Review Article

Descemet Membrane Endothelial Keratoplasty: Evolving Surgical Techniques and Contemporary Clinical Outcomes – A Narrative Review

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Abstract

Objective: To synthesize contemporary developments in endothelial keratoplasty, outlining the evolution from penetrating keratoplasty (PK) and DSEK/DSAEK to Descemet Membrane Endothelial Keratoplasty (DMEK), while summarizing modern surgical refinements, clinical outcomes, complication patterns, and emerging innovations.

Methods: A narrative review was conducted using PubMed and Scopus (January 2010–February 2026). Search terms included DMEK, DSAEK/UTDSAEK, posterior lamellar keratoplasty, DSO/DWEK, endothelial cell loss, graft detachment, preloaded grafts, and longterm outcomes. Eligible sources comprised randomized trials, cohort studies, large case series, systematic reviews, and techniquefocused reports. Findings were synthesized thematically due to heterogeneity in study designs and outcome measures.

Result: Across the literature, DMEK consistently provides the fastest visual recovery and best optical outcomes among endothelial keratoplasty techniques, with many eyes achieving ≥20/25 vision postoperatively. Early endothelial cell loss is substantial but stabilizes over time. Surgical innovations including preloaded P3 tissue, endotheliumin delivery, standardized notouch unfolding maneuvers, and orientation stamps have reduced intraoperative manipulation and improved reproducibility. Graft detachment remains the most frequent early complication, influenced by low early postoperative intraocular pressure, older age, diabetes, and Fuchs endothelial corneal dystrophy; however, timely rebubbling typically preserves longterm graft function. Despite progressive endothelial attrition, DMEK maintains high graft survival and low rejection rates over longterm followup.

Conclusion: Today, DMEK is considered the gold standard for endothelial replacement due to its exceptional optical quality and minimal immunologic risk. Looking forward, bioengineered endothelial constructs, cell-based therapies, and tissue-efficient graft formats hold promise for expanding global access and reducing reliance on donor tissue.

Keywords: Corneal transplantation, Descemet membrane endothelial keratoplasty (DMEK), Endothelial cell loss, Endothelial keratoplasty, Fuchs endothelial corneal dystrophy.

Introduction

The cornea in the human eye is a transparent, avascular tissue that plays a crucial role in the refractive function of the eye. The corneal endothelium, a single layer of hexagonal cells on the posterior surface of the cornea, is responsible for maintaining the cornea in a transparent state by virtue of a leaky barrier and an active ion pump mechanism (primarily Na^+/K^+-ATPase), which maintains stromal hydration at approximately 78%.[1,2] In contrast to the epithelium, the human endothelium is relatively non-proliferative; a loss of cells is compensated by cell hypertrophy and migration, and visual impairment occurs when cell density falls below a critical level.[2,3] The most frequent causes of endothelial decompensation are Fuchs endothelial corneal dystrophy (FECD), surgical injury (pseudophakic bullous keratopathy), glaucoma, and previous graft failure.[4]

Endothelial disorders are a significant and growing global burden, with FECD.[5] FECD is a primary indication for endothelial keratoplasty in many centres, but donor shortages

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and unequal access to modern surgical techniques maintain an unmet need, especially in resource-poor areas, and the disease's propensity for older patients multiplies societal costs due to vision-dependent disability, fractures, and decreased quality of life.[2,5]

Typically, the treatment options available for corneal endothelial dysfunction range from purely symptomatic and palliative interventions like hypertonic saline, bandage lenses, and anatomically corrective phototherapeutic keratectomy (PTK), to transplants to total organ replacement surgeries like PK.[2,3] For decades, PK was the fallback surgical option for endothelial dysfunction, but the full-thickness defect, astigmatism from sutures, slower visual recovery, and increased risk of rejection limited the success.[3,6]

The field has progressively "gone thinner". Descemet stripping endothelial keratoplasty (DSEK) or Descemet stripping automated endothelial keratoplasty (DSAEK) enabled predictable posterior lamellar transplantation, but the remaining donor stroma in the interface contributes to light scatter and delayed optical recovery.[6] Descemet membrane endothelial keratoplasty (DMEK), which transplants only Descemet membrane (DM) and endothelium, more accurately replicates corneal anatomy and optics, with faster visual recovery and significantly lower rates of immunologic rejection compared with PK or DSAEK. DMEK's rise to prominence has been fueled by advancements in surgical techniques and the development of specialized tools, including "no-touch" injectors and pre-stripped donor grafts.[6,7] However, several clinically relevant uncertainties persist, particularly regarding ECL trajectories and longterm graft durability.[7,8]

The current state of uncertainty regarding ECL and its implications for graft survival and the donor pool also invites critical review. Moreover, standardised outcome frameworks and prospective trials are only now emerging; the NIH-funded DETECT II study will compare DMEK with Descemet Stripping Only augmented by ripasudil (DSO-R),[9] providing a model for future reporting and decision-making. While there has been a rapid increase in research regarding DMEK in the past decade, there is considerable variability in methodology, duration of follow-up, and techniques used in these studies in terms of outcomes reported. Most of the studies are retrospective in nature and may not be comparable in terms of early experience cohorts used in various investigations. There is considerable variability in terms of endothelial cell loss, graft detachment, visual recovery metrics, and postoperative management protocols used in these studies, which makes a critical synthesis of available findings.

This review integrates the evolution of endothelial surgery from PK to DSEK/DSAEK to DMEK, and summarizes contemporary practices (tissue processing, implantation, tamponade, perioperative care), while critically assessing the outcomes and complications reported in the literature for the major indications. We will also compare DMEK to DSAEK and PK, emphasise how recent advances may have altered outcomes, and identify remaining knowledge gaps, including ECL paths and durability, within the context of evolving standardised frameworks. This synthesis of knowledge is intended to inform how and why DMEK has emerged as the standard of care for endothelial failure, while outlining the priorities for the next generation of endothelial surgery.

Methodology

This narrative review synthesised contemporary evidence on DMEK by examining peer-reviewed publications from January 2010 to February 2026. A targeted search was performed in PubMed and Scopus using keyword combinations centred on DMEK and related endothelial procedures, including "DMEK," "DSAEK/UT-DSAEK," "posterior lamellar keratoplasty," "DSO," "DWEK," "graft detachment," "rebubbling," "endothelial cell loss," "preloaded/pre-stripped tissue," "long-term outcomes," and "graft survival." Additional subspecialty sources such as AAO EyeWiki and corneal-surgery reviews were screened to capture evolving surgical techniques and expert consensus. Reference lists of eligible articles were also reviewed to identify additional relevant studies published within the same period.

Inclusion criteria were: (i) peer-reviewed human studies, (ii) explicit reporting of visual, endothelial, or complication outcomes, and (iii) studies describing surgical refinements or comparative techniques. We included randomized trials, cohort studies, registry analyses, large case series, systematic reviews, and technique-focused reports. Exclusion criteria were case reports (unless technique-defining), animal studies, conference abstracts without data, commentary articles, and non-English publications.

Studies were selected based on their relevance to contemporary surgical technique refinements, outcome reporting, complication profiles, and innovations in tissue preparation. Because the included literature varied widely in design and outcome metrics, no meta-analysis was attempted; instead, findings were synthesised thematically across domains such as evolution of endothelial keratoplasty, current DMEK surgical practice, visual and endothelial outcomes, and complication-mitigation strategies. This approach ensured a clear, updated synthesis that aligns with the scope and temporal coverage of the sources referenced throughout this review.

Evolution of Endothelial Keratoplasty to DMEK

The development of endothelial keratoplasty represents a gradual advancement towards a more selective, anatomical, and minimally invasive approach to restoring corneal transparency.[10,11] In the past, PK was the only treatment modality, which replaces the entire cornea, leading to a slow rate of recovery, high astigmatism, and a high rate of rejection. With advancements in surgical techniques, it was realized that only the diseased endothelial layer needed to be replaced, which paved the way for posterior lamellar surgeries like posterior lamellar keratoplasty (PLK) and

deep lamellar endothelial keratoplasty (DLEK).[12,13] Although these surgeries were safer, the interface with the stromal tissue still compromised the final result of the surgery. With advancements in surgical techniques, DSEK and its automated version using an automated microkeratome called DSEAK became widely accepted for their predictability and partial-thickness approach to endothelial replacement.[14] However, the interface with the residual donor stromal tissue still compromised the final result of the surgery. DMEK represents a major advancement in this area, as it replaces only the Descemet's membrane and endothelium, giving the best optical results, fastest rate of recovery, and lowest rate of rejection.[15,16] Further refinements such as ultrathin DSAEK (UT-DSAEK) helped bridge anatomical and practical considerations, while graft-free approaches like Descemet Stripping Only (DSO), otherwise called Descemetorhexis Without Endothelial Keratoplasty (DWEK) offer a selective option for early FECD case.[17,18] Collectively, this evolution reflects a consistent progression toward tissue-sparing precision and better visual outcomes (Figure 1).

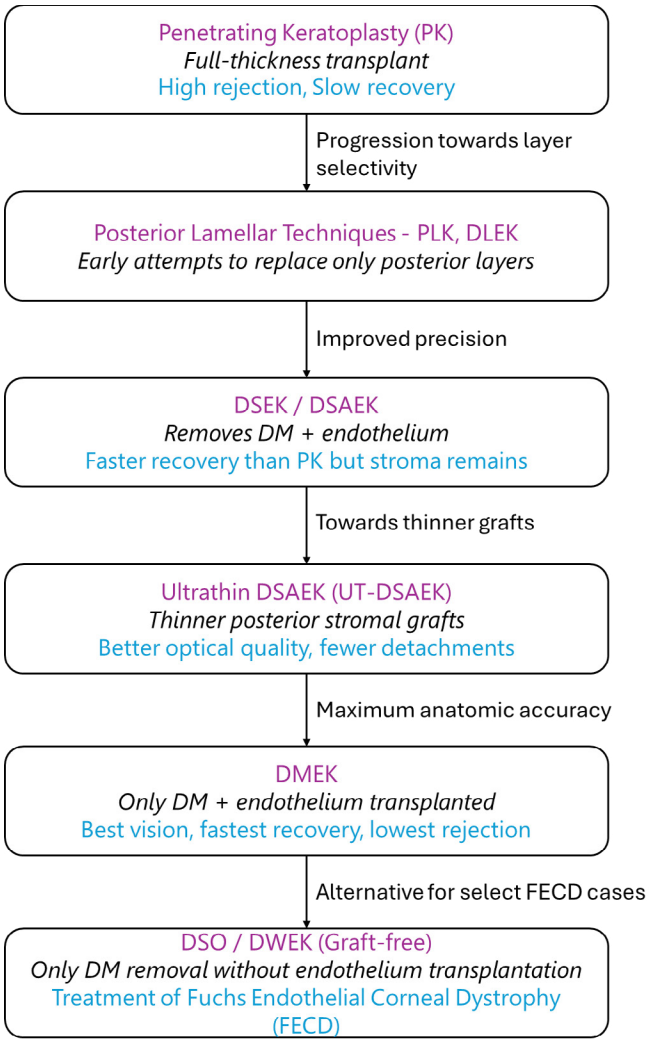

Figure 1: Evolution of endothelial keratoplasty

Indications and Patient Selection in Contemporary Practice

Primary Indications

The main indications for DMEK are FECD, pseudophakic/aphakic bullous keratopathy (PBK/ABK), and endothelial failure of a previous keratoplasty.[19] DMEK has been found to provide quick rehabilitation, excellent optical quality, and a very low rejection risk, although the selection of the eye must consider the complexity of the anterior segment, which may influence the risk of intraoperative manipulation and postoperative detachment.[20] Parameters to evaluate include the depth of the anterior chamber, cell density, working space, quality of the view, degree of synechiae, presence of vitrectomy/unicameral, iris defects, and the presence of a glaucoma tube or a previous trabeculectomy, all of which may affect the scroll, orientation, and unfolding.[20,21]

Glaucoma eyes

In eyes with glaucoma, the postoperative visual acuity outcomes are better achieved with DMEK compared to DSAEK and there may be fewer steroid responders with DMEK due to shorter steroid regimens, although graft survival outcomes seem comparable between the two techniques.[22] Prior filtering procedures or drainage devices may affect the delivery and adherence of the grafts, and careful tamponade and intraocular pressure (IOP) control strategies are critical. Surgeon experience is key in determining whether DMEK or UTDSAEK is more appropriate in these complex cases.[17]

Failed PK (EK "over PK")

For endothelial failure of a prior penetrating keratoplasty, DMEK over PK and DSAEK over PK offer good visual outcomes with acceptable graft survival. Studies indicate that DMEK over PK has better visual acuity than DSAEK over PK, with a difference of 6 months, although it has a higher percentage of re-bubbling than DSAEK over PK; therefore, selection is based on host–graft interface anatomy, anterior segment status, and surgeon experience.[16,23]

Disease substrate and risk

In comparison to FECD cases, eyes with PBK, particularly those with complicated intraocular surgery, show increased risks of persistent edema or failure after DMEK surgery; thus, the burden of comorbidity and surgical objectives must be taken into consideration in making the choice between DMEK and UT DSAEK surgery.[24]

Alternative graftfree option (DSO/DWEK)

In carefully selected FECD with central guttae, a clear peripheral cornea, and a satisfactory peripheral endothelial cell density (ECD), DSO/DWEK avoids the need for donor tissue altogether and thus eliminates rejection. Vision improvement is slower and the optical zone smaller compared to DMEK; DSO is thus indicated for earlier disease where peripheral endothelial migration can restore clarity.[25,26]

Balancing DMEK vs UTDSAEK

Studies consistently demonstrate improved 12-month BCVA outcomes for DMEK compared to UT DSAEK, although at the expense of a higher rate of detachment/rebubbling post-DMEK. Where UT DSAEK thickness is <70 µm, the difference in visual outcomes diminishes. In anatomically challenging eyes, UT DSAEK is a sensible option as a result of easier intraocular handling and reduced re-intervention rate.[17,27]

DMEK Surgical Technique

The surgical technique for DMEK transplant involves the creation of a peripheral iridotomy to prevent postoperative pupillary block, followed by a controlled descemetorhexis to remove the host Descemet's membrane and endothelium.[28] The pre-stripped donor Descemet's membrane endothelium graft is introduced into the anterior chamber, and the endothelium out injector or endothelium in pull-through system is used to facilitate the introduction of the graft.[29] This is achieved using gentle fluid waves and chamber shallowing. Once the graft is correctly positioned, the graft is centrally placed and secured with an air or 20% SF_6 gas tamponade to promote adhesion.[30] Standardized steps for the surgical technique have been shown to decrease the rates of detachment and rebubbling.[31]

Endoin vs Endoout Delivery Techniques

Emerging evidence has highlighted meaningful differences between endotheliumin ("Endoin") and endotheliumout ("Endoout") graftinsertion strategies in DMEK.[29] Endoout techniques, traditionally used with glass injectors, allow controlled fluidbased unscrolling but expose the endothelial layer externally during insertion, raising the risk of microtrauma. In contrast, the endoin approach, increasingly used with pullthrough or cartridgebased systems, protects the endothelial surface by keeping it inside the scroll during entry.[32] Comparative studies in Asian eyes demonstrate similar visual outcomes but report greater intraoperative stability and lower manipulation time with the endoin pullthrough method, especially in deep anterior chambers and dim visualization settings.[33] Overall, choice of technique is surgeondependent, but surgical standardization is trending toward endoin delivery due to reduced mechanical trauma and smoother graft unfolding.

Preloaded vs SurgeonLoaded Grafts

Workflow refinements now allow eye banks to deliver prestripped, prestained, and preloaded (P3) DMEK grafts, which significantly simplify the surgical steps.[34] Preloaded tissue reduces the duration of intraocular manipulation, minimizes endothelial touch, and shortens operative time.[35] Preloaded grafts are noninferior to surgeonprepared tissue with respect to detachment rates, visual acuity outcomes,

Table 1: Clinical outcomes of DMEK across major studies

Study/Year	*Population/ Followup*	*Visual acuity outcomes*	*ECD/ECL*	*Graft survival*	*Complications/Notes*
MouraCoelho et al., 2024[52]	129 eyes, ≥12 months followup	Significant BCVA improvement; eyes achieving ≤0.10 logMAR (≥20/25) increased from 1.6% preop to 64.4% at >5 years	Not primary outcome; predictors of better vision included younger age & better baseline BCVA	All eyes included had successful primary DMEK with no early graft failure	Retinal comorbidities predicted worse longterm BCVA
Bichet et al., PLOS ONE 2023[53]	107 eyes (majority FECD); 5year followup	BCVA improved from 0.6 logMAR to 0.05 at 1 year; remained stable for 5 years	47% ECL at 6 months, additional 4%/year decline; 65% ECL at 5 years	88% graft survival at 5 years	18% detachment requiring rebubbling; 12% graft failure within 15 months
Machalińska et al., 2025[54]	34 eyes; up to 36month followup	Continuous BCVA improvement during first 12 months; stable thereafter	~64% cumulative ECL at 36 months	High procedure effectiveness; grafts maintained structural stability	Reduction in astigmatism & higherorder aberrations by month 12; remained stable
Wilhelm et al., 2025[55]	2956 eyes; 10year comparison of DMEK vs DSAEK vs PK	DMEK achieved fastest visual recovery: median time to ≥6/12 visual acuity was 7.8 months	Faster ECD decline than PK; 10year probability of ECD >1000 cells/ mm^2: DMEK 3%	10year graft survival: DMEK 75%, DSAEK 73%, PK 92%	Lowest rejection rate among groups (10% at 10 years)
DabrowskaKloda et al., Sweden 2024[56]	162 eyes; 1–6-year followup	85.8% achieved 0.1 logMAR (20/25) or better in eyes without comorbidities	ECL: 27% at 1–2 yrs, 31% at 2–3 yrs, 42% at 3–4 yrs, >60% at 4–6 yrs	Not explicitly quantified but generally high; longterm sustainability needs further study	Results confirm consistently strong visual outcomes with progressive ECD decline
Price et al., AAO 2026[47]	362 consecutive eyes undergoing DMEK for failed EK	Mean BCVA 20/25 at 1 and 5 years (without major comorbidities)	ECD correlated with donor density and time since surgery; glaucoma increased risk of failure	Earlyfailure cases: 1yr survival 98%, 5yr 94% Latefailure cases: 1yr 93%, 5yr 77%	Higher failure risk in secondary corneal edema and glaucoma; number of prior failed grafts *not* a predictor

BCVA – Best-Corrected Visual Acuity; ECD – Endothelial Cell Density; ECL – Endothelial Cell Loss; FECD – Fuchs Endothelial Corneal Dystrophy; logMAR – Logarithm of the Minimum Angle of Resolution

Table 2: DMEK Complications - Key Risks, Prevention, and Management

Complication	*Key risk modifiers*	*Prevention / mitigation*	*Management (Processfocused)*	*Citations*
graft detachment → rebubbling	Lower early postoperative IOP (e.g., at ~2 h), older age, diabetes, FECD indication increase detachment odds.	Standardize steps; confirm PI; aim for adequate early IOP; gentle, notouch unfolding.	Timely rebubbling for central/ progressive detachments using air or shortacting gas per predefined criteria.	40,41,42
Pupillary block / early pressure spikes	Overtamponade without patent PI can precipitate block; conversely, very low IOP favors detachment.	Create/verify inferior PI; titrate bubble at case end; check pupil and AC dynamics before exit.	Partial bubble release; reconfirm PI; add IOPlowering drops as needed.	28,40,42
Orientation error / excess handling trauma	Inversion, prolonged unscrolling, endothelial touch raise risk of nonadhesion.	Orientation marks (e.g., Sstamp), endotheliumin loading; «notouch» maneuvers; consider preloaded tissue to reduce manipulation.	Prompt reorientation with minimal extra manipulation; secure with appropriate tamponade.	24,45,46,57
Recipient DM lamellar splitting	Traction during descemetorhexis can split DM layers.	Controlled rhexis; avoid scraping; keep the stromal bed smooth.	Polish residual layer; outcomes (VA, thickness, ECL, rebubble) not significantly impacted when polished.	58,59
Posture regimen	Centerdependent; with robust intraop steps, posture may be unnecessary.	If PI + 20% SF_6 and good fill are assured, noposture/brief posturing is acceptable.	Align followup with early rebubble threshold rather than prolonged posturing.	44
Anatomydriven risk (posterior surface irregularity)	Positive/lessnegative posterior irregularities on ASOCT predict rebubbling; risk persists across experience levels.	Preop ASOCT elevation maps for risk triage; plan closer surveillance.	Lower threshold for early rebubbling if clinically significant detachment.	60,61
Glaucoma / device eyes (tubes, trabeculectomy)	Altered chamber dynamics complicate unfolding/ adhesion; higher failure risk signals in some cohorts.	Coordinate tamponade/IOP strategy; in very complex chambers consider UTDSAEK for easier handling.	Early review; proactive rebubbling for significant detachments; tailor steroid taper to IOP risk.	22,62
Donor/source considerations	Concern that prep/handling or donor diabetes could worsen ECL.	Use prestripped/preloaded tissue noninferior to surgeonprepared; donor diabetes does not worsen 1yr ECL/ morphometry.	Standard care - no change solely due to donor diabetes; observe usual ECD/attachment surveillance.	34,57

AC – Anterior Chamber; ASOCT / ASOCT – Anterior Segment Optical Coherence Tomography; DM – Descemet Membrane; DMEK – Descemet Membrane Endothelial Keratoplasty; DSAEK – Descemet Stripping Automated Endothelial Keratoplasty; DSO – Descemet Stripping Only; DWEK – Descemetorhexis Without Endothelial Keratoplasty; ECD – Endothelial Cell Density; ECL – Endothelial Cell Loss; FECD – Fuchs Endothelial Corneal Dystrophy; IOP – Intraocular Pressure; PI – Peripheral Iridotomy; PK – Penetrating Keratoplasty; SF_6 – Sulfur Hexafluoride Gas; UTDSAEK – Ultrathin Descemet Stripping Automated Endothelial Keratoplasty

and ECL,[24] although there may be an increased detachment rate with preloaded compared to surgeon-prepared grafts.[36]

Orientation Marks and StampGuided Unfolding

Use of orientation stamps, particularly the "Sstamp," is a key improvement in reducing intraoperative inversion and excess handling.[37] Orientation errors remain a major contributor to tissue trauma, prolonged unfolding time, and postoperative nonadhesion. Stamped grafts allow instant identification of stromalversusendothelial side during insertion, markedly reducing unnecessary manipulation.[38] Studies consistently show that Sstamped tissue improves surgeons' control of graft orientation and decreases endothelial touch.[39] In combination with "notouch" fluidwave techniques, orientation marking contributes to lower detachment rates, fewer rebubbling procedures, and decreased endothelial loss, making it a cornerstone of contemporary DMEK practice and a recommended step in surgical training curricula.

Outcomes of DMEK

Across short-, mid-, and long-term follow-up, DMEK consistently demonstrates superior visual and endothelial outcomes. Research from multiple cohorts highlights that although ECL follows a characteristic early decline with gradual long-term attrition, overall visual quality and corneal clarity remain well preserved in the majority of patients. Graft detachment and rebubbling are still the most common issues that are encountered in the initial stages, but these are not known to affect the long-term outcome of DMEK. In the following table, the findings of several major studies are summarized (Table 1).

Complications and Management

Partial graft detachment is the most common early complication in contemporary DMEK and often requires rebubbling. The risk increases when early postoperative IOP is low, and is further influenced by older age, diabetes, and

FECD, all of which can weaken early graft–stroma adhesion and raise the chance of re-intervention.[40,41] Maintaining a patent peripheral iridotomy (PI) and a safe, adequate early IOP helps reduce detachment risk.[28] Standardized, checklistdriven protocols for atraumatic unfolding, tamponade targets, and clear rebubbling criteria further lower variability and are associated with fewer rebubbles and less endothelial cost over time.[42]

Anatomical/biomechanical predictors also matter; posterior corneal surface irregularity on preoperative anterior segment optical coherence tomography (ASOCT) elevation maps independently predicts higher rebubbling likelihood and can guide closer surveillance.[43] Pupillary block/IOP imbalance is avoidable by confirming PI patency and titrating the gas bubble; conversely, very low early IOP is itself a detachment signal, underscoring the need for balanced tamponade.[42] Centers using a posturelight or noposture strategy (with reliable PI and 20% SF_6 fill) did not observe higher rebubbling rates, supporting simplified aftercare when intraoperative steps are robust.[44]

Intraoperative challenges such as orientation errors, excess tissue handling, recipient DM lamellar splitting, and visualizationdriven stromal debridement can be mitigated by notouch unfolding techniques and the use of orientation marks such as the Sstamp, which improve graft control and reduce endothelial trauma.[45,46,38] These strategies are consistently emphasized in expert surgical guidance and educational series on overcoming DMEK handling difficulties. When recipient DM splitting occurs, gentle surface polishing is generally sufficient; this approach has not been associated with worsened vision, increased corneal thickness, excess ECL, or higher rebubbling rates when appropriately managed, supporting its safety as part of standardized intraoperative decisionmaking.[47] Similarly, visualizationrelated stromal debridement is understood to act mainly as a marker of case complexity rather than an independent risk factor for postoperative complications, an observation reported in structured analyses of DMEK technique variation.[45] Using eyebank prestripped or preloaded tissue is noninferior to surgeonprepared tissue for detachment and vision and reduces intraoperative manipulation steps.[36]

Eyes with glaucoma procedures or tubes present higher technical complexity for unfolding and adhesion; selection of UTDSAEK may be prudent in the most challenging chambers, and coordination of IOP/tamponade strategy is essential.[48]

Future Direction

DMEK is likely to be complemented and not replaced by tissueefficient and donorsparing strategies. Active fronts include bioengineered/"artificial" endothelial substitutes and carrier membranes to ease global donor shortages, and cellbased regeneration (cultured corneal endothelial cell delivery, DMET, quarter/hemiDMEK, DSO with adjuncts) to restore clarity with less (or no) donor tissue. These approaches aim to maintain DMEKlevel optics while expanding access, particularly in settings with limited eyebank supply.[49,50]

Concurrently, workflow and technique refinements such as validated prestripped/preloaded grafts (noninferior to surgeonprepared for detachment and vision), endoin/endoout delivery systems guided by intraoperative imaging, and standardized protocols are expected to reduce manipulation and variability and shorten the learning curve.[51,35] In the near term, these pragmatic gains will likely raise the baseline safety and consistency of DMEK, while mediumterm biologic/engineered solutions mature to broaden eligibility and durability (Table 2).

Conclusion

DMEK has proven to be the most anatomically precise and visually effective solution for endothelial failure, providing rapid rehabilitation, excellent optical results, and the lowest rejection rates of all endothelial keratoplasty techniques. The development of DMEK, from the initial lamellar techniques to the current standardized and minimally traumatic techniques, has reduced variability in the procedure and increased the range of applicability of DMEK to a wide range of clinical scenarios. Although issues such as graft detachment, ECL, and the complexity of the procedure remain, evidence suggests that these issues can be addressed through careful patient selection, refined technique, and a systematic approach to postoperative management.

Moving forward, developments in bioengineering, cell-based regeneration, preloaded tissue techniques, and imaging-based delivery systems may continue to expand access and longevity, especially in areas where donor tissue scarcity persists. For example, engineered endothelial substitutes, cell-based therapies, and tissue-preserving micrografts may soon support DMEK procedures by eliminating the need for donor tissue and simplifying intraoperative handling. As these technologies continue to progress, the future of endothelial restoration may continue to rely on the synergistic combination of advanced surgical techniques with regenerative and biomaterial-based solutions.

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