ARTICLE

Perspectives in trabecular surgery

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Abstract

The aim of trabecular surgery is to selectively combat the diseased structure central to the pathogenesis of chronic open-angle glaucoma, thereby reducing potential hazards during and after conventional filtering procedures. This overview considers new techniques in *ab interno* trabecular surgery. Special emphasis is placed on the description of each novel technique, its instrumentation, presumed mechanism of action and clinical results. Trabecular aspiration is evaluated as a method of clearing intertrabecular spaces of extracellular debris in pseudoexfoliation glaucoma with or without simultaneous cataract surgery or goniocurettage, while laser trabecular ablation is discussed for the treatment of absolute glaucomas. Where corneal haze has formed visualisation of the anterior chamber angle structures and trabecular surgery is performed with the aid of a microendoscope. Although the results are very promising it should be understood that some of these procedures are still in the experimental phase and are undergoing careful clinical evaluation, leaving plenty of room for refinements and further developments.

Key words Goniocurettage, Microendoscopy, Trabecular aspiration, Trabecular photoablation

Enormous progress has been made in understanding the complexity of the underlying causes of chronic open-angle glaucoma. However, indisputable concepts for effective treatment are still rare. To date, conventional filtering surgery remains the mainstay of surgical therapy in the management of glaucoma not controlled by medication.[1] Unfortunately, treatments involving full-thickness filtration are scarcely selective since healthy structures not primarily involved in the disease process are subject to surgical intervention. The application of adjunctive antimetabolites for inhibition of undesired episcleral fibroblastic proliferation dramatically increased the success rates for filtering procedures, but had the disadvantage of exacerbating serious side-effects, such as flat anterior chambers, prolonged post-operative hypotony and late endophthalmitis from infected filtering blebs.[2,3]

Mircosurgery on Schlemm's canal and the human aqueous outflow system for controlling intraocular pressure (IOP) in chronic open-angle glaucoma has been evolving over the past few decades. Theoretical considerations indicate that production of approximately 10 to 15 fistulae, each 10 μm in diameter, between the anterior chamber and Schlemm's canal should restore normal outflow facility in open-angle glaucoma.[4] The basis for most of the current approaches to microsurgery of Schlemm's canal is the finding by Grant[5] that the largest proportion of resistance to outflow is located within the trabecular meshwork, namely the cribriform layer, and can be eliminated by incising the trabecular meshwork and entering Schlemm's canal. If one agrees that the site of the pathological resistance to aqueous humour outflow is this tissue, its partial removal, taking the utmost possible care not to damage the surrounding chamber angle structures, could be a new alternative in antiglaucomatous surgery. This sort of selective non-penetrating trabecular surgery would be equivalent to internal filtration surgery without transscleral drainage of aqueous humour into the subconjunctival space, and would thereby reduce the incidence of post-operative complications typically associated with filtering procedures.

This review discusses different *ab interno* trabecular microsurgical techniques that are designed to facilitate outflow along its natural pathway. Each new technique is described in detail, newly developed instrumentation is discussed, and the presumed mechanisms of action are outlined. However, the reader must understand that none of these new microsurgical procedures threatens to replace conventional filtering approaches, since they are still in the experimental phase and under careful clinical evaluation, and there is plenty of room left for further refinements and developments. We hope this article will give impetus to the search for alternative strategies in antiglaucomatous surgery, and focus attention more closely on the diseased target structure in chronic open-angle glaucoma: the trabecular meshwork.

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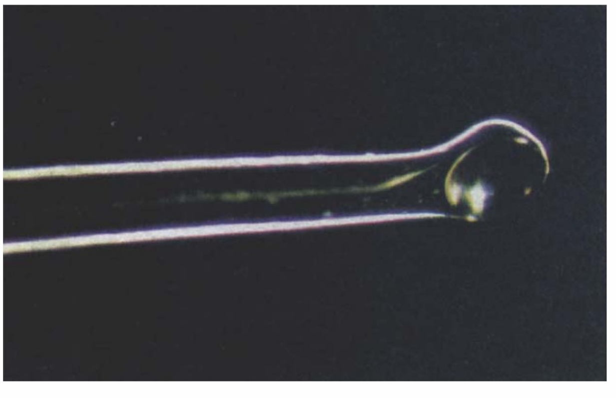
Goniocurettage

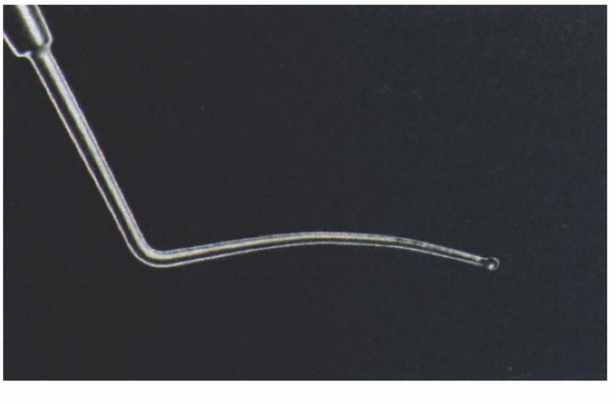
The underlying concept of goniocurettage is to remove rather than incise or disrupt pathologically altered trabecular meshwork and to open a route for aqueous humour to egress either into Schlemm's canal or, where the external wall of the canal is damaged, to ooze out through microsplittings in the posterior scleral wall.[6] The procedure is conceptually similar to goniotomy, except that trabecular tissue is scaped away from the scleral sulcus using an instrument similar to a microchalazion curette (Fig. 1). The gonioscraper consists of a small handle and a slightly convex arm for intraocular use and closely resembles a cyclodialysis spatula. However, the tip of the instrument is shaped like a minature bowl, 300 μm in diameter, with sharpened edges. To abrade clockwise and counter-clockwise, the scoop is vertically angled at 90° to either side.

Goniocurettage is usually performed under direct visualisation of the anterior chamber angle through an operating microscope and a surgical gonioscopy lens (Fig. 2). Following injection of viscoelastic, the gonioscraper is inserted into the anterior chamber through a clear corneal incision and directed against the trabecular meshwork on the opposite side. The scraper is lightly passed over 2 to 3 clock-hours to either side of the nasal circumference of the chamber angle. Great care is taken while peeling off the uveal meshwork not to traumatise adjacent intraocular structures, such as the corneal endothelium or the base of the iris. Intraoperatively, ragged strings of trabecular tissue can be seen to be removed by gonioabrasion, leaving an irregular pattern of a glistening white band corresponding to the denuded grey-white scleral sulcus (Fig. 3). At the end of the procedure, viscoelastic along with abraded trabecular debris is removed by means of irrigation-aspiration.

Morphological analysis of the treatment zones in human donor eyes clearly indicated the potential efficacy of goniocurettage for completely removing the trabecular meshwork.[6] From light microscopy of histological sections it is evident that, in addition to the peeling of the trabecular meshwork, goniocurettage also causes damage to intracanalicular septa and the endothelium of the external wall of Schlemm's canal, and in some instances a disruption along the posterior wall of Schlemm's canal. Flaps of uveal tissue, capable of returning to their predissection position, were not observed in the specimens. Scanning electron microscopy shows that the trabecular meshwork is pulled away from its attachments, leaving ragged structures of Schlemm's canal within the scleral sulcus exposing bare sclera (Fig. 4).



(a)



(b)

Fig. 1. *(a) The tip of the 'gonioscraper'. The external diameter of the bowl is 300 μm and its edges are sharpened. (b) The intraocular arm of the gonioscraper is convex to avoid inadvertent damage to the iris-lens diaphragm.*

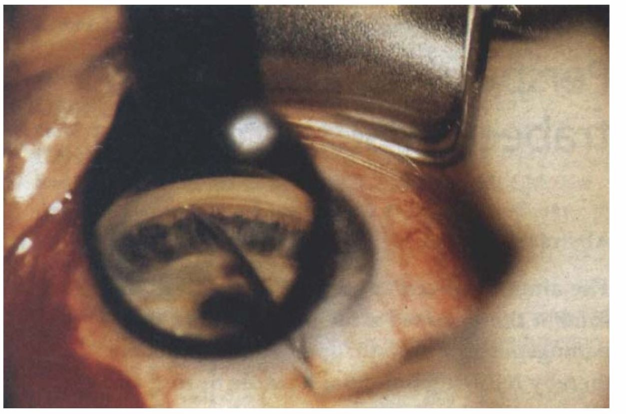


Fig. 2. Ab interno *goniocurettage is performed with the aid of an operating microscope under gonioscopic observation.*

Fig. 3. *After gonioabrasion, an irregular pattern of a glistening white band corresponding to the 'denuded' grey-white sulcus scleralis appears (black arrows).*

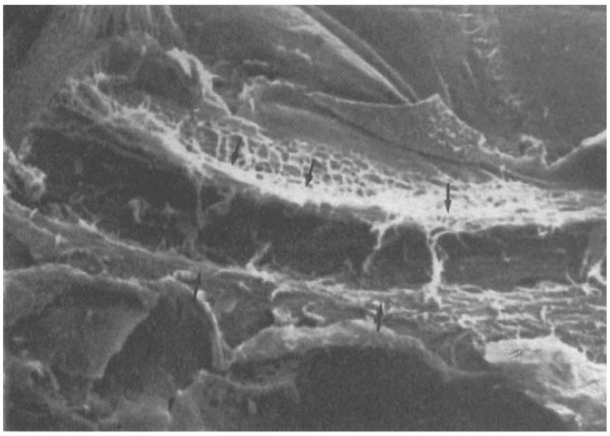


Fig. 4. *Scanning electron microscopy shows the deep furrow within the anterior chamber angle, leaving ragged structures of Schlemm's canal within the scleral sulcus. The furrow that follows goniocurettage is shown between black arrows.*

Recently, we initiated a prospective, non-randomised study to elucidate the long-term outcome of goniocurettage for advanced cases of open-angle glaucoma.[7] Patients with intractable glaucoma who met the inclusion criteria of uncontrolled IOP (> 25 mmHg) despite maximum tolerated medical therapy and a history of at least one failed filtering procedure were offered enrolment in the study. Exclusion criteria were a best-corrected visual acuity of better than 20/200; a history of uveitis, herpetic keratitis, ocular trauma, or narrow angle, traumatic or rubeotic glaucoma; previous antimetabolite treatment; previous cyclodestructive procedures; and an age of less than 40 years. Surgical success was defined as a post-operative IOP of 19 mmHg or less with one topical pressure-reducing agent allowed. Failures were defined as IOP below 6 mmHg or greater than 19 mmHg, and the necessity of more than one adjunctive topical medication or repeated antiglaucoma surgical intervention.

Between December 1993 and December 1994 a total of 25 patients (25 eyes) met the eligibility requirements and were treated by means of goniocurettage. Ages at the time of treatment ranged from 50 to 89 years. Follow-up averaged 32.6 ± 8.1 months (range 30–45 months). Overall success was achieved in 15 eyes (60%), with 5 eyes (20%) being controlled without medication and 10 eyes (40%) still requiring a single adjunctive antiglaucoma medication. The mean IOP before surgery was 34.7 ± 7.1 mmHg (± SD) (range 29–48 mmHg) and the mean number of medications was 2.2 ± 0.56 (± SD). Among the 15 successfully treated patients, the mean IOP was 17.7 ± 3.1 mmHg (± SD) (range 10–19 mmHg) and the mean (± SD) number of medications 0.63 ± 0.29 at the final visit. In 10 eyes (40%) the surgical procedures did not meet the success criteria. Four of these eyes still suffered from an uncontrolled IOP ranging from 20 to 24 mmHg. Further surgical intervention was refused by these patients owing to advanced age and deteriorating general health. In the remaining 6 eyes that failed to obtain satisfactory post-operative pressure, control could only be attained by additional topical antiglaucomatous medication. Systemic carbonic anhydrase inhibitors, however, could be discontinued in all eyes. Five of these 6 eyes with multiple antiglaucomatous medications were eventually treated using repeated cyclodestructive procedures.

Complications included perforations of prominent chamber angle vessels during surgery in 4 eyes (16%), followed by sustained anterior chamber angle bleeding in 2 eyes (8%). In the latter 2 cases surgery could not be completed, because the view of the trabecular meshwork was obstructed. Two weeks later, when all residual blood had disappeared, the same sector was retreated successfully. A reflux of blood from Schlemm's canal into the treatment area occurred in 22 eyes (88%), but had no further sequelae. Blood reflux from Schlemm's canal was taken as an intraoperative indicator of full-thickness perforation of the trabecular meshwork. In 5 eyes (20%) a localised Descemet's membrane detachment at the treatment site occurred, but did not produce any corneal haze. Transscleral perforation of the endoprobe, bleb formation, peripheral synechiae or progression of cataract formation were not among the observed side-effects. Transient phases of hypotony (IOP in the 0–6 mmHg range), choroidal effusion or flattening of the anterior chamber were also not observed. Intraocular inflammation was not prominent after surgery and no marked fibrinous reaction occurred.

In contrast to established trabecular surgical modalities, such as goniotomy or trabeculotomy, goniocurettage disrupts and removes larger segments of abnormally thickened trabecular pillars by scraping tissue off the scleral sulcus. Similar concepts of selective tissue-removing goniosurgery have been described by others.[7,8] In these earlier studies, the trabecular meshwork was either excised using a trabeculectome[7] or scraped away with the flat side of a goniotomy blade.[8] The latter technique, known as trabeculodialysis, was reported to be especially useful in cases of secondary inflammatory glaucoma where the trabecular tissue was felt to be more friable and easier to scrape away.[8] In contrast, in conventional goniotomy or trabeculotomy remnants of uveal tissue tend to fall back into place, producing a sort of 'relapsing folding door effect'. This may cause a 'filling-in' followed by secondary fibroproliferation, and eventually result in early failure.[9,10]

Our analysis of the surgical results of goniocurettage demonstrates the effectiveness of this novel procedure in a substantial percentage of eyes with uncontrolled glaucoma after previous failed trabeculectomies. The overall success rate of 60% with a follow-up period of up to 45 months signals clinical relevance. However, only 20% were controlled without medication. Moderate bleeding into the chamber angle was a regular event in correct goniocurettage. It resulted from a reflux of blood from Schlemm's canal, which is continuous with the episcleral veins. When IOP drops below the episcleral venous pressure during surgery, the blood flows back along the pressure gradient into the anterior chamber. As a rule, bleeding subsides when IOP is regained. The minimal amount of blood staining the chamber angle could be seen to disappear within 2 or 3 days after surgery. However, inadvertent damage to prominent vessels within the chamber angle created a more serious intraoperative complication. Marked bleeding within the anterior chamber angle occurred in 16% cases leading to interruption of the procedure in 8%. Even careful observation of the target area cannot prevent this in every case. Tears in Descemet's membrane might be caused by the tip of the probe when it comes too close to the endothelium during rotation. Descemet's tears were usually small and were not followed by corneal oedema. Descemet's tears may, however, remain visible for a long period of time when blood-stained. Serious problems such as a shallow anterior chamber, choroidal haemorrhage or detachment, endophthalmitis, and leakage of aqueous humour under the conjunctiva did not occur after goniocurettage.

In conclusion, this prospective study indicates that goniocurettage is an effective surgical treatment for various forms of chronic open-angle glaucoma, even in eyes with previously failed trabeculectomies. It is independent of conjunctival wound healing responses and associated with a relatively low risk profile. Although post-operative pressure levels after goniocurettage remain in the high teens, even with medication, this new procedure may in the future be considered as an alternative surgical treatment in selected cases of glaucoma. Further studies on glaucoma cases with an overall better prognosis and an evaluation of the effects of goniocurettage on visual field testing are required.

Laser trabecular ablation

Since laser trabeculopuncture was introduced by Krasnov in 1973,[11] various lasers, such as the argon or Nd:YAG laser have been used in trabecular surgery. However, the effectiveness of these procedures decreases with time.[12,13] Berlin and associates[14] were the first to investigate the potential for photoablation of the trabecular meshwork using a XeCl-excimer laser, emitting at 308 nm, which can be used in conjunction with an optical fibre system. Vogel and co-workers[15] found that in 4 of 6 glaucomatous eyes IOP was reduced by 11 mmHg over a follow-up period of 5 months, whereas in 2 patients the IOP increased by 2 mmHg despite additional antiglaucomatous medication. However, it seems that the high initial outlay and running costs of such gas laser modules, as well as the potential hazards of intraocularly applied ultraviolet radiation, may render them unsuitable for routine use.

Hill and associates[16,17] have recently proposed a promising method for treating the trabecular meshwork directly. They described the use of photoablative mid-infrared lasers to create multiple micro-openings through the trabecular meshwork into Schlemm's canal with minimum collateral thermal damage. The authors achieved smooth ablations of trabecular tissue for the macropulsed Er:YAG (2.94 μm) and the Er:YSSG (2.79 μm) laser and termed the procedure laser trabecular ablation. Radiation emitted from mid-infrared lasers is known to elicit a relatively narrow zone of thermal damage in biological tissue, with little mechanical stress. Among these the Er:YAG laser, emitting at a wavelength close to the absorption peak of water in the mid-infrared spectral region, has a short absorption length (25 μm) in water-containing tissue and ablates with minimal thermal damage to contiguous structures.[18,19] The Er:YAG laser thus seems to emit at the most favourable wavelength. It has been suggested that the removal of a larger segment of the trabecular meshwork in laser trabecular ablation may impair wound repair mechanisms and be another cause of surgical failure.[17]

Laser trabecular ablation in porcine cadaver eyes, using a macropulsed Er:YAG laser (200 μs; 5 mJ), resulted in full-thickness ablation craters, with consistent ablation widths of 200–300 μm; collateral thermal damage was less than 30 μm (Fig. 5). Moreover, outflow facility measurements revealed a significant increase from 0.128 ± 0.041 μm min^{-1} $mmHg^{-1}$ in controls to 0.308 ± 0.093 μl min^{-1} $mmHg^{-1}$ in treated eyes, thereby lowering outflow resistance by 70% from baseline – an achievement of clinical relevance.[20]

Although *in vivo* studies in rabbits revealed that ablation craters in the trabecular meshwork closed up within less than 60 days,[21] preliminary results of laser trabecular ablation in adult open-angle glaucoma are promising. Dietlein and co-workers[22] performed *ab interno* Er:YAG laser trabecular aspiration in 14 patients suffering from terminal optic nerve atrophy due to medically uncontrolled open-angle glaucoma, with a maximum follow-up of 14 months. Under gonioscopic observation each patient received 15 to 20 single laser pulses (6 mJ) to the trabeculum delivered via a 320 μm quartz fibre endoprobe (Fig. 6). No patient was treated more than once, and all experienced a significant decrease in IOP and reduction in adjunctive medication. As a rule, reflux of blood from Schlemm's canal occurred at the site of laser ablation. Moderate reflux bleeding was

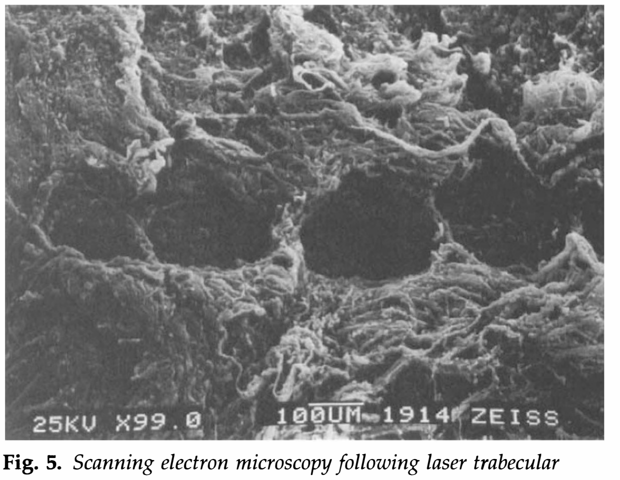


Fig. 5. *Scanning electron microscopy following laser trabecular ablation in porcine cadaver eyes. The macropulsed Er:YAG laser ablation results in full-thickness ablation craters with ablation widths varying between 200 and 300 μm; collateral thermal damage is less than 30 μm.*

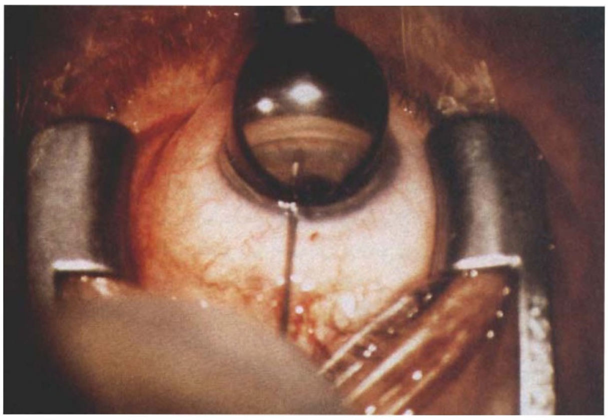


Fig. 6. *Under gonioscopic observation the quartz fibre tip of the endoprobe is inserted into the anterior chamber and directed against the trabeculum. The ablation process is initiated under tissue–instrument contact.*

assessed as an intraoperative sign of full-thickness perforation of Schlemm's canal, which is continuous with episcleral veins. No patient had heavy bleeding, hyphaema formation or undue inflammation post-operatively. The minimal amount of blood staining of the chamber angle could be seen to disappear within 2–3 days after surgery. Melamed and associates[23,24] also reported blood reflux as an intraoperative result of photodisruptive openings into Schlemm's canal. Post-operative gonioscopy of the treatment area revealed neighbouring ablation craters within the trabecular meshwork, easily identified in most patients by a distinct loss of pigmentation (Fig. 7). Long-term studies on laser trabecular ablation in adult glaucoma are now being performed to assess the full potential of this promising procedure.

Microendoscopic trabecular surgery

Of great importance to the success of trabecular surgery is a clear cornea to observe and identify the fine details of anterior chamber angle structures. Unfortunately, the scarring and corneal oedema frequently associated with IOP dysregulation hamper the gonioscopic view of the anterior chamber angle in many cases. Removal of the cloudy corneal epithelium does not always improve visibility, so that gonioscopic identification of the anterior chamber angle structures is not possible in every case. Intraocular microendoscopy is an exciting development that affords the surgeon new opportunities in the management of vitroretinal disease,[25] cyclophotocoagulation,[26] complicated transscleral intraocular lens fixation,[27] and possibly in the management of antiglaucomatous trabecular surgery. Following earlier *in vitro* studies, anterior segment microendoscopy has already been successfully applied as a diagnostic tool[28,29] or in combination with various trabecular microsurgical procedures.[30,31]

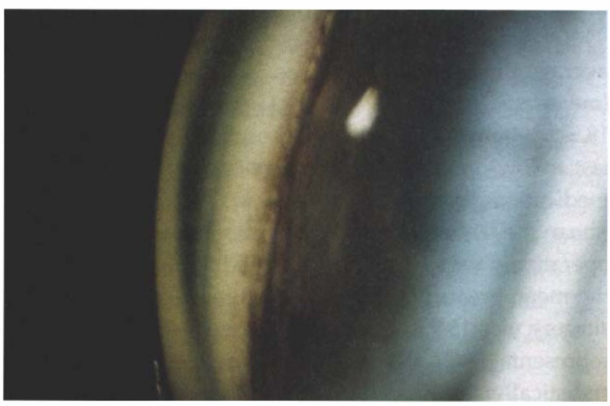


Fig. 7. *Post-operative gonioscopy of the treatment area reveals neighbouring ablation craters within the trabecular meshwork, easily identified by a distinct loss of trabecular pigmentation.*

Recently, we conducted a prospective, non-randomised study in human glaucomatous eyes in order to assess the surgical technique, practicability, surgical outcome and intraoperative complication rate of microendoscopic trabecular surgery.[32] In 15 patients with medically uncontrolled open-angle glaucoma and advanced corneal opacification, visualisation of the anterior chamber angle structures and trabecular surgery was performed under microendoscopic control. Exclusion criteria were a visual acuity of more than 20/200 in the treated eye, worse visual function in the contralateral eye, a history of uveitis, herpetic keratitis, ocular trauma, narrow angle, traumatic or rubeotic glaucoma and young age (less than 40 years).

In this study, we used an ophthalmic microendoscope (Endo Optiks, Little Silver, NJ), which is basically a triple-function endoscope consisting of three fibre groupings: the image guide (3000 and 10 000 pixels), the light guide and a diode laser guide. In the current experiments the laser guide was disconnected. This endoscope came with a 20 gauge (0.88 mm diameter) probe, providing a 70° field of view and a depth of focus ranging from 0.5 to 15 mm. Additionally, an 18 gauge (1.2 mm diameter) endoscope with the same three components was used. The field of view in this iteration is 110° with a depth of focus ranging from 1 to 30 mm. The advantages of the larger-diameter endoscope are the greater clarity provided by the image bundle and the panoramic field of view that it creates. The microendoscope is used in conjunction with a light source, video camera, television monitor and video recorder. Both intraocular endoscopes were gas-sterilised before surgery. Trabecular surgery was performed using either laser trabecular ablation or goniocurettage. Patients were randomly assigned to treatment with one of the two techniques.

Seven eyes were treated by means of laser trabecular ablation and 8 eyes by means of goniocurettage. The average age at surgery was 69.7 ± 9.1 years (mean ± SD) (range 55–83 years). Twelve of 15 patients had undergone previous antiglaucoma procedures involving the conjunctiva. Four eyes had failed trabeculectomy with adjunctive mitomycin C and 8 eyes had argon laser trabeculoplasty before trabecular surgery. The average follow-up time was 21.1 ± 3.0 months (range 19–28 months).

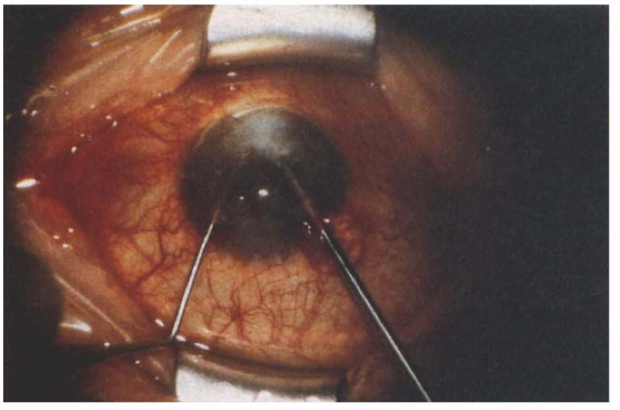


Fig. 8. *Following the injection of viscoelastic, the microendoscope is introduced into the anterior chamber through a 1.2 mm paralimbal clear corneal tunnel incision.*

Intraoperatively, the microendoscope was introduced into the anterior chamber through a 1.2 mm paralimbal clear corneal tunnel incision followed by the injection of viscoelastic (Fig. 8). While the endoscope was pushed forward to the pupillary margin, the posterior cornea and anterior lens surface simultaneously came into view on the video screen. The goniocurette or the laser endoprobe entered the anterior chamber through a second paralimbal paracentesis. Following insertion the surgical instruments came instantly into view on the monitor, helping to avoid inadvertent damage to any of the internal structures as the endoprobes were advanced into the anterior chamber angle. When using the Er:YAG laser the He–Ne aiming beam of the laser was readily identified on the trabecular meshwork, and the tip of the microendoscope moved between 0.5 to 7.0 mm away from the chamber angle structures (Fig. 9).

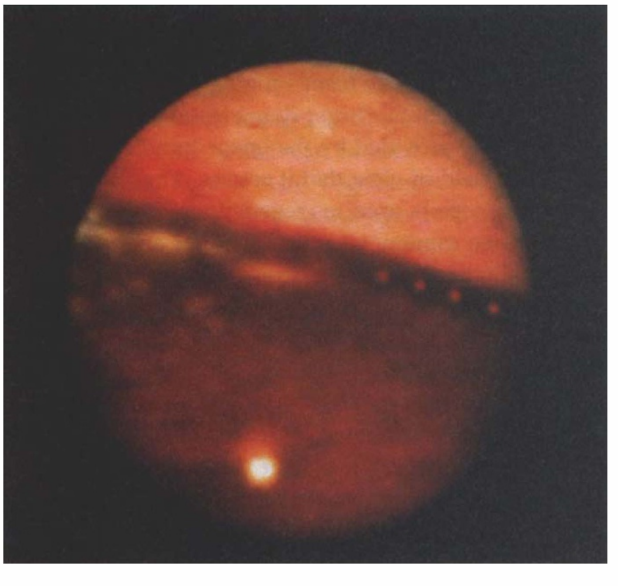


Fig. 9. *Endoscopic view of the anterior chamber angle as the laser probe approaches the trabecular meshwork. Laser ablation craters can be distinguished by a 'whitening' of the trabeculum. Resolution and clarity of the endoscopic picture are somewhat higher when observed in real time than they are in a freeze-frame.*

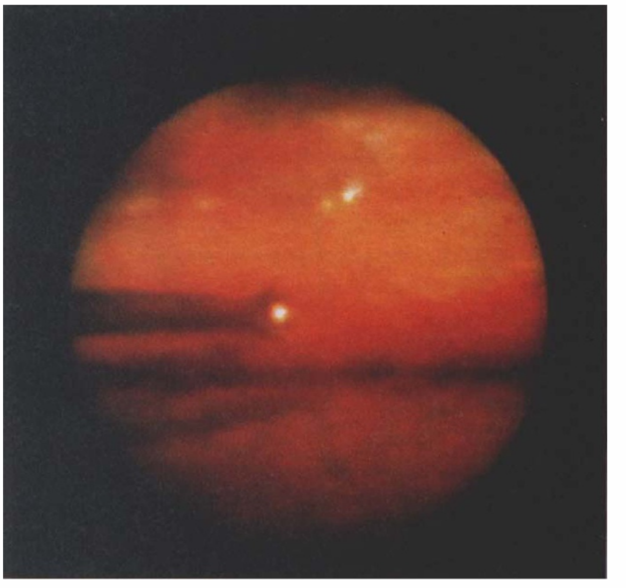


Fig. 10. *Endoscopic view of the anterior chamber angle as the goniocurette approaches the trabecular meshwork. The white reflex at the tip of the instrument is the bowl of the curette.*

Laser trabecular ablation at 6 mJ pulse energy reproducibly yielded round to oval tissue whitening post-operatively. At the time of treatment, all 7 eyes demonstrated low-thermal photovaporisation of the trabecular meshwork and various degrees of exposure of the outer wall of Schlemm's canal. A reflux of blood from Schlemm's canal into the anterior chamber was observed at the treatment site. Gas bubble formation and heavy pigment dispersion did not, however, occur. No frank hyphaemas were detected.

In endoscopically controlled goniocurettage the minicurette was observed to pass alongside the scleral spur, tending to push trabecular tissue ahead of it, but usually leaving the anterior portion of the trabecular meshwork and Schwalbe's line in place (Fig. 10). Endoscopically, it was possible to see strings of trabecular tissue being removed intraoperatively, leaving a white band corresponding to the scleral sulcus. Complications included a small peripheral descemetolysis and a reflux of blood from Schlemm's canal within the treatment area, neither of which had any further sequelae.

IOP was reduced in all eyes as a result of surgery. The average pre-operative IOP was 34.5 ± 6.1 mmHg (mean ± SD) (range 27–46 mmHg), compared with 18.5 ± 3.0 mmHg (range 13–23 mmHg) after surgery at last follow-up. The average number of glaucoma medications used before surgery was 2.3 ± 0.6 (mean ± SD) while the average number used post-operatively was 1.1 ± 0.7. Considering all treated eyes, the mean pressure reduction after endoscopic trabecular surgery was 15.9 ± 4.3 mmHg (range 9–23 mmHg). This represents a 46% decrease from baseline (Δ%), which is statistically significant ($p < 0.05$). There was no statistically significant difference in pressure-reducing effect between eyes receiving laser goniopuncture and those treated by goniocurettage. Transient phases of hypotony (IOP in the 0–6 mmHg range), choroidal effusion or flattening of the anterior chamber were not observed.

Since the surgeon was applying microendoscopy of the anterior segment of the eye for the first time, great caution had to be exercised during the procedure. Video monitor control and non-stereoscopic viewing demanded particular technical adaption. In our series, however, substantial complications related to the endoscopy itself were not observed. Patients enrolled in this study were treated only once and experienced a decrease in IOP and reduction in adjunctive medication. Moderate reflux bleeding occurred in most patients and was assessed as an intraoperative sign of full-thickness perforation of Schlemm's canal. None was detected to have heavy bleeding, hyphaema formation or undue inflammatory response. The minimal amount of blood staining of the chamber angle was seen to disappear within 2 or 3 days after surgery. However, before this procedure can be considered as a viable concept in glaucoma surgery, i.e. in the treatment of primary infantile glaucoma, further experience in a greater number of patients is needed.

Trabecular aspiration

Despite the many different causes of secondary obstructive glaucomas, such as pseudoexfoliation (PEX), pigmentary, phacolytic and silicone oil glaucoma, all these conditions develop via the same pathogenetic pathway: IOP dysregulation arising from trabecular obstruction. Extraneous material within the anterior chamber eventually causes obstruction of the trabecular outflow channel, leading to a non-physiological pressure increase. Assuming that the primary pathogenetic factor in secondary obstructive glaucoma is obstruction of filtering pores of the trabecular meshwork (which, over time, become increasingly clogged by deposits of debris and pigment granules), a surgical procedure that relieves the uveal meshwork of its obstruction should, in theory, be effective.

In previous studies, we described a new form of non-filtering glaucoma surgery – trabecular aspiration – designed to facilitate trabecular outflow in secondary glaucomas such as PEX glaucoma.[33–35] Morphological analysis of the trabecular aspirate clearly illustrated the efficacy of trabecular aspiration for removing pretrabecular and intertrabecular debris.[33] Trabecular aspiration in combination with extracapsular cataract extraction substantially lowered the IOP in a small group of cataractous eyes complicated by medically uncontrollable PEX glaucoma.[34] Moreover, when applied as primary therapeutic surgical intervention in PEX glaucoma, this procedure also turned out to be an effective tool for pressure management.[35] These early results were obtained with a form of trabecular aspiration requiring a single-handed irrigation-aspiration device and a deep anterior chamber intraoperatively in order to avoid contact with the anterior surface of the crystalline lens in phakic eyes

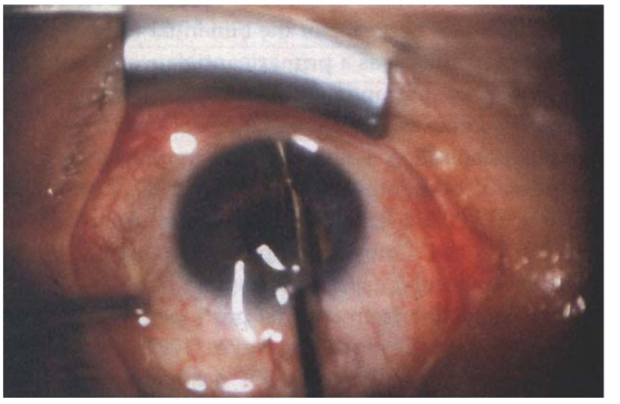


Fig. 11. *Single-handed irrigation-aspiration device designed to sweep over the trabecular meshwork with negative suction pressure, thereby clearing the intertrabecular filtering pores in pseudoexfoliation glaucoma.*

(Fig. 11). As a refinement of the single-handed aspiration technique, which is easy and safe to use in combination with lens extraction, we now recommend the bimanual technique, in which irrigation and aspiration are separated from each other to further increase the safety and efficacy of the procedure (Fig. 12).[36]

The opening of the trabecular aspirator is 400 μm wide and angled horizontally at 45° to comply with the configuration of the anterior chamber angle. The intracameral portion of the aspiration cannula is convex to prevent damage to the iris-lens diaphragm during the intraocular manoeuvre. For irrigation, a second cannula with an outlet diameter of 650 μm is used. The surgical procedure is performed under the operating microscope without the use of a gonioscope. Intracameral access is gained by two self-sealing paracenteses at the limbus. The aspirator probe is pushed transcamerally into the opposite chamber angle and is directed against the trabeculum. Under gentle instrument–tissue contact, suction pressure of 100 and 200 mmHg is applied over 4 to 5 clock-hours of the inferior and temporal circumference of the chamber angle. Thereafter, irrigation and aspiration probes are exchanged between hands so that the contralateral side of the chamber angle is accessible for aspiration treatment. Switching probes yields a potential treatment area of 270°.

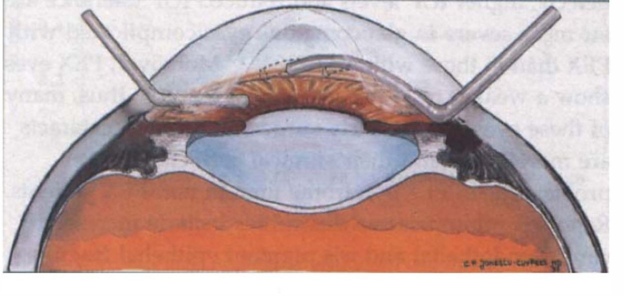


Fig. 12. *Artist's rendering of the intraoperative view of the bimanual technique of trabecular aspiration. The aspirator is pushed deep into the anterior chamber angle, while the irrigation probe just enters the eye. Note the convexity of the aspirator's intraocular arm. Under constant tissue contact and negative suction pressure, the aspirator sweeps over the trabecular meshwork.*

The safety and efficacy of the bimanual technique of trabecular aspiration as a primary antiglaucoma surgical procedure was substantiated in a prospective study.[36] Twenty-two eyes of 18 PEX patients were treated by trabecular aspiration. Follow-up was continued for a minimum of 14 months and a maximum of 27 months (mean ± SD, 20.2 ± 4.5 months). The mean pretreatment IOP was 31.4 ± 7.1 mmHg (range 23–42 mmHg). Bimanual trabecular aspiration resulted in a consistent pressure reduction from the first post-operative week in 19 eyes (86%). In the remaining 3 eyes (12.5%), trabecular aspiration neither reduced the IOP nor had any positive effect on the glaucoma medication post-operatively. Most interestingly, all these patients had had argon laser trabeculoplasty (ALT) prior to the aspiration procedure.

With regard to the successfully treated eyes ($n = 19$), the mean pressure reduction after surgery was 12.6 ± 0.7 mmHg (range 6–22 mmHg) at the final visit. At 6 months, the mean reduction in IOP from baseline was 12.5 mmHg. The mean reduction was 12.7 mmHg at 1 year and 13.6 mmHg at 18 months. Before surgery, these 19 treated eyes required 2.3 glaucoma medications on average to control IOP. Post-operatively, the average number of medications was 0.3 at 6 months and 1.5 at 18 months. At 6 months, 75% of patients were using no medication, and at 18 months 45% of patients were well controlled without glaucoma medication.

Trabecular aspiration was not associated with any serious intraoperative complications or long-lasting side-effects. In 10 eyes (47%) a blood reflux from Schlemm's canal was observed intraoperatively, with 3 eyes (14%) showing small blot clots in the chamber angle post-operatively. However, no anterior chamber angle bleeding, hyphaema or marked inflammatory reaction was noted. In 4 eyes (19%), minor descemetolyses at the treatment site occurred. No corneal haze was associated with the treatment, and no episodes of hypotony, flattened anterior chamber depth or choroidal effusion were observed.

The clinical importance of PEX syndrome lies in its reported association with open-angle glaucoma and age-related lens opacities.[37–39] PEX syndrome as such does not induce optic nerve head damage but presents a relevant risk factor for IOP elevation.[40] Various studies suggest that optic nerve head damage, visual field defects, higher IOP levels and reduced IOP tolerance are far more severe in glaucomatous eyes complicated with PEX than in those without PEX.[41–43] Moreover, PEX eyes show a weaker response to medical therapy; thus, many of these eyes require early surgery.[44] Besides, cataracts are more likely and their surgical correction more problematic in PEX syndrome than in non-PEX patients. Reported intraoperative difficulties include increased corneo-endothelial and iris pigment epithelial fragility, increased vascular leakage and inflammation, fibrin deposition, zonular instability often associated with zonular dialysis and vitreous loss.[45–49] Post-operative problems may include an increased risk of synechia formation and pupillary block, rapid development of capsular thickening requiring laser capsulotomy, cystoid macular oedema in the presence of capsular trauma resulting in vitreous loss, transient IOP spikes, and progression of glaucoma optic neuropathy.[48,49] Consequently, PEX glaucoma coexisting with cataract poses a management dilemma. On the one hand, considering the potential intraoperative and post-operative complications in exfoliative eyes it would seem better to avoid or minimise perioperative problems by keeping the surgical procedure as simple as possible, i.e. favouring a two-stage approach rather than a combined operation. On the other hand, a combined approach eliminates extra morbidity and costs, reduces the risk of transient post-operative pressure spikes, and may result in faster rehabilitation.

In a recent study,[50] we compared a randomised series of combined phacoemulsification, IOL implantation and trabecular aspiration (asp+IOL) with a series of phacoemulsification and IOL implantation alone (IOL-alone). Performing the cataract incision temporally reduced the development of against-the-rule astigmatism and spared the superotemporal conjunctiva in both groups, making subsequent filtering procedures easier to perform. Trabecular-aspiration-treated eyes were also compared with a case-matched group that had undergone a standard glaucoma triple procedure (triple procedure). With the combined cataract and filtering approach, a temporal clear corneal incision also reduces inflammation around the filter, increasing the chances of a successful glaucoma procedure. We evaluated the impact of the two different approaches (i.e. filtering versus non-filtering approach) in glaucoma triple procedure on post-operative visual acuity, the efficacy of the glaucoma procedure in reducing IOP and dependence on glaucoma medication, and complications experienced. Further evaluation of the efficacy of combined cataract and glaucoma surgery should enhance the surgeon's ability to make an informed choice for each cataract patient with PEX.

The study group consisted of 74 eyes of 74 cataract patients with concurrent PEX glaucoma undergoing phacoemulsification with IOL implantation. Forty-eight consecutive patients were randomised to either adjunctive trabecular aspiration (asp+IOL group, 26 eyes) or no trabecular aspiration (IOL-alone group; 22 eyes). All patients who fulfilled the inclusion criteria but opted against enrolment in this prospective randomised study of trabecular microscopy were treated by a standard glaucoma triple procedure (triple procedure) with conventional trabeculectomy without the use of antimetabolites. For each asp+IOL case a standard triple procedure case that best matched the asp+IOL group with respect to age, race, gender, cup:disc (C:D) ratio, and any systemic diseases (diabetes mellitus, hypertension) was chosen for comparison.

Failure was defined as the need for additional antiglaucomatous surgical or laser treatment (except for laser suture lysis), including bleb needling revision, or the need for more than one medication to reduce IOP to the target pressure as described by Shin *et al.*[51] The target pressure was set before surgery and implemented in

Table 1. *Mean intraocular pressure (mmHg) and mean number of glaucoma medications*

	triple procedure			asp+IOL			IOL-alone			p value[a]	
Time	IOP	Meds	n	IOP	Meds	n	IOP	Meds	$2n$	IOP	Meds
Pre-operative	32.5 ± 7.3	2.1 ± 0.9	26	31.9 ± 8.0	2.1 ± 0.9	26	32.0 ± 7.7	2.2 ± 0.8	22	0.87	0.87
1 week	14.3 ± 4.8	0	26	18.3 ± 2.1	0	26	21.6 ± 4.4	0.3 ± 0.4	22	0.02	0.056
2 weeks	14.8 ± 3.6	0	26	18.2 ± 2.0	0.1 ± 0.3	26	21.3 ± 3.1	0.4 ± 0.5	22	0.02	0.067
1 month	17.4 ± 2.4	0.1 ± 0.3	26	18.1 ± 2.2	0.4 ± 0.5	26	21.3 ± 3.1	0.6 ± 0.7	22	0.04	0.04
3 months	18.0 ± 2.4	0.2 ± 0.4	26	18.4 ± 2.3	0.4 ± 0.5	26	18.9 ± 1.9	0.7 ± 0.7	20	0.45	0.02
6 months	18.1 ± 2.3	0.2 ± 0.4	26	18.3 ± 2.2	0.4 ± 0.5	26	18.5 ± 1.7	0.9 ± 0.5	17	0.42	0.02
1 year	18.3 ± 2.3	0.3 ± 0.5	26	18.3 ± 2.2	0.6 ± 0.6	26	18.4 ± 1.7	0.8 ± 0.6	16	0.43	0.01
2 years	19.0 ± 2.7	0.4 ± 0.6	26	18.4 ± 2.3	0.7 ± 0.6	26	18.0 ± 1.3	1.1 ± 0.8	13	0.54	0.002
2.5 years	18.5 ± 2.7	0.4 ± 0.6	13	18.8 + 2.5	0.8 + 0.6	13	19.1 ± 1.9	1.5 ± 0.7	7	0.12	0.001
p value[b]	0.0001	0.0001		0.0001	0.0001		0.0001	0.001			

IOP, intraocular pressure; Meds, number of glaucoma medications. IOP and Meds are expressed as mean ± standard deviation. Triple procedure = phacoemulsification + IOL implantation + trabeculectomy; asp+IOL = phacoemulsifcation + IOL implantation + trabecular aspiration; IOL-alone = phacoemulsification + IOL implantation.
[a]Kruskal–Wallis test.
[b]ANOVA.

accordance with our clinical practice. In the majority of patients undergoing long-term therapy, we regarded the IOPs at which there was no progression of the glaucomatous optic nerve damage as acceptable target pressures. In the absence of information on previous stability, the initial target pressure was based on the severity of existing optic nerve damage. Follow-up was artificially terminated when subsequent non-glaucoma surgery was performed.

The post-operative IOPs were significantly lower than the pre-operative IOPs at all times in all three groups ($p = 0.0001$) (Table 1). The mean pre-operative and post-operative IOPs at 3, 6, 12, 24 and 30 months were not significantly different in the three groups. However, mean post-operative IOPs at 1, 2 and 4 weeks did differ significantly ($p < 0.05$). The mean IOPs in the triple procedure group at 1 and 2 weeks (14.3 ± 4.8 and 14.8 ± 3.6 mmHg) were significantly lower than in the asp+IOL group (18.3 ± 2.1 and 18.2 ± 2.0 mmHg) and the IOL-alone group (21.6 ± 4.4 and 21.3 ± 3.1 mmHg). At 1 month post-operatively, triple procedure eyes (17.4 ± 2.4 mmHg) still had significantly lower IOPs than the IOL-alone group (21.3 ± 3.1 mmHg) The percentage of patients who had pressure spikes of greater than 21 mmHg in the first 2 weeks or first month post-operatively was significantly higher in the IOL-alone group (9 eyes, 41%) than in the asp+IOL group (2 eyes, 7%) or triple procedure group (1 eye, 3%). In contrast, patients with transient ocular hypotony (IOP < 6 mmHg) were seen only in the triple procedure group (3 eyes, 11%). Pressure spikes greater than 5 mmHg above pre-operative IOP occurred in neither group.

Pre-operatively, the mean number of glaucoma medications did not differ significantly between the groups. Overall, the post-operative mean number of glaucoma medications was significantly lower than the pre-operative number of glaucoma medications at all times. The mean number of glaucoma medications was significantly lower in the triple procedure group compared with the asp+IOL group from the first post-operative month onwards ($p = 0.001$). Similarly, the mean number of medication was significantly lower in the triple procedure group and asp+IOL group than in the IOL-alone group at all times after the first post-operative month. The percentage of patients who were controlled without additional glaucoma medication at 6 months and 2 years after surgery was lowest in the triple procedure eyes (22 eyes (84%) and 22 eyes (65%) respectively), followed by the asp + IOL group (14 eyes (53%) and 10 eyes (38%) respectively) and IOL-alone group (4 eyes (18%) and 2 eyes (9%) respectively.

Before surgery, best-corrected visual acuity ranged from 20/50 to light perception in each of the three groups. Results of pre-operative and post-operative best-corrected visual acuity did not vary significantly among these three groups, but the ranking system and the Wilcoxon test revealed a statistically significant post-operative improvement in visual acuity in all groups.

The Kaplan–Meier survival plots for all three groups are shown in Fig. 13. Using the Kaplan–Meier survival curve, cumulative life-table success rates for the IOL-alone group were 45% at 6 months and 36% at 1 year and 2 years. In the asp+IOL group the success rates were 89% at 6 months, 71% at 1 year and 64% at 2 years. The

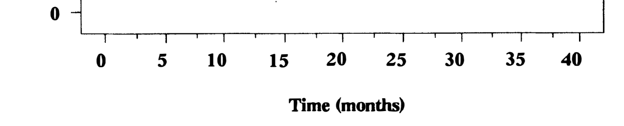


Fig. 13. *Survival plots of phacoemulsifcation and intraocular lens (IOL) implantation alone (IOL-alone), combined trabecular aspiration, phacoemulsification and IOL implantation (asp+IOL) and standard filtering glaucoma triple procedure (triple procedure). There was a significantly higher success rate in the triple procedure group than in the asp+IOL or IOL-alone groups (p = 0.001, log-rank test). There was also a significantly higher success rate in the asp+IOL group than in the IOL-alone group (p = 0.001, log-rank test).*

differences between the two groups were statistically significant ($p = 0.001$). The triple procedure group had cumulative life-table success rates of 92%, 88% and 78% at 6 months, 1 and 2 years post-operatively. The differences in the probability of success were statistically significant when compared with either the asp+IOL or the IOL-alone group ($p = 0.001$).

Intraoperative and post-operative complications are shown in Table 2. Combining all three groups, minor zonulolysis (< 2 clock-hours) occurred during cataract surgery in 10 eyes (6 of them already presenting slight lens subluxation before surgery). Posterior capsule tear without vitreous loss occurred in 2 eyes, while capsular tear with vitreous loss occurred in 1 eye. In all these patients, an intraocular lens (IOL) was securely implanted into the sulcus. Posterior capsule opacification requiring neodymium:YAG-laser capsulotomy arose in 36 eyes. Subclinical IOL decentration was found in 2 eyes, both of which had already had minor zonulolysis intraoperatively. These cataract-surgery-related complications were equally distributed among groups. Hyphaema was the most common complication in the triple procedure group, occurring in 12 eyes (46%) and causing a transient reduction in best-corrected visual acuity in these eyes. None of them, however, required surgical re-intervention, such as lavage of the anterior chamber. Conversely, hyphaema was found in neither the asp+IOL group nor the IOL-alone group. The incidence of fibrinous reaction was significantly higher in the triple procedure group, and was observed in 38%, 19% and 13% of eyes in the triple procedure, asp+IOL and IOL-alone groups, respectively. The difference in the incidence of fibrinous reaction between the asp+IOL group and the IOL-alone group was not significant. Likewise, the prevalence of anterior synechia formation was higher in the triple procedure group (15%) than in the asp+IOL group (8%) and IOL-group (4%). Ocular hypotony (IOP < 6 mmHg) lasting longer than 2 weeks was detected exclusively in the triple procedure group. In the 3 eyes (8%) with hypotony (IOPs ranging from 1 to 4 mmHg), the condition resolved spontaneously without surgical intervention. In the triple procedure group a total of 7 patients (26%) required digital massage of the filtering bleb at the 1 and 2 day post-operative visits, because they had an IOP greater than target pressure. This intervention resulted in adequate lowering of the IOP in 5 patients (19%), so that these patients required no additional intervention. In the remaining 2 eyes (8%) argon laser suture lysis succeeded in lowering the IOP further. Filtering bleb revision (i.e. needling, resection of Tenon's cysts, wound leak) was performed in 3 eyes (11%), and failed to improve filtration in 2 of them (8%). Blood reflux from Schlemm's canal was found only in the asp+IOL group (61%), but did not lead to hyphaema formation or sustained bleeding into the anterior chamber. Likewise, minute descemetolyses without further sequelae were seen in the asp+IOL group.

In the past, various attempts have been made to develop surgical techniques allowing simultaneous cataract and glaucoma surgery. Some authors believe that combined surgery is associated with a higher incidence of complications and less favourable prognosis for IOP control compared with a two-stage approach. One serious problem in the early post-operative phase, besides severe inflammatory or fibrinous reactions, is a flattened anterior chamber. Furthermore, during this hypotensive phase, choroidal detachment, maculopathy and hyphaema can easily develop. Trying to counteract a possible flattening of the anterior chamber in the early

Table 2. *Surgical complications*

	Triple procedure	asp+IOL	IOL-alone
Capsular tear	2 (8%)	–	1 (4%)
Zonular tear	3 (11%)	3 (11%)	4 (9%)
Vitreous loss	–	–	1 (4%)
Blood reflux	–	16 (61%)	–
Hyphaema	12 (46%)	–	–
Fibrinous reaction	10 (38%)	5 (19%)	3 (13%)
Descemetolysis	–	5 (19%)	–
Capsulotomy	12 (46%)	15 (53%)	9 (40%)
Iris prolapse	1 (4%)	–	–
IOL decentration	2 (8%)	–	–
Giant-cell reaction	4 (15%)	2 (8%)	1 (4%)
Anterior synechia	4 (15%)	2 (8%)	1 (4%)
IOP spikes (> 21 mmHg)	1 (3%)	2 (7%)	9 (41%)
Filtering bleb intervention	12 (48%)	–	–
Digital massage	7 (26%)	–	–
Laser suture lysis	2 (8%)	–	–
Surgical bleb revision	3 (11%)	–	–
Ocular hypotony	3 (11%)	–	–
Choroidal detachment	3 (11%)	–	–
Flattening of AC	3 (11%)	–	–
Shifted IOL	1 (4%)	–	–
Positive Seidel test	1 (4%)	–	–
Transient loss of VA	2 (8%)	–	–

Values are the number of eyes (%).
AC, anterior chamber; VA, visual acuity; IOL, intraocular lens.

post-operative phase by filling the chamber with viscoelastics increases the risk of post-operative pressure spikes.

The surgical procedure recommended here offers a solution to this dilemma. With trabecular aspiration in combination with phacoemulsification and IOL implantation a closed system can be maintained throughout surgery and, thereafter, through a simple modification of irrigation-aspiration. Although trabecular aspiration in the glaucoma triple procedure did not achieve target pressure in all patients, especially in the low target pressure range, the risk profile appears to be more favourable in trabecular-aspiration-treated eyes than in the filtering glaucoma triple procedure group. *Ab interno* trabecular aspiration facilitates outflow through the trabecular meshwork and precludes the need for additional episcleral preparation, which can be time-consuming. Moreover, subconjunctival filtration, especially when combined with cataract surgery, can be difficult to titrate. Besides, a temporal clear corneal approach leaves the conjunctiva untouched superiorly for possible future filtration surgery.

Conclusion

The different procedures for microsurgery of Schlemm's canal and a diseased trabecular meshwork, described above, though varying in technique, have the common goal of facilitating outflow along the trabecular meshwork and Schlemm's canal. The theoretical basis for these approaches has long been established. Until recently, however, the clinical potential of Scheie's concept of goniopuncture has not been fully realised, possibly owing to a lack of adequate surgical instrumentation. With the vast improvements in microsurgical equipment and techniques, trabecular surgery, especially in combination with modern laser technology, could revolutionise glaucoma treatment.

Of utmost importance to the success of trabecular surgery is a clear cornea through which the fine detail of anterior chamber angle structures can be seen and identified. Unfortunately, the corneal oedema or opacities frequently associated with IOP dysregulation hamper observation of the anterior chamber angle. Modern microendoscopy facilitates visualisation of the intraocular structures, and even of the anterior chamber angle during invasive trabecular surgery. At present, microendoscopy may still be an unfamiliar technique to most ophthalmologists, who will need to adapt their surgical skills to the new approach. However, once mastered, it will enable them to avoid many intraoperative and even post-operative complications associated with other methods of treatment.

Various attempts have been made to develop surgical techniques allowing simultaneous cataract and glaucoma surgery. Some authors believe that combined surgery is associated with a higher incidence of complications and a less favourable prognosis for IOP control than a two-stage approach. One serious problem in the early post-operative phase, in addition to severe inflammatory or fibrinous reactions, is a flattened anterior chamber. Furthermore, during this hypotensive phase, choroidal detachment, maculopathy and hyphaema can easily develop. Trying to counteract a possible flattening of the anterior chamber in the early post-operative phase by filling the chamber with viscoelastics increases the risk of post-operative pressure spikes developing.

The surgical procedures recommended here offer a solution to this dilemma. As a technically undemanding modification of irrigation-aspiration, trabecular aspiration in combination with phacoemulsification and IOL implantation makes it possible to maintain a closed system throughout surgery and thereafter. Although trabecular aspiration in glaucoma triple procedure did not achieve target pressure in all patients, especially in the low target pressure range, the risk profile appears to be more favourable in the trabecular-aspiration-treated eyes than in the filtering glaucoma triple procedure group. *Ab interno* trabecular aspiration facilitates outflow along the trabecular meshwork and precludes the need for additional episcleral preparation which can be time-consuming. Moreover, subconjunctival filtration, especially when combined with cataract surgery, can be difficult to titrate. Lastly, a clear corneal approach leaves the conjunctiva untouched superiorly for possible future filtration surgery.

Unlike filtering procedures, which can be expected to produce IOP levels in the low teens, IOP levels after trabecular surgery reach the high teens, sometimes even with medication. If the mechanism of lowering IOP levels in trabecular surgery is the relief of outflow resistance in the trabecular meshwork, then post-operative IOP levels in the high teens may simply represent the sum of episcleral venous pressure, intracanalicular resistance, and the resistance to aqueous humour flow of tissue remaining after the operation. As a result, successful trabecular surgery can, at best, only achieve approximate 'normalisation' of IOP levels. Whether this is enough to avoid the development of visual defects even after successful surgical treatment needs to be assessed over longer-term follow-up periods. On the other hand, an assessment of the potential risks of post-operative complications typically associated with full-thickness filtering procedures, such as shallow or flat anterior chamber, choroidal detachment, malignant glaucoma, progression of nuclear cataract and late infection of the filtering bleb were not within the scope of this study of an antiglaucoma procedure. Clearly, we need more clinical experience with these microsurgical techniques to establish the effectiveness and safety of such approaches.

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