Technology needs for corneal transplant surgery

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ABSTRACT

Corneal transplant surgery has undergone numerous modifications over the years with improvements in technique, instrumentation and eye banking. The main goals of corneal transplantation are achieving excellent optical clarity with long-term graft survival. Penetrating, anterior and posterior lamellar surgery along with femtosecond laser technology have partially met these goals, but outcomes are often unpredictable and surgeon dependent. Technology to predictably separate stroma from Descemet's membrane, techniques to minimize endothelial cell loss, improvements in imaging technology and emerging techniques like laser welding that might replace suturing, eventually making corneal transplantation a refractively predictable procedure are on the wish list of the cornea surgeon.

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Over the last few decades, the greatest improvements in the field of Ophthalmology have been the ones, which have improved predictability, reduced individual variability in skill, improved outcomes and hastened rehabilitation. It is easy to envision how technology has improved predictability or improved outcomes but it is strange that one of the requirements of innovation is to reduce variability in individual skill. While it is true that all surgeons are not born equal, the measure of success of any individual procedure would be the ease with which it can be performed by the vast majority of its practitioners, not by the level of difficulty conquered by one exceptionally gifted surgeon. An example of this is refractive surgery, where laser in situ keratomileusis (LASIK) has been by far the most successful and commonly performed surgery worldwide, which is a testament to its accuracy and ease of adaptability [1].

This review of the contribution of technology to the advancement of corneal transplantation and the technology gaps that still exist in the field will address the following:

1. Penetrating keratoplasty (PKP)
2. Anterior lamellar keratoplasty
3. Endothelial keratoplasty
4. Diagnostics
5. Surgical tools

1. PENETRATING KERATOPLASTY

Corneal transplantation, broadly referred to as keratoplasty, has evolved since the beginning of the 20th century, beginning with the first reported clear graft by Edward Zirm in 1905[2], and through the contributions of Castroviejo, Fine, Paton, and many others[3]. By the mid 1970s, keratoplasty was a commonly performed procedure, with increasingly refined techniques. However, since that time, there have been numerous developments in the areas of trephination, suturing, combined procedures, adjunctive aids such as viscoelastics, and treatment of ensuing refractive errors and complications[4, 5].

Though penetrating keratoplasty, or full thickness corneal transplantation has been the most popular kind of corneal transplantation until the last decade, lamellar keratoplasty, partial thickness corneal transplantation, has developed rapidly, both in terms of technique and popularity over the last few years[6].

Barraquer in 1950 laid down the requirements for any keratoplasty and these included replacing only the diseased cornea, restoring optical quality, maintaining integrity of the eye, achieving a predictable refraction and long-term graft survival[7].

Though these still hold true today, only the goal of restoring optical clarity is relatively satisfied by penetrating keratoplasty and the rest of the goals remain unfulfilled thus far.

In spite of all these perceived shortcomings, penetrating keratoplasty remains the most successful organ transplantation performed today and the most common form of corneal transplantation performed today.

Indications

Any disorder of the cornea that impedes the passage of light through it may be an indication for penetrating keratoplasty. These may include conditions like corneal scarring, keratoconus and dystrophies of the cornea (Figure 1).

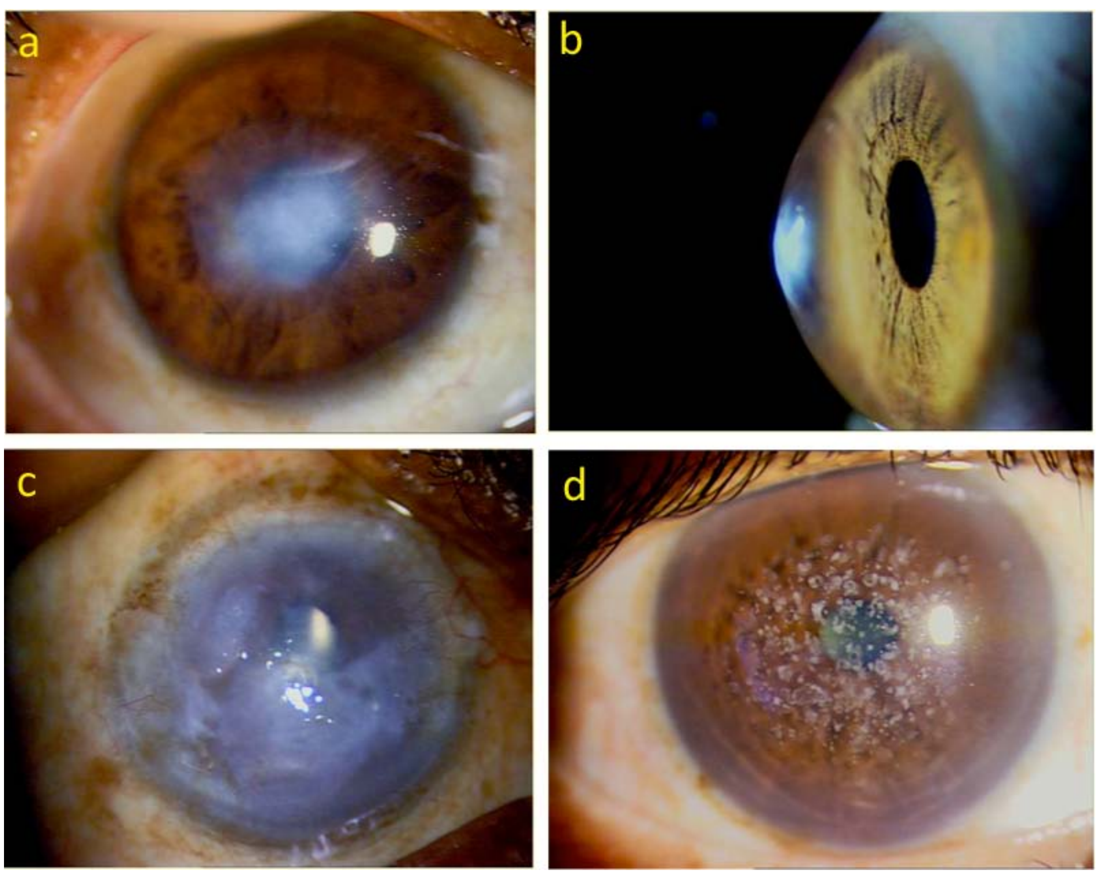

Figure 1: Indications for keratoplasty; a. corneal scar; b. keratoconus; c. corneal edema; d. Granular dystrophy

The indications for keratoplasty have changed over time due to a number of factors. These have included surgical experience and expertise in keratoplasty, treatment of diseases that can prevent the need for keratoplasty like better anti-infectives and better contact lenses, and changing surgical techniques for other diseases like cataract and intraocular lens (IOL surgery[5].

The top three indications for penetrating keratoplasty in developing countries include previously failed grafts, corneal edema and keratoconus, while the top three indications in developing countries are corneal scar, corneal infection and keratoconus[8].

The current procedure of keratoplasty can be divided into three steps

i) Host bed preparation
ii) Donor preparation
iii) Suturing

I) HOST BED PREPARATION

The host cornea is prepared for full thickness transplantation by defining the center of the cornea (often a blind procedure) and trephining a circular portion of central abnormal cornea from the eye. Typical diameters of this trephination range from 7mm to 8.5mm but may be larger or smaller. Many instruments may be used to create this central opening in the cornea. The simplest of these trephines is a hand held circular metal blade of varying diameter with a sharp edge that is placed on the cornea and rotated circularly with downward pressure to achieve a circular opening on the cornea (Figure 2).

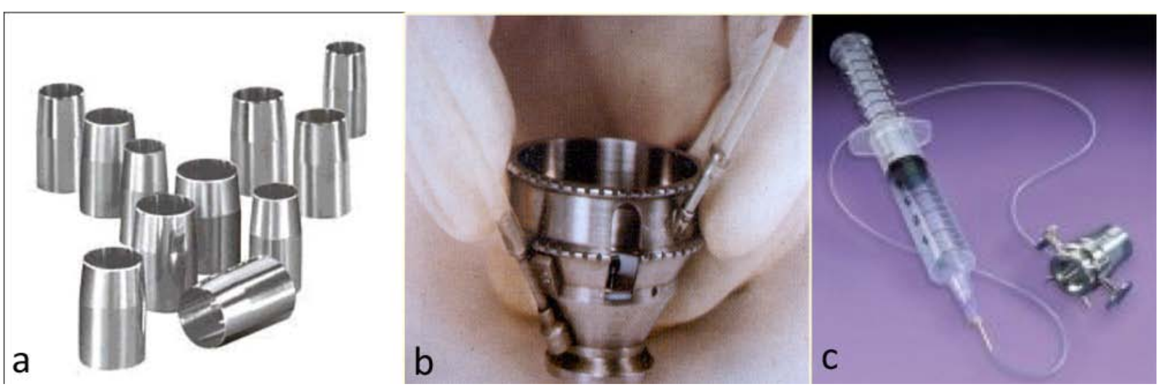

Figure 2: Types of mechanical trephines; a. free hand trephine; b. Hanna trephine; c. Barron vacuum trephine

The main issue with this kind of hand held trephine is the variable edge configuration that is caused by varying intraocular pressure during this procedure. (Figure 3)

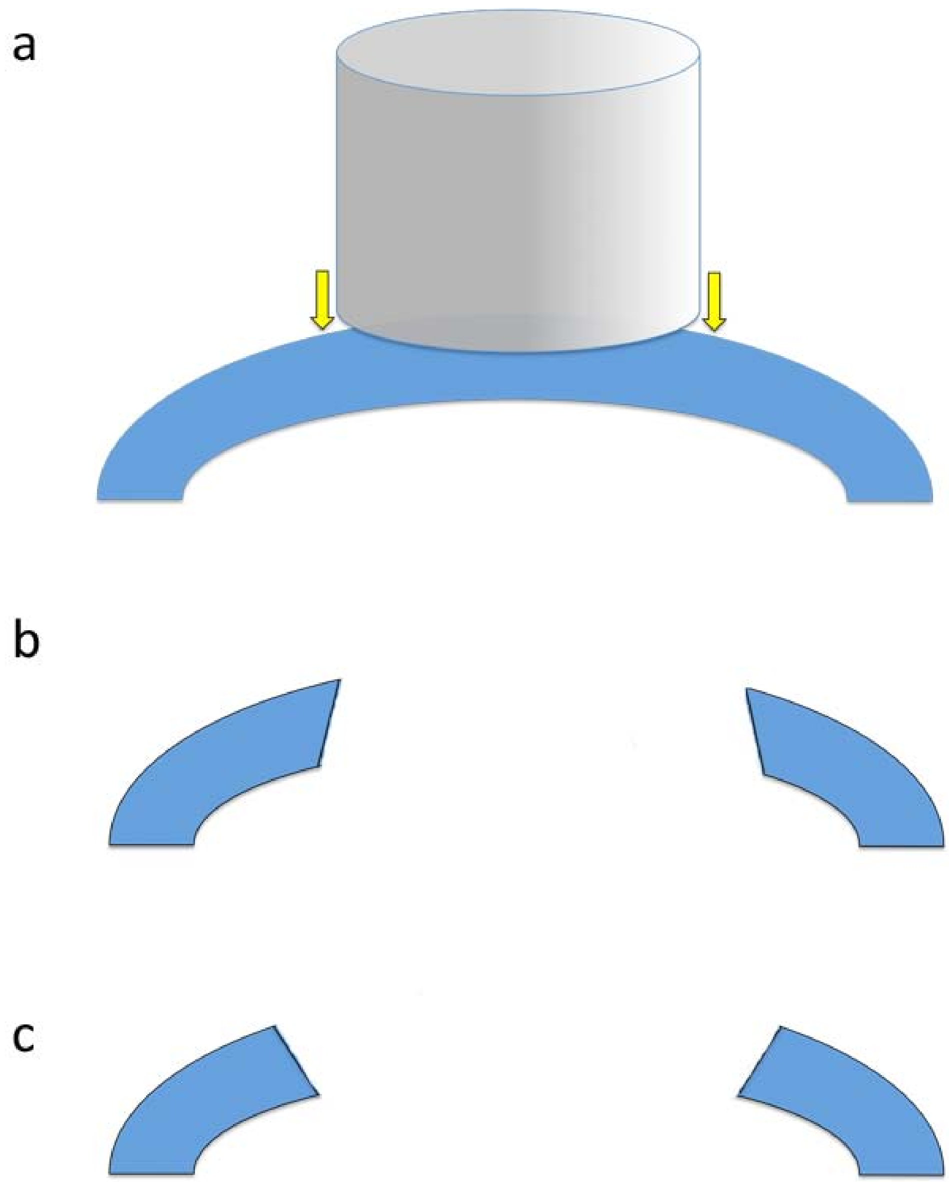

Figure 3: Effect of mechanical trephines on edge profile of host corneal bed; a. free hand trephining of host cornea showing direction of force; b. Low intraocular pressure leading to an acute angle edge profile; c. High intraocular pressure leading to an obtuse angled edge profile

As can be imagined, this could result in problems with apposition of the graft and host edges leading to irregular healing and unpredictable astigmatism. In addition to the edge profile being variable, other downsides of using a free hand trephine are potential slippage of the trephination leading to a decentered host bed, the host bed not being circular, the edges being irregular and potential injury to intraocular structures during the entry into the anterior chamber during trephination (Figure 4).

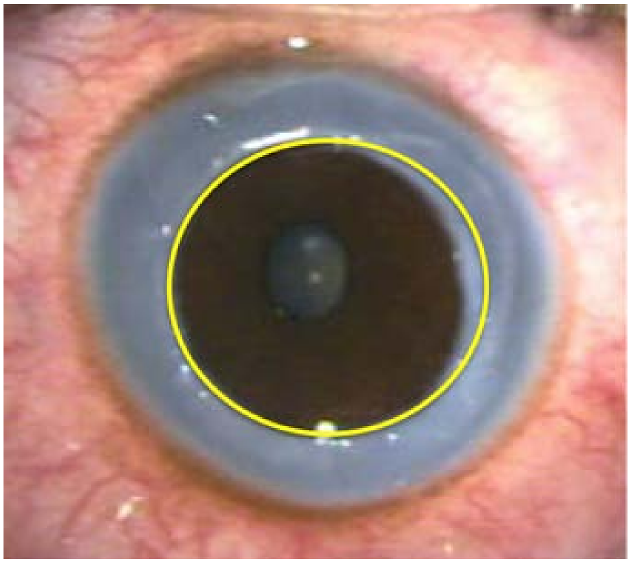

Figure 4: Trephined host bed showing oval margin and irregular edges (yellow circle corresponds to circular profile)

The Barron vacuum trephine and the Hanna vacuum trephine circumvent these problems to a certain degree by providing firm support during trephination but issues with centration and edge profile remain. (Figure 2) These issues with manual trephines can lead to irregular and poor wound healing, predisposing such grafts to early wound leaks and irregular astigmatism due to differential healing. Such grafts are also at increased risk of dehiscence of the graft host junction[9].

II) DONOR BED PREPARATION

The second step of penetrating keratoplasty is donor graft preparation. Donor graft preparation is commonly performed either using a manual trephine such as the Iowa punch trephine (Figure 5a) or the Barron vacuum punch trephine (Figure 5b).

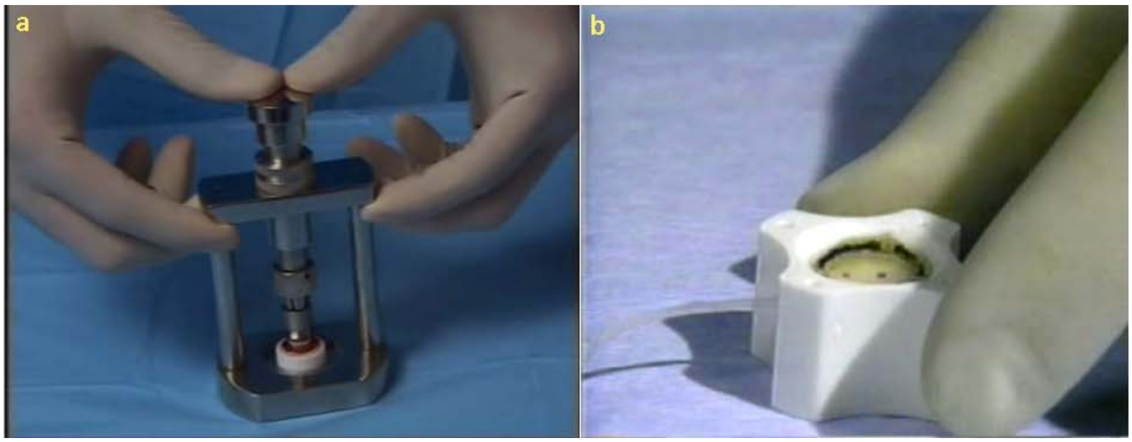

Figure 5: Types of donor punches for preparation of donor cornea; a. Iowa corneal punch; b. Barron vacuum donor corneal punch

These devices require the donor to be punched from the endothelial side leading to potential endothelial damage, oval shaped grafts and unpredictable centration[5].

Difficulties with the mechanical preparation of the host and donor have led to the advent of femtosecond laser assisted keratoplasty. The femtosecond laser works by creating multiple micro-cavitation bubbles within the corneal stroma, which when joined together form a precise incision. (Figure 6)

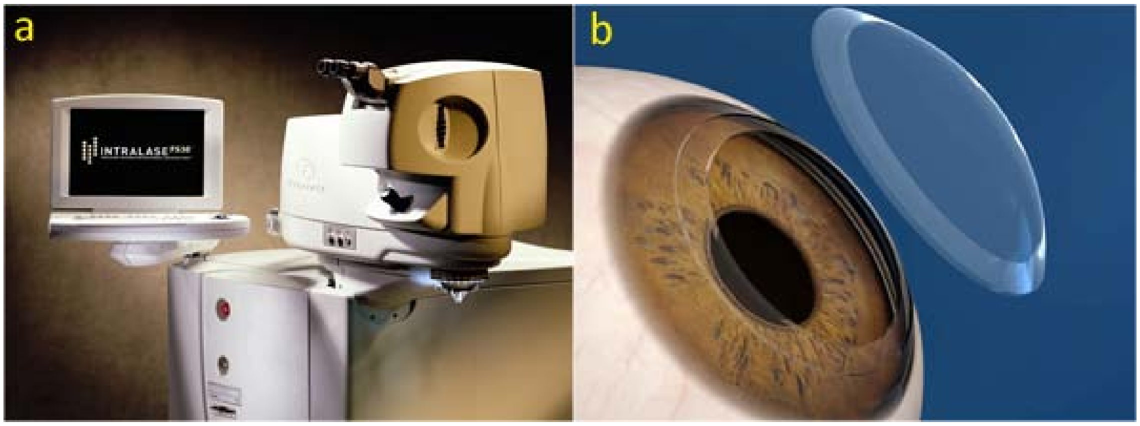

Figure 6: a. Intralase (AMO, Santa Ana, CA) femtosecond laser; b. schematic profile of a corneal donor prepared by a femtosecond laser

Femtosecond laser technology has changed the way that corneal transplant surgery is performed at many centers. Femtosecond lasers are able to achieve greater precision and accuracy with corneal wound construction than conventional and manual blade techniques. In addition, laser-generated, multiplanar incision conformations not achievable with manual trephination techniques provide greater wound stability and increased resistance to wound leakage compared with conventional PK[10]. (Figure 7)

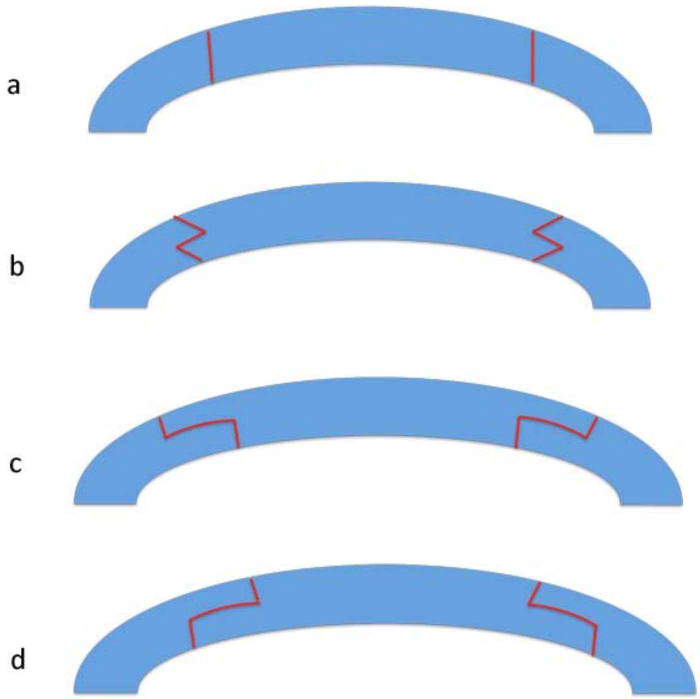

Figure 7: Edge profiles of donor and host trephination using the femtosecond laser; a. conventional; b. zigzag; c. mushroom; d. top hat

Femtosecond laser keratoplasty can achieve better centration, better host and donor edge profiles with custom shapes and contours, increasing the area of apposition between the graft and host, leading to potentially stronger wounds and more predictable astigmatism[11, 12, 13]. Though femtosecond laser keratoplasty has heralded a whole new era in penetrating keratoplasty, its application is limited to conditions that have pathology of the central cornea and its high cost still limits access of this technology to many doctors and patients.

III) SUTURING

The third important step of penetrating keratoplasty is suturing of the graft and host. Over the past 25 years, there have been a number of changes in suturing of keratoplasties, in technique as well as suture material and needles. Early keratoplasties used non-appositional or overlay sutures. Now, monofilament sutures are used almost exclusively, with the addition of finer caliber sutures. Nylon, however, tends to slowly hydrolyze and suture disruption can lead to changes in astigmatism. Suture materials that do not degrade over time have been used by some surgeons, including polyester (Mersilene; Ethicon, Inc., Sommerville, NJ, U.S.A.) and polypropylene (Prolene; Ethicon, Inc.), which provide greater refractive stability. Nonetheless, nylon remains the most frequently used suture material.

Needles have become finer and stronger over the past 25 years, and the configuration of needle tips has been modified to provide sharper, wider tips to allow for more ready tissue penetration, less tissue drag, and easier rotation of knots into tissue. In addition to changes in materials, techniques have evolved as well. Interrupted, interrupted combined with continuous, continuous, and double continuous sutures have been techniques used by corneal surgeons. Using interrupted sutures, surgeons have been able to reduce postoperative astigmatism with selective suture removal. This can be done with interrupted sutures alone or interrupted combined with continuous sutures. Dissatisfaction with the rate of visual recovery as well as with irregular astigmatism has led to further attempts to improve suturing techniques[5].

Even with all the modifications in sutures and techniques, corneal graft suturing remains the most time consuming and unpredictable step in keratoplasty. In addition, suture related complications account for the majority of complications in the post-operative period including vascularization of sutures and corneal infection caused by loose sutures. (Figure 8)

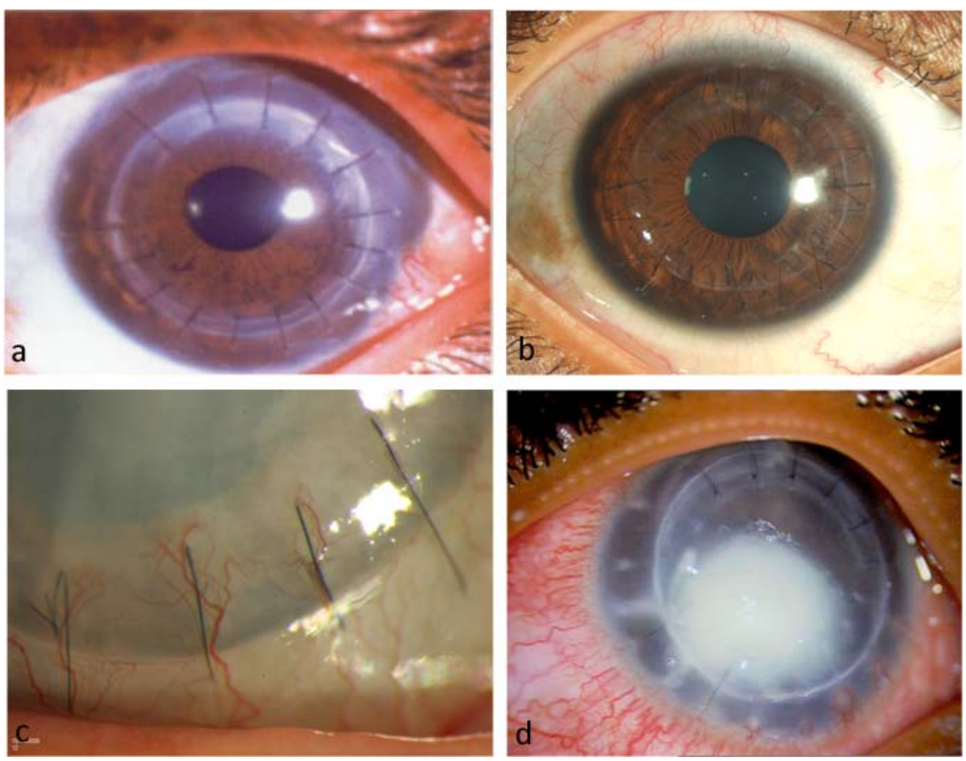

Figure 8: Corneal sutures and their complications. a. interrupted sutures; b. continuous sutures; c. vascularized sutures; d. suture related infiltrate

The use of alternative methods of wound closure like staples in general surgery is not new[14] but their recent use in microvascular surgery[15], leads us to believe that they may have a role in the closure of keratoplasty wounds in the future and this would be an exciting new avenue to investigate that might save time and achieve a more predictable method of wound closure. Similarly the application of surgical bioadhesive glue could potentially be used for wound closure in corneal transplantations is currently used in cardiovascular surgery [16].

Another interesting method of wound closure that is being investigated is the use of corneal laser welding to seal corneal incisions. In this procedure, a diode laser is used to bond a corneal wound stained with indocyanine green and has the potential to replace sutures in the future[17] (Figure 9).

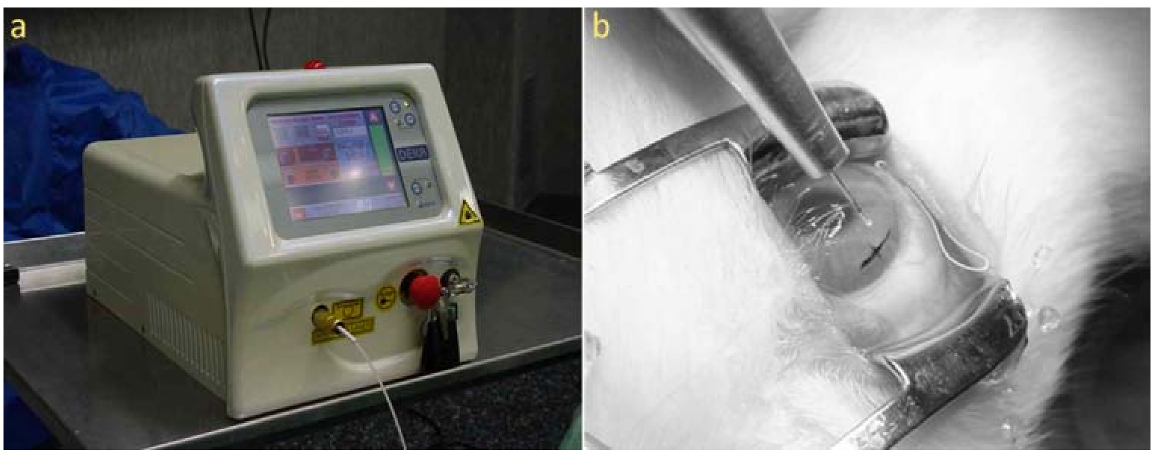

Figure 9: Apparatus for corneal welding; a. diode laser; b. corneal welding in process in a rabbit cornea *(Image courtesy Dr Roberto Pini,, Firenze, Italy)*

Complications of penetrating keratoplasty

In addition to the complications related to wound healing and sutures, the biggest risk of penetrating keratoplasty is graft rejection. The most common form of rejection is endothelial rejection and this has been the bane of long-term success in terms of graft survival.

Though penetrating keratoplasty has come a long way from the early 20th century, there still remain numerous gaps in its understanding and success. The complications of corneal transplantation discussed in the preceding section help to form a surgeon's "wish list" for the technology needs in corneal transplant surgery.

WISH LIST FOR PENETRATING KERATOPLASTY

- Predictable way of orienting tissue
- Accurate techniques to prepare donor and graft
- Objective methods to predict suture tension
- Less expensive alternative to femtosecond laser that can be used for every indication
- A mathematical model for astigmatism that will help understand the various factors involved and may help limit and manage it better
- Alternatives to sutures for wound closure such as surgical adhesives, staples and laser welding
- Effective methods to improve graft survival and safe and inexpensive drugs to reduce graft rejection

As of today, penetrating keratoplasty is a time consuming procedure lasting about 45 minutes, requiring significantly skilled surgeons. The outcomes are unpredictable, with variable long-term survival rates and over 6 months of visual rehabilitation for the patient. We would like to see it transform into a shorter surgical procedure that can be performed by the majority of ophthalmic surgeons, with predictable outcomes and better graft survival rates with a shorter recovery time for the patient.

2. ANTERIOR LAMELLAR KERATOPLASTY

While penetrating keratoplasty remains the most common form of corneal transplantation worldwide, there has been a renewed interest in lamellar keratoplasty over the past decade. The first successful lamellar keratoplasty (LK) for visual improvement was performed in the last quarter of the 19th century by Arthur von Hippel. The rapid progression and refinement of this surgical procedure has been fueled not only by advances in technology and techniques but also by a greater understanding of corneal physiology and optics.

The inherent philosophy for LK is to replace only that part of the cornea that is diseased and leave the recipient's normal anatomic layers intact; to do the least amount of resection, with the least amount of risk, for the greatest amount of benefit.

In anterior lamellar keratoplasty, the diseased anterior cornea is replaced, leaving the recipient's healthy endothelium and Descemet's membrane as an immunologic barrier to rejection. This has been successful with reasonable visual results for many decades. What has evolved is the precision of depth and smoothness achieved in the recipient bed and the refined edge of the cut[6].

Among the goals of keratoplasty propounded by Barraquer, all of which are met by lamellar keratoplasty, the last challenge that remains is to maximize visual acuity. The terminology used for delineating the different types of lamellar keratoplasty can be confusing (Figure 10).

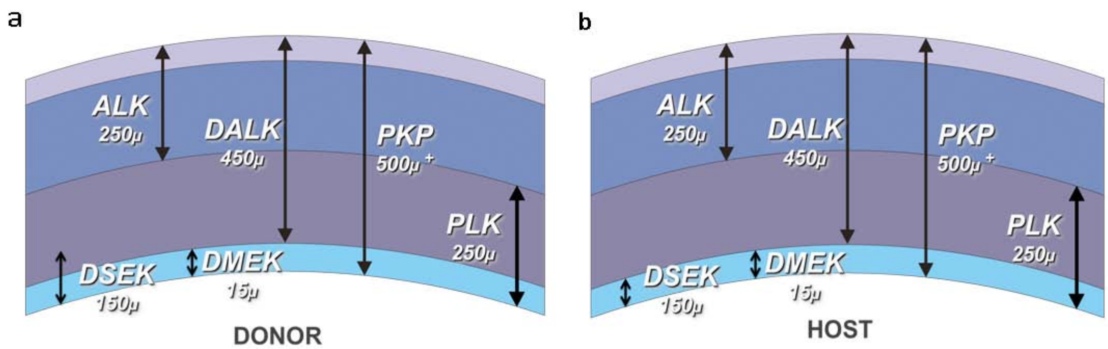

Figure 10: Schematic diagram representative of the commonly used nomenclature for lamellar keratoplasty; a. donor; b. host

Anterior lamellar keratoplasty refers to any procedure that replaces the anterior layers of the cornea, keeping the posterior layers, namely the Descemet's membrane and endothelium intact. There are many variations of anterior LK, but the term traditionally is reserved for surgeries that also leave some part of stroma intact in the host. (Figure 10) Anterior LK is useful for conditions that affect the anterior 250 to 300 microns of the cornea like superficial corneal scars and certain dystrophies. (Figure 11)

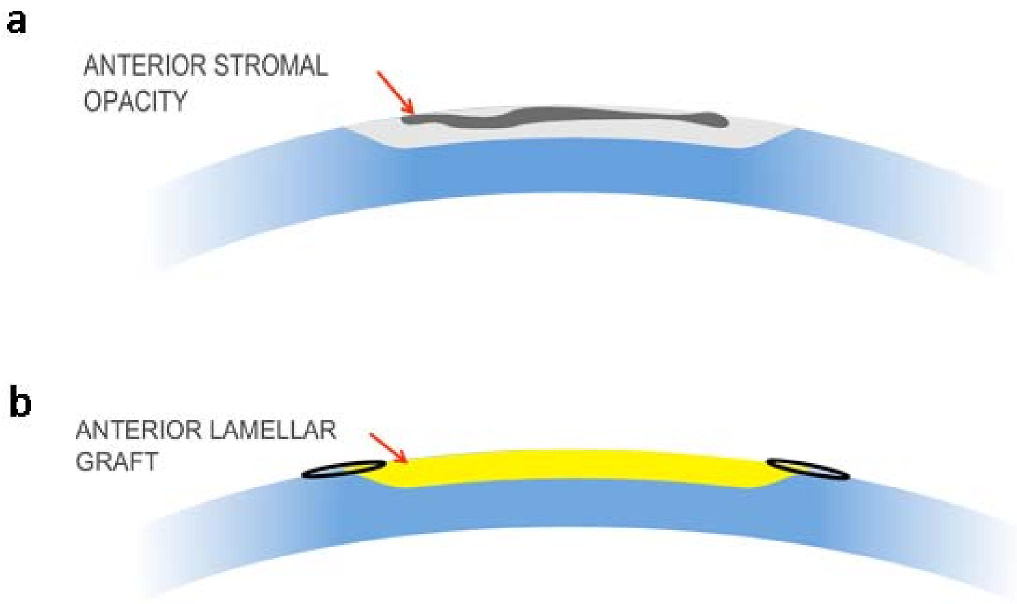

Figure 11: Schematic diagram showing the principle of anterior lamellar keratoplasty; a. cornea with anterior scar; b. showing area of excision following anterior lamellar keratoplasty

Anterior LK used to be a crude surgery involving lamellar hand dissection of the anterior layers of the cornea and replacing the dissected area with a similarly dissected clear donor cornea and suturing it in place. This led to numerous undesirable complications like graft host mismatch, irregular astigmatism and interface scarring limiting the best-corrected visual acuity[18]. Some of these issues were addressed by the use of automated microkeratomes for the lamellar dissection to achieve a smoother interface and minimize scarring[19, 20]. Microkeratome assisted anterior lamellar keratoplasty showed promising results (Figure 12)

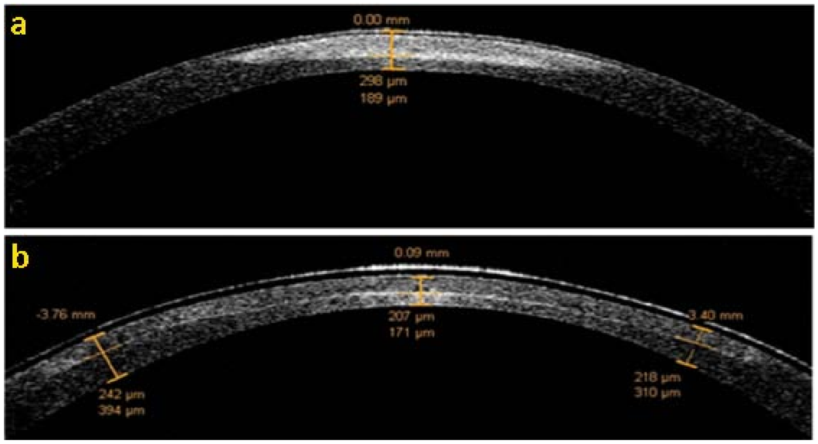

Figure 12: Visante OCT picture showing a patient with a corneal scar (a) and following femtosecond laser assisted lamellar keratoplasty (b)

but there were still issues with mismatch of the size of the donor and recipient. In addition, due to the variable edge profile of the cut, these donor lenticules still needed to be sewn into place to achieve good apposition[21]. Femtosecond assisted anterior lamellar keratoplasty, where the femtosecond laser is used to accurately size both the donor and recipient has improved the problems with mismatch. In addition the precise depth of cut with the femtosecond laser and the optimal edge profile of the graft has precluded the use of sutures for holding these grafts in place[22]. (Figure 13)

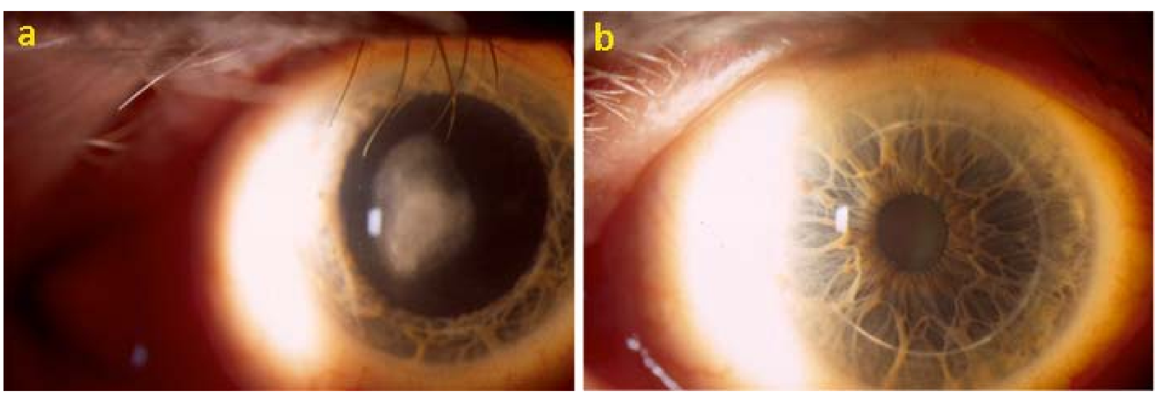

Figure 13: Slit lamp photograph of a patient with an anterior stromal scar before (a) and after (b) femtosecond assisted anterior lamellar keratoplasty

In spite of all these advances, the issues with interface scarring resulting in less than optimum visual acuity remain and irregularity of the surface of the donor and host bed probably leads to interface haze. (Figure 14)

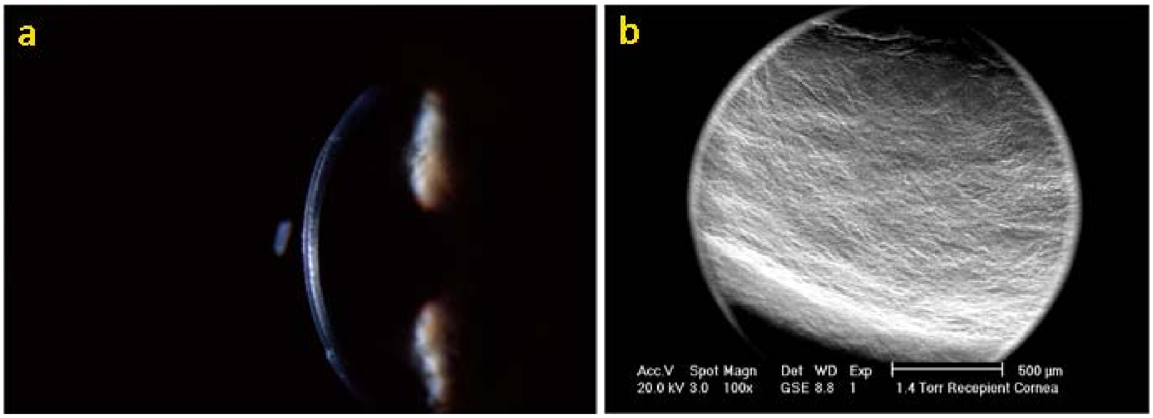

Figure 14: a. Slit lamp photograph of a patient's cornea showing interface haze following femtosecond laser assisted lamellar keratoplasty (FALK); b. Scanning electron microscopy photograph of the anterior lenticule from a patient following failed FALK

The femtosecond laser is also limited in its capabilities and does not penetrate dense scars and can lead to problems with apposition of the donor and host in cases where the thickness is variable. There are areas where significant improvement can be achieved and a 'wish list' for anterior LK would be as follows:

WISH LIST FOR ALK

- A femtosecond laser that penetrates dense scars
- An instrument to accurately measure interface haze
- An instrument to measure scattered light from the interface haze and its effect on vision
- A smooth interface to minimize haze

DEEP ANTERIOR LAMELLAR KERATOPLASTY

Deep anterior lamellar keratoplasty, where the entire stroma along with the epithelium and Bowman's membrane of the host is replaced, leaving only the host Descemet's membrane and the endothelium has reduced issues with haze due to the smoother interface achieved between the host Descemet's membrane and the posterior stroma of the donor[23, 24].

DALK was initially performed using a tedious, manual dissection technique but Anwar in 2002, popularized a technique of using an air bubble to separate the host Descemet's membrane from the posterior stroma resulting in better outcomes[25]. (Figure 15)

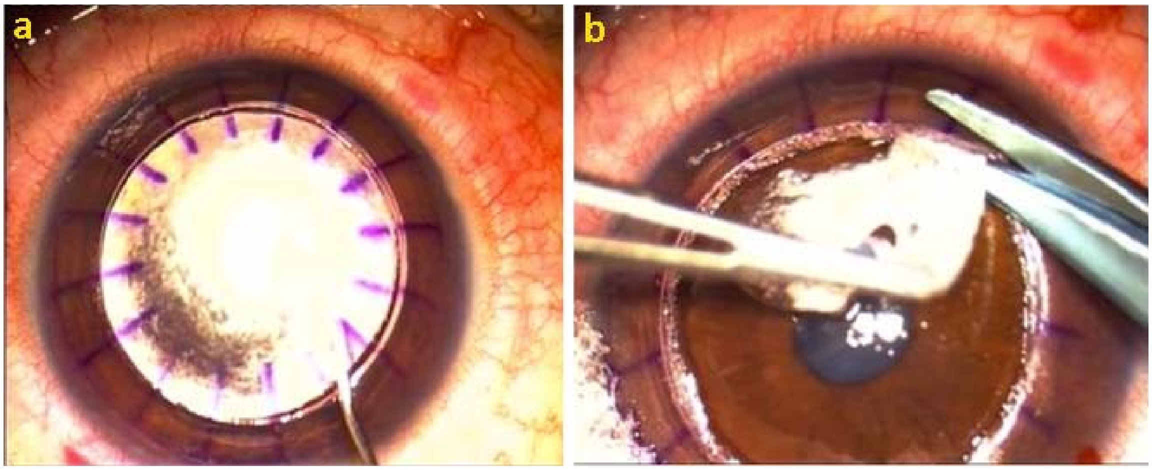

Figure 15: Deep anterior lamellar keratoplasty (DALK) showing the steps of intrastromal air injection (a) and stromal dissection and excision (b)

DALK is equivalent to PK for the outcome measure of best spectacle corrected visual acuity, particularly if the surgical technique yields minimal residual host stromal thickness. However, there is no advantage to DALK for refractive error outcomes due to the need for sutures. Although improved graft survival in DALK has yet to be demonstrated, postoperative data indicate that DALK is superior to PK for preservation of endothelial cell density. Endothelial immune graft rejection cannot occur after DALK, which may simplify long-term management of DALK eyes compared with PK eyes. As an extraocular procedure, DALK has important theoretic safety advantages, and it is a good option for visual rehabilitation of corneal disease in patients whose endothelium is not compromised[26].

Though DALK seems to be an excellent procedure compared to PKP, the surgery is unpredictable and takes significantly longer. The final few steps involving separating the posterior stroma from the Descemet's membrane is challenging and perforation of the Descemet's membrane necessitating conversion to conventional PKP is common. (Figure 16)

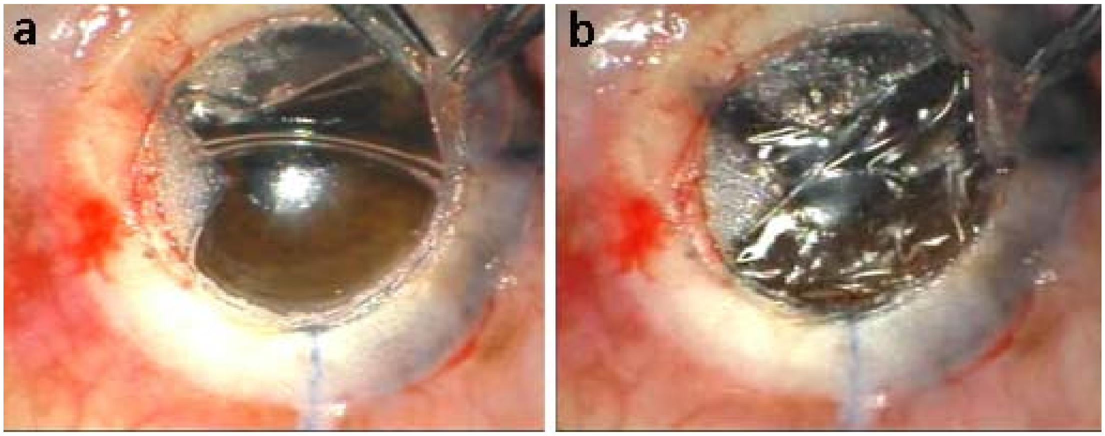

Figure 16: Perforation of Descemet's membrane during DALK. Sequence of video grabs showing the final stage of donor dissection (a) and perforation of the Descemet's membrane by the dissection scissors (b)

This and the much greater surgical time involved have undermined to popularity of DALK as a frontline surgery in areas where good quality donor tissue is available.

WISH LIST FOR DALK

- Shorter surgical time
- Predictable way of dissecting up to Descemet's membrane
- Repeatable results
- A mechanical device or a laser device that can dissect precisely up to the level of Descemet's membrane
- Avoid sutures

3. ENDOTHELIAL KERATOPLASTY

Selective replacement of the diseased or damaged posterior corneal layers was conceptualized and implemented over half a century ago. However, it has only been in the past decade that improved techniques and instrumentation have allowed endothelial keratoplasty (EK) to become the treatment of choice for patients with endothelial dysfunction. EK provides more rapid visual recovery, minimizes induced astigmatism and, most importantly, maintains globe integrity better than penetrating keratoplasty[27].

The main indications for EK are

• Endothelial dysfunction

- Traumatic
- Surgical

• Endothelial dystrophy (eg. Fuchs' dystrophy)

• Failed grafts

• Descemet's membrane injury

EK can potentially be done for any indication with dysfunctional endothelium.

Early attempts at posterior corneal replacement used an anterior flap approach that suffered from many of the same limitations as a full-thickness graft and additional new complications such as interface epithelial ingrowth[28, 29]. Eventually, it was a posterior approach, elimination of sutures to secure the graft, and a series of key techniques and improvements in instrumentation that led to widespread adoption of endothelial keratoplasty (EK)[30, 31].

A key break- through occurred in 1998, when Gerritt Melles described a posterior lamellar keratoplasty (PLK) technique that utilized air, rather than sutures, to affix the graft to the recipient cornea[32]. A variant of this procedure was introduced by Mark Terry and William Culbertson who popularized it as deep lamellar endothelial keratoplasty (DLEK)[33, 34]. However, PLK/DLEK never gained widespread popularity because of its technical difficulty and suboptimal visual recovery resulting from apposition of manually dissected donor and recipient stromal surfaces.

Melles subsequently eliminated the most technically challenging aspect of the PLK/DLEK procedure, the recipient stromal dissection and excision, by substituting descemetorhexis, or peeling of the recipient Descemet's membrane (DM) and endothelial layer from the area to be covered by the donor graft. This variation became known as Descemet stripping endothelial keratoplasty[35, 36] (DSEK) (Figure 10)

Descemet stripping automated endothelial keratoplasty (DSAEK), the term coined when the microkeratome was introduced for the donor graft preparation, is still a surgery in evolution with a multitude of individual techniques propagated by individual surgeons being popular. In its current form, it has four major steps (Figure 17)

i) Descemet's stripping
ii) Donor lenticule preparation
iii) Donor lenticule insertion
iv) Donor lenticule adherence

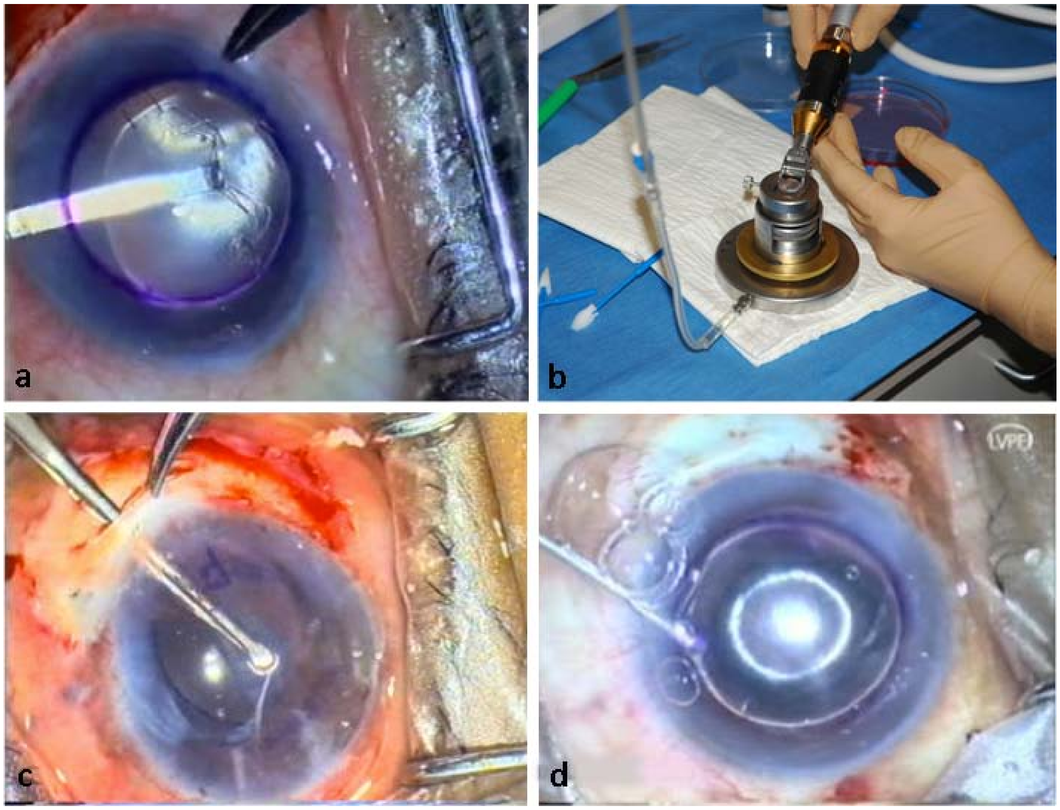

Figure 17: Steps of Descemet's stripping endothelial keratoplasty (DSEK): a. Descemet's stripping; b. donor dissection using the Moria microkeratome (Moria Inc, Antony, France);

c. Donor insertion; d. Donor adhesion using an air bubble

I) DESCEMET'S STRIPPING

A central circular area of the recipient Descemet's membrane (DM) and endothelium is usually stripped from within the area that will be covered by the donor graft (Figure 16a). In particular, endothelial guttae that are liable to cause significant light scattering and must be removed for optimal postoperative vision. Though this a relatively simple procedure, the DM is removed as a circular sheet and may be removed in excess, leading to peripheral uncovered stroma. DM tags may also be left behind leading to poor adherence and may even predispose the eye to formation of synechiae[37].

II) DONOR PREPARATION

Preparation of the donor lenticule for DSEK involves creating a lamellar separation in the cornea at a predetermined depth, thus dividing the cornea into an anterior layer consisting of the epithelium, Bowman's layer and part of the stroma and the posterior layer consisting of posterior stroma (Figure 16b), Descemet's membrane and endothelium. A central disc of this posterior layer of the cornea is referred to as the donor lenticule. A donor lenticule can be prepared manually using an artificial anterior chamber and a set of dissectors or using a microkeratome. (Figure 18)

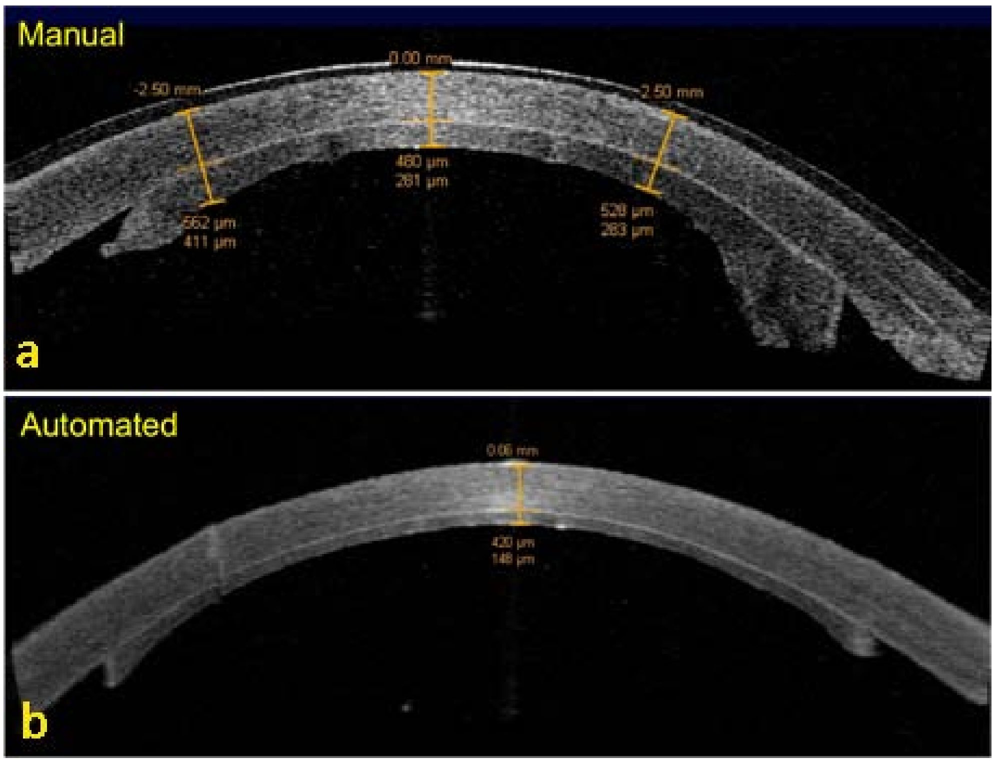

Figure 18: Visante OCT images of patient's corneas following DSEK surgery: a. donor lenticule dissected manually, showing variable thickness and profile with irregular edges; b. donor lenticule dissected with a microkeratome showing uniform, thin, planar profile

The surface of the lenticule is smoother and the depth is more predictable when using the microkeratome but literature has not shown a difference in visual quality between manually dissected tissues and those dissected using a microkeratome[38].

The donor lenticule can also be prepared using the femtosecond laser for greater predictability of depth, but experiments conducted at our lab have shown that the best quality of cut using a femtosecond laser is in the anterior stroma and the surface roughness increased proportionally with the depth of the cut (Figure 19).

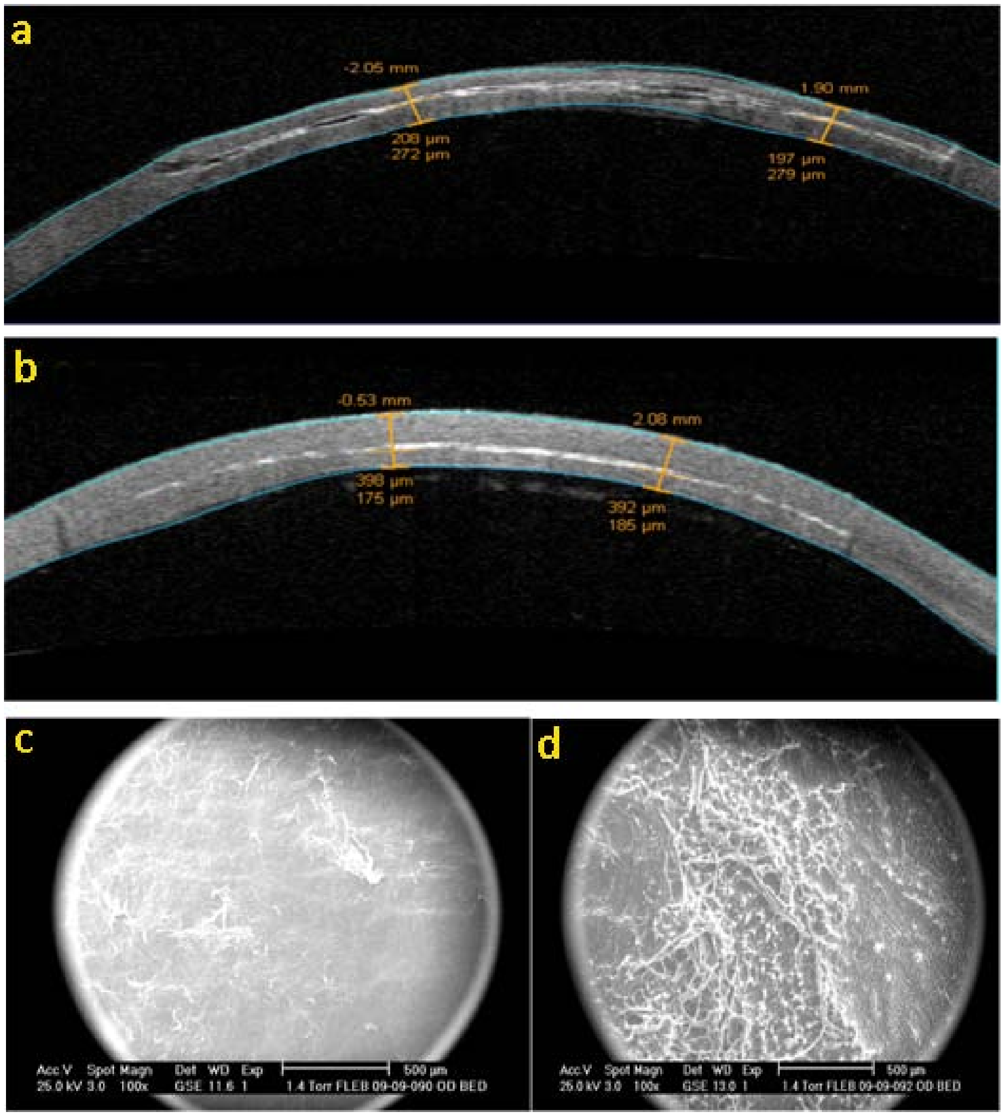

Figure 19: Visante OCT images of an eye bank cornea showing a cornea with a lamellar cut made at a depth of 200 microns (a) and at 400 microns (b). Scanning electron microscopy images of an eye bank cornea showing a smooth surface with a cut made at 200 microns (c) and a rough surface with a cut made at 400 microns (d)

A femtosecond laser that would achieve a predictable and smooth cut quality deep in the stroma would be desirable. In addition it must be remembered that the donor is prepared from tissue sourced from the eybank and stored in preservation media for varying amounts of time. This leads to variable thickness of the donor lenticule when prepared and it would be ideal to have a consistent way to deturgesce the donor cornea prior to preparation.

III) DONOR INSERTION

Once the donor lenticule is prepared, a central disc is punched out and inserted using varying methods into the anterior chamber of the eye (Figure 16c). It has been noted that an initial marked reduction of endothelial cells occurs immediately following surgery, presumably from surgical trauma during donor insertion[39, 40]. A wide variety of methods have been described to insert the donor lenticule into the anterior chamber of the eye. These range from folding the donor like a taco and inserting using a forceps, various devices designed to protect the endothelium and newer devices that resemble injectors[27].

In spite of a frenetic pace of development to identify an ideal device to deliver the donor lenticule into the anterior chamber with minimal endothelial loss, we still await the development of a device that will allow insertion of donors of different thickness and diameters predictably with a minimum of endothelial trauma.

IV) **DONOR ADHESION**

After the donor is successfully inserted into the eye with the endothelial side facing downwards, the next step is to unfold it and appose the stromal surface to the bare posterior stroma of the host. This is achieved with a complete air bubble in the anterior chamber behind the donor lenticule, that tamponades it. This air bubble is left in place for a variable amount of time, based on surgeon preference and in the interim, graft adhesion occurs by a combination of hydrostatic pressure and the negative suction of the functioning endothelium of the donor. Graft dislocation due to inadequate adherence between the donor and host is the most common early post-operative complication[41].

The time required for the air tamponade is arbitrary with no proof of the amount of intraocular pressure required to keep the lenticule attached following absorption of air. Some studies about using optical coherence tomography (OCT) technology are indicative of trends to answer these questions. It would be ideal to have an OCT mounted on a microscope for a real time assessment of the adherence of the graft[42, 43].

Graft dislocation is the most frequent early postoperative complication after DSAEK, particularly during the learning curve of the procedure. Reported dislocation rates have varied from 0% to 82% with an average rate of 15%. Generally, the rate decreases with increasing surgeon experience. Usually graft dislocation is detected within the first day or two but occasionally it may be detected several weeks later[44].

WISH LIST FOR DSAEK

- Reliable and repeatable method of dissecting donor buttons
- Consistent thickness of donor buttons
- A method to deturgesce corneas prior to preparation of the donor lenticule
- Minimize interface haze
- Minimize endothelial cell damage while inserting lenticule
- Real time OCT on operating microscope to assess adhesion

Recently, another surgical procedure called Descemet's membrane endothelial keratoplasty (DMEK) that involves replacing the stripped DM with only a donor DM and endothelium. This procedure though reportedly successful by several surgeons, has been limited in its popularity due to difficulty in preparing the donor DM, issues with unfolding of the DM within the eye and eyes requiring repeated air injections to attach the donor DM[45].

Recent modifications in the surgical technique by leaving a thin rim of stroma attached to the donor DM and novel methods of harvesting the donor DM have renewed interest in this procedure and with more innovations in this field to unfold the DM and improve adhesion, this eventually may become the endothelial keratoplasty procedure of choice[46, 47].

4. SURGICAL TOOLS

The wish list for surgical tools for keratoplasty is probably too long and beyond the scope of this review but basically a few desirable changes to current instrumentation would include

WISH LIST FOR SURGICAL TOOLS

- Microscopes with better slit illumination
- Instruments that are cheaper, longer lasting
- Lasers – faster, more precise with more flexible software

5. DIAGNOSTICS

A number of diagnostic devices like specular microscopes, corneal topographers and confocal microscopes play an important role if the management and planning of a keratoplasty including but one instrument that has proved singularly important in the last few years in the optical coherence tomography (OCT). The greatest advantage of an OCT is that it provides morphological and structural detail of the anterior segment of the eye that is otherwise not appreciated by slit lamp biomicroscopy. It has proved especially useful is identifying and managing complications of corneal lamellar surgery[48]. (Figure 19) However, as mentioned before an ideal adaptation of this versatile instrument during surgery would be its adaptation to the surgical microscope to function as an intraoperative tool[42, 43].

WISH LIST FOR DIAGNOSTIC EQUIPMENT

- Confocal microscope providing greater cellular detail
- Higher resolution OCT
- OCT attached to a microscope
- Hand held attachment for OCT

In this review, we have outlined the various steps of different types of keratoplasty and tried to point out areas where innovative ideas and developments could make surgical outcomes more predictable, successful and long lasting. The collaboration between engineers and corneal surgeons hopefully will lead to the ultimate goal of keratoplasty, which is to restore optical clarity and visual function in a safe, predictable, and long-term manner.

FIGURE LEGENDS

Figure 1: Indications for keratoplasty; a. corneal scar; b. keratoconus; c. corneal edema; d. Granular dystrophy

Figure 2: Types of mechanical trephines; a. free hand trephine; b. Hanna trephine; c. Barron vacuum trephine

Figure 3: Effect of mechanical trephines on edge profile of host corneal bed; a. free hand trephining of host cornea showing direction of force; b. Low intraocular pressure leading to an acute angle edge profile; c. High intraocular pressure leading to an obtuse angled edge profile

Figure 4: Trephined host bed showing oval margin and irregular edges (yellow circle corresponds to circular profile)

Figure 5: Types of donor punches for preparation of donor cornea; a. Iowa corneal punch; b. Barron vacuum donor corneal punch

Figure 6: a. Intralase (AMO, Santa Ana, CA) femtosecond laser; b. schematic profile of a corneal donor prepared by a femtosecond laser

Figure 7: Edge profiles of donor and host trephination using the femtosecond laser; a. conventional; b. zigzag; c. mushroom; d. top hat

Figure 8: Corneal sutures and their complications. a. interrupted sutures; b. continuous sutures; c. vascularized sutures; d. suture related infiltrate

Figure 9: Apparatus for corneal welding; a. diode laser; b. corneal welding in process in a rabbit cornea *(Image courtesy Dr Roberto Pini,, Firenze, Italy)*

Figure 10: Schematic diagram representative of the commonly used nomenclature for lamellar keratoplasty; a. donor; b. host

Figure 11: Schematic diagram showing the principle of anterior lamellar keratoplasty; a. cornea with anterior scar; b. showing area of excision following anterior lamellar keratoplasty

Figure 12: Visante OCT picture showing a patient with a corneal scar (a) and following femtosecond laser assisted lamellar keratoplasty (b)

Figure 13: Slit lamp photograph of a patient with an anterior stromal scar before (a) and after (b) femtosecond assisted anterior lamellar keratoplasty

Figure 14: a. Slit lamp photograph of a patient’s cornea showing interface haze following femtosecond laser assisted lamellar keratoplasty (FALK); b. Scanning electron microscopy photograph of the anterior lenticule from a patient following failed FALK

Figure 15: Deep anterior lamellar keratoplasty (DALK) showing the steps of intrastromal air injection (a) and stromal dissection and excision (b)

Figure 16: Perforation of Descemet’s membrane during DALK. Sequence of video grabs showing the final stage of donor dissection (a) and perforation of the Descemet’s membrane by the dissection scissors (b)

Figure 17: Steps of Descemet's stripping endothelial keratoplasty (DSEK): a. Descemet’s stripping; b. donor dissection using the Moria microkeratome (Moria Inc, Antony, France);

c. Donor insertion; d. Donor adhesion using an air bubble

Figure 18: Visante OCT images of patient's corneas following DSEK surgery: a. donor lenticule dissected manually, showing variable thickness and profile with irregular edges; b. donor lenticule dissected with a microkeratome showing uniform, thin, planar profile

Figure 19: Visante OCT images of an eye bank cornea showing a cornea with a lamellar cut made at a depth of 200 microns (a) and at 400 microns (b). Scanning electron microscopy images of an eye bank cornea showing a smooth surface with a cut made at 200 microns (c) and a rough surface with a cut made at 400 microns (d)

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