Microincisions in cataract surgery

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Improvements in phacoemulsification technology and instrumentation and intraocular lens materials and design have enabled cataract surgery to be performed through incisions smaller than 2.0 mm in external width. This evolution has occurred over time, with new challenges arising at each step of the decrease in incision size. This article reviews the current trend of using increasingly smaller incisions to perform phacoemulsification. Specifically, each facet of phacoemulsification is briefly reviewed from a historical context and then evaluated predominantly from a current perspective to better understand the development of the microincision in cataract surgery. The goal is to help the operating surgeon recognize the potential benefits as well as the potential weaknesses of the smaller incision.

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Currently, cataract surgery is performed through the smallest incision of any surgery on a major organ system in the human body. In most procedures, the incision is merely a portal; however, it is well-recognized that the design and construction of the corneal incision for cataract surgery is fundamental to the functional result of the surgery. Efforts to reduce the incision size to 2.2 mm and smaller have required several innovations in intraocular lens (IOL) design, instrumentation, and phacoemulsification technology. Each step taken in reducing the incision size comes with mixed success but has led ultimately to measurable improvements in outcomes.

TECHNIQUES OF INCISION CREATION

Since 1998, the temporal clear corneal incision (CCI) has been the most commonly used incision in cataract surgery.[1] The current incision has many advantages over its predecessor superior scleral incisions but continues to be improved with emerging technologies including the femtosecond laser.

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The benefits of today's cataract incision include its efficient creation, lack of conjunctival trauma, bloodless operative field, suitability for topical anesthesia, good intraoperative maneuverability, sutureless self-sealing nature, minimal induction of astigmatism, allowance for rapid visual recovery, and nearly immediate stability. Some potential clinical issues remain such as lack of consistency and reproducibility, incompetence under certain intraocular pressure (IOP) extremes, risk for bacterial influx and endophthalmitis, and vulnerability to mechanical or thermal damage from phacoemulsification and IOL insertion.

Architecture

By incorporating both vertical and horizontal elements, multiplane incisions are thought to better resist leakage under pressure extremes.[2–4] Some authors propose that square incisions have particular strength over more rectangular incisions.[5,6] Finally, longer tunnel lengths (ie, 2.0 mm over 1.0 mm) are also more resistant to leakage.[7] However, when too long, manipulations through the incision can result in distortion of the wound and corneal striae, impairing visualization during surgery.

Location

Compared with corneal incisions, scleral incisions are stronger and more self-sealing over longer lengths, more forgiving to stretch and damage, and may

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produce less astigmatism (for constant size) by virtue of their further distance from the visual axis. The exact location of the incision can be varied, affecting these benefits. Locations include posterior limbal,[8] sclerocorneal,[9] and blue-line incisions.[10] While posterior limbal incisions produced an earlier fibroblastic healing response than CCIs,[11] they were also associated with more bleeding and perhaps more intraocular inflammation.[12]

The temporal cornea affords advantages in both accessibility and minimal astigmatic effect[13] compared with superior incisions. Since the superficial horizontal diameter of the cornea is greater than the vertical, temporal incisions are farther from the visual axis and therefore have less astigmatic effect. The incision can be made temporally for consistency and astigmatic neutrality or on the steep axis to affect the final refractive outcome.

Material: Steel Versus Diamond

Most authors agree that the achieved wound architecture is more important than the material used. Diamond-blade advocates enjoy the exceptionally clean incisions, while steel keratome proponents prefer the tactile feedback and perceived control with steel. Disposable blades are affordable, frequently bundled in phaco packs, easily interchangeable for different incision sizes, and presterilized; diamond blades are expensive, require maintenance, and have theoretical prion and toxic anterior segment syndrome risk.

Blades themselves come in different bevels, angulations, steps, and shapes, with each surgeon having his or her favorite. No studies directly compare the benefits of these blade characteristics; however, Calladine et al.[14] report more reproducible length and planar architecture using a blade that had an incision-length measuring guide.

Scanning electron microscopy studies have shown diamond blades to produce cleaner cuts on a cellular level than steel.[15–17] A single-use silicon blade material was also found to be smoother than steel on electron microscopy.[18]

Unenlarged Incision Size

Two issues pertinent to the final incision size are often unrecognized by the surgeon. The first is the simple variability within the manufacture of keratomes. While they are typically within 0.1 mm of their labeled size, considerable range can be found between keratomes labeled as the same size, and any claims of consistency in size to within 0.05 mm do not correspond to true measurements.

The second is the simple movement of the keratome during incision creation. Unless the blade is perfectly placed into and out of the intended incision, movement in the horizontal plane may inadvertently enlarge an incision. Although this enlargement does not appear to affect the clinical stability, it does mean that a surgeon's intended incision is not typically the final measured incision, especially considering the manipulations through the incision during the performance of cataract surgery.

Femtosecond Laser–Assisted Cataract Surgery

As femtosecond laser cataract surgery matures, customization of the incision will evolve with increasing reproducibility.[7] The femtosecond laser allows precision crafting of the lengths, angles, planes, and shapes of CCIs to levels of consistency exceeding any manual technique.

CAPSULORHEXIS CREATION

Although no study has demonstrated superiority of manual capsulorhexis techniques using a smaller incision, numerous tools and devices have been developed to work through the smaller incision to achieve consistent results. In contrast, the femtosecond laser has demonstrated the ability to create a properly centered, properly sized capsulotomy independent of the incision size or location, with an accuracy superior to those created manually.[19] However, capsulotomy creation using this modality in the presence of corneal folds can occasionally lead to an incomplete capsulotomy, with the potential for radial tears.[A]

PHACOEMULSIFICATION

Continuous longitudinal ultrasound (US) has an inherent repulsive characteristic that can cause chatter, induce turbulence, and create substantial heat along the shaft of the phaco needle. Larger bore needles allow greater fluid flow allowing better cooling and transfer of larger fragments of nuclear material. Fortunately, none of the current generation phaco units rely solely on continuous longitudinal power.

Advancements in phacoemulsification modalities include micropulse phacoemulsification. This technology results in less power use and shorter procedure times. In addition, the operating temperature of the needle in the incision is decreased.[20,21] Torsional phacoemulsification (Ozil, Alcon Laboratories, Inc.) provided the next progression, with needle temperature also reduced.[22] The next nonlongitudinal movement, transversal phacoemulsification (Ellips, Abbott Medical Optics, Inc.), yielded a similar effect. Each of these power modulations has resulted in improved ultrasonic efficiency and, most important, can use smaller gauge needles to effectively emulsify nuclear material.

Fluidics

The balance of infusion and aspiration enables the maintenance of chamber stability, cooling of the phaco needle, and efficient translation of the power at the tip to achieve emulsification. Acting as flow restrictors, microincision phaco needles with appropriately matched infusion sleeves inherently improve chamber stability. In a coaxial system, precision of incision size becomes increasingly critical, with too small an incision restricting infusion flow and too large an incision allowing fluid leakage, which decreases effective infusion. Software advances allow greater accuracy in monitoring and, by reducing tubing compliance in the infusion and aspiration lines, improve the replication of desired parameters.

Interaction of the Needle with the Incision

Two sources of heat created during phacoemulsification are of concern: friction against the walls of the incision and flexing of the needle under ultrasonic stress. Coaxial systems rely on flow within the infusion sleeve for cooling. Biaxial phacoemulsification requires that cooling takes place through incision leakage. The critical temperature for an incision burn is 122°F or 45°C.[23]

Decreased flow results in chamber instability and a reduced cooling effect. Thus, significant interruptions in irrigation flow can reduce the effectiveness of any strategy to reduce thermal injury. This can be a result of too small an incision or by the reduction of aspiration flow. Maintaining proper irrigation/aspiration balance can be aided by ensuring that the infusion tubing is properly attached to the phaco handpiece,[B] removing any kinks in the tubing, adjusting the height of the infusion bottle,[24] maintaining adequate fluid in the bottle, and irrigating and aspirating the ophthalmic viscosurgical device out of the needle prior to initiating phacoemulsification.[25] Significant interruptions in irrigation flow can reduce the effectiveness of any strategy to reduce thermal injury.[C]

The effectiveness of biaxial phacoemulsification or sleeveless phaco is based on 2 concepts.[D] Paracentesis-type incisions are flat and assume a shape resembling an ellipse with points as they are opened. Round phaco needles within these incisions inherently have small but adequate fluid leakage at the lateral aspects to enable proper cooling. Also, micropulse power modulation reduced effective heat generation sufficiently to keep the needle temperature below the burn threshold.[26] Osher[E] found that higher flow parameters with smaller needles worked to maintain lower temperatures at the incision.

Corneal Wound Burns

Severe corneal wound burns are rare, and anecdotal reports of etiologies are valuable but do not fully explore the commonalities. Bradley and Olson[27] surveyed 106 surgeons and found the risk for thermal injury to be about 1 in 1000. Comparing technologies, continuous US was the highest risk factor, seven times more likely to produce a burn than micropulse power modulation. For techniques, divide-and-conquer was the highest risk and vertical chop the lowest. The authors noted that most burns occurred during tip occlusion, when cooling fluid flow was reduced to near zero.

More difficult to measure is the intrinsic heat of the needle generated through mechanical stress during ultrasonic movement. Schmutz demonstrated asymmetric heating in the hub, shaft, and tip of the needle, differing in region and magnitude between torsional to transversal US.[28] Schafer[F] has profiled the heating of phaco needles during the various modes of ultrasonic movement and has also shown differential heating along the shaft of the needle.

INTRAOCULAR LENS DESIGNS AND INJECTORS

It is clear that the IOL injection has the greatest effect on incision stability and size.[29–31] The cornea's capacity for stretching, or elastic deformation, is limited and beyond a point can be damaged by excessive stretching.[32,33] This damage has been shown to occur at all levels of the corneal architecture, and the impact on refractive outcomes and incision integrity has been well documented. The relative effect on wound enlargement is influenced by many variables, including the type of insertion (closed versus wound assist),[31] speed of insertion,[29,34] IOL power,[29] and cartridge size and design.[35] Efforts to standardize the insertion speed have led to the development of automated insertion systems.[34]

Other strategies for IOL delivery include the use of a preloaded IOL injector system. Such a system may improve the safety of IOL insertion by reducing the risk for contamination as well as the potential damage from mishandling.

Wound-Assist Insertion

The limits of IOL deformation and cartridge compressibility ultimately constrain the size of the incision. One strategy is to use "wound assist" in which the cartridge tip is applied to the outside or partly into the incision. This directs the compressed IOL through the incision but outside the confines of the cartridge,[30] effectively reducing the necessary incision size by the thickness of the cartridge walls. Studies have shown that wound-assist insertion

Table 1. Optimal wound size of several IOL delivery systems.

Delivery System	Optimal Wound Size (mm)
Alcon	
Monarch II A	3.74[B]
Monarch II B	3.44[B]
Monarch II C	2.96[18,B]
Monarch II D	2.3, 2.4[10,19]
Abbott Medical Optics	
Platinum	3.2[23]
Silver	2.8[21]
Sapphire	3.2, 3.52[22,B]
Emerald	3.2, 3.11[20,B]
Hoya	
iSert	2.4[24]

IOL = intraocular lens

allows smaller post-implantation incisions with less associated wound stretch.[30,31,33] No major IOL manufacturer has recommended wound-assist insertions over cartridge insertions (Table 1). In the future, efforts to control and limit wound stretch may lead to modifications in cartridge design to allow specific and consistent wound entry depth, thus creating a hybrid between full-closed insertion and wound assist at the surface that would enable hydrophobic acrylic IOLs to be inserted through even smaller incisions.

Whichever insertion technique is chosen, it is better to match the initial incision to the post-implantation wound size as the least amount of tissue distortion enables good closure of the incision across its entire length.[32,33,36] Minimizing enlargement and avoiding tears in Descemet membrane and the corneal stroma at the lateral border of the incision result in minimal dislocation of the collagen lamellae and better wound apposition, functional stability, and healing postoperatively.[16,32,36]

Consideration of the final wound size will factor into the injection approach and enable one to recognize the potential for wound damage that could lead to leakage, potential hypotony, and subsequent ingress of contaminated surface fluid.[16,33,36] However, it has not known whether the increase in postoperative endophthalmitis associated with temporal CCIs is connected with contamination associated with the injection technique and damage to the wound.[37,38]

Comparing phacoemulsification/IOL platforms designed specifically for 1.8 mm incision surgery and 2.2 mm incision surgery, Vasavada et al.[G] report influx of trypan blue placed topically on the eye after surgery with the smaller 1.8 mm incision. While no adverse effects were noted clinically, the authors considered that the incision size was too small to accommodate the instrumentations and manipulations, leading to incision tension and stretch. Subsequent rabbit-eye studies demonstrated localized epithelial loss with minimal Descemet detachment in both groups but showed exaggerated stromal damage after IOL insertion in the 1.8 mm group.[39]

TREATING THE INCOMPETENT WOUND

Wound integrity testing after clear cornea cataract surgery is critical due to the association of corneal incisions and endophthalmitis.[40] Although well-crafted triplanar square corneal incisions may be self-sealing in most cases, they may be less so in some instances and warrant further security.

Stromal Hydration

Clinically, most cataract surgeons have experienced the wound-sealing benefit of stromal hydration; it is almost universally effective in stopping wound leakage at the conclusion of surgery. Mifflin et al.[41] show that 50% or more of incisions leaked before hydration but none leaked after hydration. In another stromal hydration study, Calladine and Tanner[42] report higher IOPs 1 hour postoperatively in the stromal hydration group versus the control, likely due to less early microleakage. These higher IOPs may protect from early postoperative hypotony and its potential vacuum effect. Furthermore, Vasavada et al.[43] that the ingress of trypan blue was decreased several-fold by stromal hydration. Nevertheless, inflow of surface fluid has been described despite stromal hydration.[44]

Early opponents of stromal hydration argued that the effect lasted hours only. Optical coherence tomography (OCT) imaging studies[3] have shown stromal hydration to be present at least 24 hours after surgery. Recently, high-resolution Fourier-domain OCT imaging showed the effect lasted for at least 1 week after surgery.[45] These OCT studies also showed distortion of the original wound architecture and an increase in Descemet detachment in the stromal hydration group, leading some to question the benefit of stromal hydration in the future era of "touchless" minimally invasive surgery.[46]

Sutures

Besides the obvious immediate effect of wound closure, many advocate suturing of corneal incisions to minimize the slowly rising endophthalmitis rates observed with transition to sutureless clear cornea surgery. However, the literature is mixed on the role of sutures. Although some studies suggest that sutured corneal incisions are protective of endophthalmitis,[47] others report no such protective benefit from suture placement.[48]

Optical coherence tomography imaging shows no architectural difference between sutured and unsutured wounds in the 1-day to 1-month postoperative period.[49] Surprisingly, May et al.[50] show convincingly that sutured corneal incisions had more India ink influx than unsutured incisions under sudden IOP fluctuations. The authors observe that a single radial 10-0 nylon suture increased inner wound gaping on OCT and conjecture that the suture tract itself contributed to potential infiltration.[51]

Although suture placement may stem leakage if stromal hydration is ineffective or if gross wound distortion is present, placement of a suture to reduce the theoretical risk for endophthalmitis is not supported in the literature. Sutures have the associated problems of increased surgical time, inconsistent effect on astigmatism, and later postoperative removal. Sutures that are left in place can break spontaneously and potentially induce neovascularization and suture abscesses.

Tissue Adhesives

Cyanoacrylates, including the more elastic 2-octyl cyanoacrylate, have been used in vivo[52] for sealing the cataract wound, but foreign body sensation and hyperemia are common. Fibrin adhesive was investigated[53] in eyebank CCIs and found to prevent ingress of India ink and egress of fluid compared with a placebo. However, fibrin adhesives are more difficult to prepare, have a high cost, have the inherent transmission risks of pooled plasma, and have not been studied for intraocular toxicity.

Several novel adhesives are being evaluated experimentally for sealing the corneal incision. They range from biologic to synthetic to combinations or biosynthetics. One promising class of sealants is based on polyethylene glycol (PEG) hydrogel polymers. Cadaver eye studies have shown these PEG ocular bandages to be watertight and highly effective in preventing ingress of fluid through the incision under supraphysiological IOP fluctuations.[54,H] Clinical studies have confirmed these results. There are at least 2 commercially available PEG formulations available for wound closure: Ocuseal liquid ocular bandage (Beaver-Visitec International) and Resure adherent ocular bandage (Ocular Therapeutix, Inc.). At the time of this publication, only Resure has received Food and Drug Administration approval.

SURGICALLY INDUCED ASTIGMATISM

Corneal astigmatism is common, with 35% of patients having 1.00 diopters (D) or more and the majority of these patients having anterior corneal astigmatism in the range of 1.0 to 2.0 D.[55,56]

Although the anterior component of corneal astigmatism has been extensively studied, it also has a posterior component, which has only recently been investigated.[57] In most patients, the anterior corneal astigmatism tends to be with the rule (WTR) with a positive axis in the 90-degree meridian and shifts to against the rule (ATR) (to the horizontal axis) with age. Alternatively, the posterior corneal curvature has an ATR tendency in most age groups and this tends to shift to WTR orientation with age.[58]

Surgically induced astigmatism (SIA) is a vector quantity expressed as a magnitude and a direction The magnitude of the SIA using current small-incision phacoemulsification techniques is between 0.30 D and 1.00 D depending on a number of factors, which will be outlined in this article.[59–62]

Astigmatism: Incision Length and Location

One key virtue of microincisions is their ability to limit SIA. Many studies have looked at incision length and determined that larger incisions cause increased SIA. Comparing 3.2 mm, 4.0 mm, and 5.2 mm CCIs, studies have found that the smaller incisions had 0.50 D less astigmatism and less rotation of the axis of astigmatism.[63,64] In a comparison of 3.0 mm incisions and 2.2 mm and 1.6 mm incisions, the SIA was approximately 0.50 D in the 3.0 mm and almost zero to 0.25 D in incisions of 2.2 mm or less.[65] The most significant comparison of temporal CCIs found that a 1.8 mm incision produced 0.35 D less SIA than a 2.75 mm incision (0.42 D $\pm$ 0.30 [SD] versus 0.77 $\pm$ 0.55 D).[66]

The location of the cataract incision has been shown to significantly influence the amount of SIA. Superior incisions induce the greatest amount of astigmatism followed by superotemporal, nasal, superonasal, and, least of all, temporal. For CCIs, the difference between the greatest and least amount of induced astigmatism is about 0.25 D.[67]

Placing the wound posterior to the cornea also induces less astigmatism. Using the same wound parameters and an incision of 2.2 mm, a posterior limbal incision produced approximately 0.25 D of astigmatism and, more importantly, less variability than a CCI, which can induce 0.68 D.[68] Scleral tunnels produce less astigmatism than limbal and CCIs.[63]

Although much has been published regarding wound architecture and wound integrity, the effect of wound architecture on SIA is less studied. Looking at scleral incisions, a curved or smile incision results in the most SIA followed by a straight, then frown, then Blumenthal type (straight with oblique cuts), and least with a chevron or V-shaped incision.[62,69] Uniplanar incisions have been proposed to induce less SIA than multiplanar incisions.[I]

The SIA is not a static value; it is greatest immediately following surgery and decreases over time. With the

smaller incisions used in phacoemulsification, the SIA has been shown to become stable soon after surgery. Stromal hydration can increase the amount of SIA, and this effect can last up to 1 week postoperatively.[45] At the time of cataract surgery, Descemet membrane detachment, stromal edema, and posterior corneal wound gape occur. Resolution of these changes are a good indication of corneal wound healing; resolution has been reported by 3 months postoperatively.[49] Similarly, stabilization of SIA has been reported at 3 months following surgery.[70] Right and left eyes show similar SIA amplitude but different SIA axis orientation.[63] The SIA is greater in thinner corneas than in thicker ones.[H]

Positional cyclotorsion is important in planning the management of corneal astigmatism. On average, cyclotorsion results in an average of 4 degrees of axis misalignment, 8% of patients having cataract surgery having greater than 10 degrees of rotation.[71] Although positional cyclotorsion affects the axis, it does not have an effect on the mean absolute SIA arising from the cataract incision. This hidden error should be accounted for in evaluating an individual surgeon's postoperative results.[72]

The effect of the surgical incision on the higher-order aberrations (HOAs) of the anterior corneal surface has been studied and found to be clinically insignificant.[73] Evaluation of ocular HOAs report no difference in the root-mean-square value of total HOAs or individual HOAs for spherical aberration, coma, and trefoil when comparing 3.2 mm and a 1.7 mm incisions despite the smaller incision having significantly less SIA.[74]

Several other factors have been shown to influence SIA. The amount of preoperative corneal astigmatism correlates with the amount of SIA.[68] The degree of eccentricity of the anterior corneal surface also correlates with the amount of SIA. A weak association of SIA with age has also been reported; however, the increase is less than 1/8 D across the range of ages 60 years and older.[18] If wound closure is to be considered, the use of fibrin glue adhesives induces less astigmatism than sutures.[75]

SUMMARY

The size and configuration of the cataract incision are challenged by the limitations of working within the confines of the created incision. These factors determine the anatomic stability of the incision and the refractive change the incision induces.

The greatest determinant of the final incision size is currently the IOL and its associated insertion system. While there may be benefits in anatomic stability with smaller incisions, no studies clearly demonstrate an advantage in SIA in reducing incision size below 2.6 mm. Given the recognized variability in manual incision creation, appropriately targeting for a 2.2 mm final incision is more likely to achieve consistency in the desired result.

Every case should be evaluated, and some circumstances may warrant a larger incision to use a larger phaco needle. This applies particularly to cataracts of greater density in which greater amounts of phaco power will be needed for effective emulsification. Continuous phaco power delivery should be avoided, with a reduction in risk associated with chopping techniques.

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FINANCIAL DISCLOSURES

Drs. Dewey, Beiko, Braga-Mele, Nixon, Raviv, and Rosenthal are consultants to Abbott Medical Optics, Inc. Drs. Braga-Mele, Raviv, and Rosenthal are consultants to Alcon Laboratories, Inc. Dr. Nixon is a consultant to Novartis Corp. and Oculus Surgical, Inc. Drs. Raviv and Rosenthal are consultants to Bausch & Lomb. Dr. Rosenthal is a consultant to Rayner Intraocular Lenses, Ltd.

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