (a KDB) and an active dual-blade goniectome (aDBG) were used. Using the aDBG, the nasal angle remained wide open during the surgery (above 90°) and did not change until surgery was completed. In contrast, using the KDB, the ACD was less stable and the angle continuously narrowed by 40 ± 12%. However, canalograms revealed a similar degree of access to SC using the two techniques. AS-OCT revealed that anterior chamber maintenance was improved due to active irrigation and aspiration. Use of aDBG in the study's training model also improved ease of handling. The immediate postoperative outflow using each device was improved.[81] One of the disadvantages is that, in theory, use of the trabectome and the KDB will not decrease the IOP under the low-teens in mmHg. On the other hand, certain procedures—such as trabecular micro-bypass and SC stents—are indicated for patients with mild and moderate open-angle glaucoma. The KDB is not limited to a certain severity or type of glaucoma, and its effectiveness in moderate-to-severe POAG has been demonstrated.[61]

One aspect that requires investigation is the impact of the elimination of the filtering role of the TM on the other eye tissues. It is important to determine the exact extent of tissue removal for the optimal balance in the IOP-lowering effect and preservation of the filtering action of the TM.

Beyond doubt, elucidation of the most effective technique for AIT requires more randomized controlled trials. This in turn will offer guidance for surgeons in the selection of the surgical intervention most suitable for each individual patient.

Future developments in the field of AIT may include intra- and postoperative imaging of SC and distal pathways using AS-OCT. Ideally, preoperative evaluation could be used to identify regions near CCs that are collapsed, and intraoperative imaging could be used to ablate TM in those regions. Canalography or AS-OCT could be used postoperatively to identify the source of obstruction to AH outflow. Finally, adjunctive use of canal-based procedures requires further research, such as for cases where trabeculectomy is unsuccessful.

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