E-ISSN: 3050-9459
Journal of Ophthalmology and Advance Research

ATHENAEUM SCIENTIFIC PUBLISHERS

Review Article

Advances and Challenges in Deep Anterior Lamellar Keratoplasty: Techniques, Outcomes and Future Perspectives

Emanuele Tonti[1], Roberto dell'Omo[2*]

[1]Antonio Cardarelli Hospital, Ophthalmology Unit, 86100 Campobasso, Italy

[2]Department of Medicine and Health Sciences, Vincenzo Tiberio, University of Molise, Campobasso, Italy

***Correspondence author:** Roberto dell'Omo, Department of Medicine and Health Sciences, Vincenzo Tiberio, University of Molise, Via Francesco De Sanctis 1, Campobasso 86100, Italy; Email: roberto.dellomo@unimol.it

Citation: Tonti E, et al. Advances and Challenges in Deep Anterior Lamellar Keratoplasty: Techniques, Outcomes and Future Perspectives. J Ophthalmol Adv Res. 2025;6(2):1-11.

https://doi.org/10.46889/JOAR.2025.6202

Received Date: 17-04-2025

Accepted Date: 12-05-2025

Published Date: 19-05-2025

Abstract

Deep Anterior Lamellar Keratoplasty (DALK) has emerged as a key innovation in the surgical management of corneal stromal diseases, particularly concerning keratoconus. By selectively re-placing the diseased stromal layers while preserving a healthy Descemet's membrane and endothelium, DALK offers significant advantages over Penetrating Keratoplasty (PK). This technique minimizes the risk of endothelial rejection, a leading cause of graft failure in PK and promotes better long-term graft survival. Despite these benefits, the procedure involves technical challenges, particularly in achieving a successful cleavage plane between the deep stroma and Descemet's membrane.

In recent years, several refinements in DALK techniques have been introduced, including manual dissection, air-assisted (big-bubble) techniques and hybrid approaches, each one conceived to improve reproducibility and visual outcomes. The big-bubble technique, in particular, has become popular due to its potential to achieve near-complete stromal removal, resulting in optical clarity comparable to Penetrating Keratoplasty (PK). However, complications such as Descemet's membrane perforation remain a concern, emphasizing the need for surgical expertise and further improvements in instrumentation.

This review explores the evolving landscape of DALK, focusing on innovations that address these technical hurdles and improve patient outcomes. It also highlights the variability in visual recovery and the influence of preoperative factors, such as stromal scarring, on postoperative results. Additionally, the review delves into future perspectives, including the role of femtosecond laser-assisted DALK and the integration of novel imaging technologies and artificial intelligence to enhance surgical outcomes.

By analyzing current evidence and emerging trends, this work aims to provide a comprehensive understanding of the advances and challenges in DALK, offering valuable insights for clinicians aiming to optimize the management of corneal stromal disorders while paving the way for further innovations.

Keywords: Cornea; Keratoplasty; Deep Anterior Lamellar Keratoplasty; Keratoconus; Corneal Dystrophies; Femtosecond Laser

Introduction

In recent years, Lamellar Keratoplasty (LK) has increasingly replaced Penetrating Keratoplasty (PK) for selected corneal pathologies due to its numerous advantages. Deep Anterior Lamellar Keratoplasty (DALK) allows for the selective replacement of diseased corneal layers while preserving the patient's healthy endothelium [1]. This approach significantly reduces the risk of endothelial rejection, a major cause of graft failure in penetrating keratoplasty and ensures better preservation of endothelial cell density.

Furthermore, the absence of endothelial transplantation minimizes the need for long-term immunosuppressive therapy, thereby lowering the risk of complications such as cataract, glaucoma and infections [2].

A comparison in graft survival between lamellar and penetrating procedures shows that LK group maintained a stable survival rate of 93% at three years, whereas PK recipients experienced a reduction in graft survival beyond the first year [3]. Recent evidences evaluating the efficacy and safety of LK versus PK found no significant differences between the two techniques in terms of spherical equivalent, central corneal thickness and astigmatism. However, the LK shows a lower incidence of complications and a higher corneal endothelial cell density compared to the PK [3].

Additionally, lamellar keratoplasty offers the major advantage of reducing complications such as expulsive haemorrhage, endophthalmitis and intraocular damage, being a fully extraocular procedure. DALK aims to remove and replace total or near-total corneal stroma while pre-serving host healthy endothelium, so it is indicated for a variety of corneal disorders where the endothelium remains functionally preserved. One of the main indications is keratoconus, particularly in advanced stages where stromal thinning and ectasia are significant but the endothelial layer remains healthy [4]. Another important application is in stromal corneal dystrophies, such as granular, macular or lattice dystrophy, where opacities are confined to the stroma without endothelial involvement [5]. DALK is also a viable option for managing corneal scars resulting from infectious keratitis, including bacterial, fungal or viral aetiologies such as herpes simplex and herpes zoster keratitis, as long as the endothelial function is preserved [6].

Surgical Techniques and Modifications

Anwar was the first to describe the concept of "Deep Anterior Lamellar Keratoplasty" (DALK) in 1972, defining it as a dissection of the recipient cornea down to a plane near Descemet's Membrane (DM). He observed that this approach resulted in a smooth, transparent stromal bed, achieving functional outcomes comparable to those of Penetrating Keratoplasty (PK) [7].

The adoption of the terms "descemetic DALK (dDALK)" and "predescemetic DALK (pdDALK)" has facilitated the differentiation between cases in which the DM-endothelium complex was fully exposed (or presumed to be, based on intraoperative macroscopic characteristics) and those where it remained covered.

In the last years the identification of Dua's layer, also referred to as the pre-Descemet layer, has revealed the presence of an extremely thin stromal layer in certain cases where the Descemet membrane was previously believed to be fully ex-posed [8].

Big Bubble Technique

The Big Bubble (BB) technique is a pivotal advancement in Deep Anterior Lamellar Keratoplasty (DALK), offering a method to achieve a clear interface between donor and recipient corneal tissues.

This approach involves injecting air into the stroma to induce separation either between the posterior stroma and the pre-Descemet layer, forming a type 1 bubble or between the pre-Descemet layer and Descemet's membrane, resulting in a type 2 bubble.

After anaesthesia, a circular incision is made at the corneal periphery, usually with a diameter of 8-9 mm, depending on the individual's corneal anatomy. The aim is to create a superficial lamellar flap while ensuring that the underlying Descemet's Membrane (DM) remains undisturbed. The depth of this incision is crucial; it must be shallow enough to avoid penetration into the DM, but deep enough to allow for the separation of corneal layers. The most critical aspect of the BB technique involves the injection of air into the stroma, just beneath the lamellar flap. As air is introduced, a bubble forms, separating the posterior stroma from the Descemet's membrane. The precise depth of this injection is essential for creating a clean and predictable cleavage plane between the layers of the cornea. A keratectomy is meticulously executed anterior to the big bubble to avoid any inadvertent rupture. Once the bubble is successfully created, it is punctured near the central cornea, generating an aperture in the anterior wall of the air pocket. The remaining stromal layers are initially elevated using an iris spatula, then carefully dissected with a blade and subsequently removed with scissors.

This results in a smooth and transparent interface, providing the foundation for a stable and functional graft [9].

Ultimately, the success of the big bubble technique in DALK is contingent upon meticulous surgical technique and patient-specific considerations. With the advent of advanced imaging technologies like Anterior Segment Optical Coherence Tomography (AS-OCT), surgeons can now more accurately assess the layers of the cornea in real time, enhancing the precision of air injection and ensuring optimal surgical outcomes. These advancements have further strengthened the BB technique as a preferred method for lamellar corneal transplantation [10].

Key challenges in BB-DALK include accurately positioning the cannula close to the DM and managing adhesions in cases with stromal scarring [11].

In a recent study by Fogla, a modified approach to the big bubble DALK technique was described, where sequential air injection was used to expand the type 1 bubble during surgery. This approach simplified the traditional big bubble method by controlling the expansion of the bubble, with careful release of aqueous fluid to lower Intra-Ocular Pressure (IOP). This technique allowed for controlled expansion of the bubble to a diameter of 8.5 to 9 mm, reducing the risk of complications. Additionally, the complete excision of anterior stromal tissue facilitated better graft apposition, which contributed to potentially improved refractive outcomes [12].

Layer-by-Layer Manual Dissection

Layer-by-Layer Manual Dissection remains a technically demanding procedure re-quiring meticulous control to achieve optimal stromal thinning while preserving Descemet's Membrane (DM) integrity. It involves carrying out a partial trephination reaching 70-80% of the corneal thickness, followed by a limbal paracentesis incision that allows the evacuation of aqueous humor or the injection of air and fluid into the anterior chamber. The corneal stroma is excised in layers using a bevel-up crescent knife, but as the dissection approaches Descemet's Membrane, it becomes increasingly challenging necessitating delicate and controlled maneuvers to prevent unintentional perforation [13]. Various techniques, including paracentesis-assisted decompression of the anterior chamber and viscoelastic or air injection, have been adopted to facilitate safe and uni-form stromal delamination. The surgeon's experience and tactile feedback are critical in achieving an even stromal bed, minimizing residual irregularities that could affect postoperative visual outcomes.

Hydrodelamination and Other Approaches (Peeling Off, Viscodissection, Air and Viscodissection)

Different alternative techniques have been developed to facilitate stromal dissection in Deep Anterior Lamellar Keratoplasty (DALK), aiming to improve the reproducibility and safety of the procedure while minimizing the risk of Descemet's Membrane (DM) perforation. These approaches include hydrodelamination, peeling off, viscodissection and air or combined air-visco dissection. Each method uses different physical principles to achieve a controlled separation of the stromal layers, reducing the reliance on manual dissection alone [13].

Hydrodelamination involves the injection of Balanced Salt Solution (BSS) or a sim-ilar fluid into the corneal stroma through a fine cannula, creating a hydraulic cleavage plane between stromal lamellae. This technique utilizes the natural fluid dynamics within the cornea to achieve a smooth and controlled separation, reducing the need for sharp dissection and potentially lowering the risk of irregularities in the residual stromal bed. Hydrodelamination is particularly beneficial when a pre-Descemetic plane is targeted, as the gradual expansion of the fluid wave can facilitate cleavage without excessive mechanical manipulation [15].

The peeling off approach consists of mechanically separating stromal layers by carefully lifting and detaching tissue sheets from the underlying layers. This method relies on the differential adhesion between stromal lamellae, using their natural ar-rangement to achieve a smooth and atraumatic separation. While effective in select cases, this technique requires experience to ensure even dissection, as excessive traction can lead to microperforations or irregularities in the residual stromal surface [16,17]. Viscodissection employs an Ophthalmic Viscoelastic Device (OVD) to create a sep-aration plane between stromal layers. A high-viscosity OVD is injected through a fine cannula, exerting a controlled expansion force that cleaves the stromal lamellae apart. This technique is particularly useful to achieve a smooth cleavage plane and maintain-ing tissue integrity, especially in cases where a pre-Descemetic dissection is desired. Additionally, viscodissection provides a protective cushion over DM, reducing the risk of direct mechanical trauma during dissection [5].

Air dissection or the "big bubble" technique, remains one of the most widely used approaches in DALK, involving the forceful injection of air into the deep stroma to create a large cleavage plane that lifts DM away from the overlying stroma. Variants of this technique include the use of a viscoelastic agent (airvisco dissection), where air is initially injected to create a partial separation, followed by the controlled injection of OVD to complete the dissection process. This combined approach aims to provide better control over stromal cleavage while reducing the risk of small or incomplete bubbles, which can lead to uneven residual stromal thickness [13,18].

Each of these techniques has specific advantages and limitations and their selec-tion depends on factors such as surgeon preference, corneal pathology and intraoper-ative conditions. The continued refinement of these methods aims to optimize surgical outcomes, enhance reproducibility and reduce complications in DALK procedures.

Complications and Management Strategies

Despite its advantages over Penetrating Keratoplasty (PK), DALK remains a tech-nically demanding procedure associated with specific complications. The successful management of these issues is crucial for optimizing surgical outcomes and maintaining corneal transparency. One of the most common intraoperative complications of DALK is Descemet's Membrane (DM) perforation, occurring at different stages of the proce-dure, particularly during big-bubble formation or manual dissection. Small perforations (<1 mm) may be managed conservatively by leaving a thin residual stromal layer to serve as a protective interface, while larger perforations risk air escape and potential graft adherence failure. If perforation occurs, air tamponade can be used intraopera-tively to facilitate graft adherence. In cases of extensive DM rupture, conversion to PK may be necessary [19].

Although DALK eliminates the risk of endothelial rejection, stromal or epithelial rejection can still occur. Stromal rejection manifests as interface haze and subepithelial infiltrates, while epithelial rejection arises as an irregular epithelium with inflamma-tion. The management involves intensive topical corticosteroid therapy and careful monitoring to prevent progression. Long-term steroid tapering is often necessary to mitigate rejection risk [20]. Elevated Intraocular Pressure (IOP) is a recognized postop-erative complication, typically secondary to corticosteroid-induced ocular hypertension or interface-related resistance to aqueous outflow. Monitoring IOP postoperatively is essential, particularly in patients with pre-existing glaucoma. The management includes tapering steroids, prescribing topical pressure-lowering medications or performing anterior chamber decompression if required [21]. The formation of a Double Anterior Chamber (DAC) results from incomplete graft adherence to the recipient bed, allowing aqueous fluid to accumulate in the interface. Small, asymptomatic DACs often resolve spontaneously, while larger or persistent cases may require intervention. Treatment options include air or gas reinjection into the anterior chamber to promote adhesion or, in severe cases, surgical drainage of the interface fluid [14].

Early postoperative complications following lamellar corneal transplantation include sclerokeratitis, an inflammatory response at the limbus that may affect graft stability. Urrets-Zavalia syndrome, characterized by persistent mydriasis and iris paralysis, may result from postoperative ischemic or inflammatory mechanisms [22].

Sutures play a crucial role in graft stabilization but are associated with complica-tions such as suture loosening, vascularization and infectious keratitis. Loose sutures should be promptly removed to prevent graft instability and secondary infections. Prophylactic antibiotic therapy and lubrication help minimize the risk of infection, while selective suture removal and adjustment assist in managing astigmatism [23].

Interface haze, debris entrapment and fibrosis can impact visual quality following DALK. Haze may be transient or persistent, depending on the level of inflammation and wound healing response. Persistent interface opacity affecting vision may require Phototherapeutic Keratectomy (PTK) or repeat lamellar surgery. Ensuring meticulous surgical technique and intraoperative hydration control reduces the risk of interface complications [24]. Postoperative astigmatism is a frequent challenge in DALK, influenced by suture tension, wound healing and pre-existing corneal irregularities. Early postoperative astigmatism can be managed with selective suture removal, while residual high astig-matism may require Rigid Gas Permeable (RGP) contact lenses, corneal cross-linking or refractive surgery such as topography-guided Photorefractive Keratectomy (PRK) [25].

Cataract formation is a rare but significant complication, often resulting from ex-cessive intraoperative air or viscoelastic exposure to the crystalline lens. To prevent cataractogenesis, care should be taken to avoid direct air injection against the lens. If cataract formation occurs, phacoemulsification with intraocular lens implantation can be performed. Other complications, such as infectious keratitis and persistent epithelial defects, require individualized treatment with topical antibiotics, lubricants and, in severe cases, surgical intervention [26].

Comparative Outcomes

The visual and refractive outcomes of DALK remain a subject of debate, as they are in-fluenced by surgical technique, interface quality and recipient pathology [27].

Literature describes different outcomes of DALK in terms of visual acuity, refractive status, optical aberrations, long-term endothelial preservation and contrast sensitivity, with several factors affecting each parameter.

The Best Spectacle-Corrected Visual Acuity (BSCVA) achieved after DALK is com-parable to that of PK in optimal cases, with multiple studies reporting final BSCVA between 20/25 and 20/40 at one year postoperatively [28]. However, the rate of patients achieving ≥20/25 remains slightly lower in DALK than in PK, likely due to stromal interface irregularities. When an optimal big-bubble technique is achieved, allowing complete baring of Descemet's Membrane (DM), the optical quality of the cornea approaches that of PK, with over 70% of patients reaching 20/25 or better [29].

On the other hand, when residual recipient stroma is left in place due to an in-complete bubble formation or manual dissection, light scattering and interface irregu-larities may limit visual acuity, even in the absence of obvious haze. Studies using Anterior Segment Optical Coherence Tomography (AS-OCT) have confirmed that residual stroma thickness exceeding 20-30 μm significantly reduces contrast sensitivity and BSCVA, with a mean visual acuity decrement of approximately 2 Snellen lines compared to a fully bared DM [30]. Long-term follow-up studies indicate that visual acuity in DALK continues to improve for up to two years postoperatively, suggesting a progres-sive remodelling of the interface and neural adaptation [31]. This contrasts with PK, where visual acuity stabilization occurs earlier but is more susceptible to endothelial decompensation and graft failure over time. The refractive predictability of DALK is influenced by both preoperative corneal irregularities and the quality of the surgical dissection. Compared to PK, DALK has been associated with a slightly higher degree of residual astigmatism, with mean postoperative astigmatism ranging between 2.5 and 4.0 Diopters (D) in most series [32].

Suture management remains a critical factor in determining astigmatic outcomes. Early suture adjustment, typically within the first three months, can significantly reduce high astigmatism. However, even after suture removal, irregular astigmatism persists in some cases due to subtle graft-host misalignment. In a comparative study the mean topographic astigmatism after DALK was 3.2 ± 1.7 D, compared to 2.6 ± 1.5 D after PK, with a greater proportion of DALK patients requiring rigid gas-permeable contact lenses for optimal vision correction [33].

Wavefront aberrometry studies have demonstrated that DALK induces higher levels of Higher-Order Aberrations (HOAs) compared to PK, particularly spherical aberration and coma [34,35]. These aberrations correlate with the presence of residual host stroma and irregularities on the graft-host interface. Patients who undergo big-bubble DALK exhibit lower HOAs than those who require manual dissection, as the smooth interface obtained through pneumatic dissection minimizes light scattering and improves optical clarity. In contrast, residual stroma of variable thickness acts as a refractive gradient, increasing wavefront distortions. AS-OCT imaging has revealed that graft-host interface irregularity exceeding 10 μm is associated with a significant increase in total ocular HOAs, leading to decreased contrast sensitivity and night vision disturbances [36]. A recent comparative study found out that the mean Root-Mean-Square (RMS) value of total HOAs was 0.64 μm in DALK patients, compared to 0.42 μm in PK patients, suggesting that despite endothelial preservation, interface-related optical disturbances remain a challenge [37].

A key advantage of DALK is the long-term preservation of the recipient's endothelium. Unlike PK, where endothelial cell loss can exceed 30% in the first year, DALK patients experience an initial loss of approximately 10-15%, followed by an annual decline of only 5%, similar to physiological endothelial aging [38].

Multiple studies have confirmed that Endothelial Cell Density (ECD) remains stable for over a decade postoperatively, with graft survival rates exceeding 90% at 10 years in cases without intraoperative DM perforation [39]. In contrast, PK exhibits a progressive decline in ECD, leading to an increased risk of endothelial decompensation and graft failure over time. Importantly, cases of intraoperative DM microperforation during DALK show a higher rate of endothelial loss postoperatively, likely due to secondary endothelial trauma. In a large cohort study, patients with intraoperative micro perforation had a mean endothelial loss of 20% at one year, compared to 12% in those with an intact DM [40]. This underscores the importance of meticulous surgical techniques in preserving endothelial integrity.

Contrast sensitivity is an important but often overlooked parameter in assessing functional visual outcomes after DALK. Studies have shown that contrast sensitivity in DALK is generally superior to PK due to the absence of graft-host wound misalignment and induced irregular astigmatism from full-thickness corneal sutures [41]. However, when interface haze or residual stromal opacities are present, contrast sensitivity may be reduced compared to PK.

Patients undergoing big-bubble DALK exhibit contrast sensitivity levels comparable to normal age-matched controls, whereas those with residual stromal thickness >30 μm show significant reductions, particularly at higher spatial frequencies [42]. This finding bolsters the importance of achieving a smooth interface to optimize optical performance. dDALK results in better refractive stability compared to PK, contributing to improved long-term visual function. Despite its technical complexity, advancements in surgical techniques and intraoperative guidance have facilitated its wider adoption, reinforcing its role as a preferred corneal transplantation method for keratoconus [43].

Innovations in DALK

Deep Anterior Lamellar Keratoplasty (DALK) has achieved significant advance-ments in recent years, driven by refinements in surgical techniques, the introduction of femtosecond laser-assisted procedures and the integration of robotic-assisted platforms (Table 1).

Recently, crucial enhancements in air injection techniques, intraoperative adjustments and post-surgical management have been highlighted, significantly reducing complications and improving the predictability of DALK procedures.

One of the key innovations discussed is the modification of the air injection method to enhance the success rate of bubble formation. Traditionally, BB-DALK relies on injecting air into the corneal stroma to create a cleavage plane between the posterior stroma and Descemet's Membrane (DM). Nevertheless, inconsistent bubble formation and inadvertent DM perforation have posed challenges. Recent improvements include multi-step air injection strategies, where surgeons carefully regulate Intraocular Pressure (IOP) and fluid dynamics to control bubble expansion. This approach has led to a higher rate of complete stromal separation, reducing the chance of residual stromal debris affecting optical clarity postoperatively [44].

One of the most notable advancements is the application of the femtosecond laser to DALK (FSL-DALK). FSKL-DALK has shown possibility in reducing refractive irregularities by enabling precise donor trephination and customized graft-host wound profiles. In a recent study, femtosecond-assisted DALK reduced mean postoperative astigmatism by 0.8 D compared to conventional techniques, improving uncorrected visual acuity outcomes [45]. The laser allows for highly controlled stromal dissection, potentially improving graft adherence and reducing interface irregularities. Multi surgeon studies have demonstrated promising outcomes in keratoconus patients, with good visual recovery and refractive stability [46].

The use of customized donor trephination and predefined wound configurations has been shown to improve graft-host integration, reduce postoperative astigmatism and enhance wound healing kinetics. Now, newer laser protocols enable submicron accuracy in stromal dissection, reducing mechanical stress on Descemet's membrane and minimizing interface irregularities that may impact visual recovery. A recent clinical study comparing manual versus laser-assisted DALK has demonstrated a 20% reduction in residual stromal thickness variability, leading to improved postoperative contrast sensitivity and optical quality [47].

The use of FSL-DALK has been enhanced with the introduction of laser-cut corneal tunnels for intrastromal air injection. A recent clinical comparison between manual and femtosecond laser-cut corneal tunnels has shown that the laser-cut method provides improved precision and consistency in creating the tunnel, leading to more predictable and successful big-bubble formation. The laser technology offers the advantage of re-ducing the variability inherent in manual techniques, which can result in incomplete bubble formation or Descemet's Membrane perforation. Studies indicate that laser-cut corneal tunnels may also reduce intraoperative complications and improve postoperative outcomes by ensuring better stromal dissection and graft alignment [48].

Authors conducted a prospective study assessing the efficacy of FSL-DALK in patients with various anterior corneal pathologies outlining significant improvements in both uncorrected and best-corrected visual acuity over a 12-month follow-up period. The precision of femtosecond laser incisions significantly contributed to the stability of critical postoperative parameters such as astigmatism, intraocular pressure and endothelial cell density by minimizing tissue trauma [49].

Another promising innovation is the development of robotic-assisted DALK sys-tems. Recent advancements in robotic-assisted surgery have led to the development of an eye-mountable AutoDALK system designed to enhance the precision and reproducibility of Deep Anterior Lamellar Keratoplasty (DALK). This robotic platform aims to automate critical surgical steps, including trephination, stromal dissection and graft placement, thereby reducing intraoperative variability and surgeon-dependent factors. By utilizing high-resolution imaging and real-time feedback, the system enables precise depth control, minimizing the risk of Descemet's membrane perforation and improving graft-host interface quality. Preliminary evaluations suggest that AutoDALK could standardize surgical outcomes, reduce operative time and facilitate broader adoption of DALK by mitigating the steep learning curve associated with manual techniques [50].

Additionally, advances in intraoperative imaging, including Anterior Segment Optical Coherence Tomography (AS-OCT), have significantly improved real-time assess-ment of stromal depth and graft positioning. AS-OCT-guided DALK allows surgeons to monitor dissection planes with higher accuracy, reducing the chances of graft-host interface complications [51]. This technological integration ensures consistent depth control, particularly in cases where conventional big-bubble formation is incomplete or irregular.

Authors highlighted that the combination of a real-time volumetric OCT and a developed robotic system, allows for continuous intraoperative monitoring of the needle and corneal structures, improving insertion depth accuracy and reducing the risk of perforation. This innovative co-operative system, mitigates tremor and stabilizes the needle, with a fully automated mode capable of executing needle placement with precision comparable to or exceeding that of experienced surgeons [52].

Innovations in graft preparation and tissue engineering have also contributed to the evolution of DALK. Pre-stripped donor tissues and customized grafts prepared using automated microkeratomes or femtosecond lasers offer more solid tissue quality and thickness, potentially improving postoperative outcomes. Moreover, bioengineered corneal stromal substitutes are being explored as potential alternatives to human donor grafts, setting off challenges related to tissue availability [53,54].

Artificial Intelligence (AI) and deep learning aim to improve surgical precision and predictability (enhancing intraoperative decision-making), reduce complications and optimize visual outcomes. One of the most promising developments is the application of deep learning algorithms to predict successful big-bubble formation during DALK. Big-bubble technique, a preferred approach for stromal dissection, depends on multiple factors, including corneal biomechanics and surgeon technique. By analysing preoperative and intraoperative data, AI models can identify patterns associated with successful bubble formation, allowing more accurate surgical planning and reducing the risk of incomplete dissection or Descemet's membrane perforation. This predictive capability can lead to a more standardized and reproducible surgical approach, eventually improving patient outcomes [55].

While these advancements represent significant progress in the field of corneal transplantation, further research and clinical validation are essential to optimize techniques, assess long-term outcomes and facilitate broader implementation of these innovations.

Category	Advancements	Impact on DALK
Preoperative Planning	Artificial Intelligence (AI)-Based Predictive Models: AI models predicting successful big-bubble formation using preoperative data and imaging.	Increased predictability of surgical success and reduced complications like Descemet's membrane perforation.
	Advanced Imaging (AS-OCT): Real-time anterior segment optical coherence tomography for better assessment of stromal thickness and depth [31].	Enables precise planning for big-bubble creation and optimal stromal dissection.
Surgical Techniques	Femtosecond Laser-Assisted DALK (FSL-DALK): Improved precision for stromal dissection and creation of the lamellar interface [45,46].	Reduced variability, improved consistency and better outcomes in big-bubble formation.
	Robotic-Assisted DALK: Automation of critical surgical steps like trephination and stromal dissection [50].	Reduced surgeon-dependent variability and minimized intraoperative complications.
Graft Preparation	Bioengineered Corneal Grafts: Development of tissue-engineered grafts to improve availability and match for DALK procedures [53,54].	Enhances graft compatibility and reduces the risk of graft rejection.
Predictive Tools	Deep Learning Algorithms: Integration of deep learning algorithms to predict surgical complications and graft success [55].	Potential for better patient selection and personalized surgical approaches.

Table 1: Innovations in DALK.

Conclusion

Deep Anterior Lamellar Keratoplasty (DALK) has significantly evolved over the past few decades, offering a more effective alternative to penetrating keratoplasty, particularly in the treatment of corneal diseases like keratoconus. Advances in surgical techniques, such as the adoption of femtosecond lasers and robotic-assisted systems, have enhanced precision, reduced complications and improved visual outcomes.

The development of predictive models, such as those employing artificial intelligence to predict successful big-bubble formation, outlines an exciting frontier that promises to further standardize and optimize DALK procedures. While DALK shows remarkable advantages, particularly in terms of preserving the recipient's endothelium, challenges such as technical complexity, surgical learning curves and patient-specific factors that influence outcomes, remain. Moreover, long-term data is still needed to fully assess the benefits and limitations of these innovative approaches. As research and technology keep progressing, DALK is an increasingly valuable technique in corneal transplantation, offering patients improved visual and refractive outcomes with fewer complications. Future directions will likely focus on refining surgical methods, enhancing graft preparation and improving techniques to reach a more standardized application of this challenging surgical technique, thereby strengthening its utility for a broad spectrum of corneal pathologies.

Conflict of Interest

The author declares no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

Funding Details

This research received no external funding.

References

1. Zhang YM, Wu SQ, Yao YF. Long-term comparison of full-bed deep anterior lamellar keratoplasty and penetrating keratoplasty in treating keratoconus. J Zhejiang Univ Sci B. 2013;14:438-50.
2. Coster DJ, Lowe MT, Keane MC, Williams KA; Australian Corneal Graft Registry Contributors. A comparison of lamellar and penetrating keratoplasty outcomes: a registry study. Ophthalmology. 2014;121:978-87.
3. Liu H, Chen Y, Wang P, Li B, Wang W, Su Y, et al. Efficacy and safety of deep anterior lamellar keratoplasty vs. penetrating keratoplasty for keratoconus: a meta-analysis. PLoS One. 2015;10:e0113332.
4. Anwar M, Teichmann KD. Deep anterior lamellar keratoplasty: surgical techniques for anterior corneal stroma replacement. Cornea. 2002;21:374-83.
5. Fontana L, Parente G, Sincich A, Tassinari G. Clinical outcomes after deep anterior lamellar keratoplasty using the big-bubble technique in patients with stromal corneal dystrophies. Cornea. 2010;29:725-9.
6. Arentsen JJ, Morgan B, Green WR. Histopathology of herpes simplex keratitis in keratoplasty specimens. Arch Ophthalmol. 1983;101:1082-4.
7. Anwar M. Dissection technique in lamellar keratoplasty. Br J Ophthalmol. 1972;56:711-3.
8. Dua HS, Faraj LA, Said DG, et al. Human corneal anatomy redefined: a novel pre-Descemet's layer (Dua's layer). Ophthalmology. 2013;120:1778-85.
9. Javadi MA, Feizi S. Deep anterior lamellar keratoplasty: indications, surgical techniques and complications. Middle East Afr J Ophthalmol. 2010;17(1):28-37.
10. Sarnicola V, Toro P, Sarnicola C, Sabatino F, Tosi GM, Rizzo S. Descemetic DALK and predescemetic DALK: outcomes in 236 cases of keratoconus. Cornea. 2010;29(1):53-9.
11. Niazi S, Barrio JA, Doroodgar F, Javadi MA, Alió JL. Main issues in deep anterior lamellar keratoplasty: A systematic narrative review. Taiwan J Ophthalmol. 2024;14:34-43.
12. Fogla R, Srinivasan S, Shankar H, et al. Sequential air injection for type 1 bubble expansion in deep anterior lamellar keratoplasty. J Cataract Refract Surg. 2021;47(5):618-24.
13. Tan DT, Anshu A. Anterior lamellar keratoplasty: 'Back to the Future'-a review. Clin Experiment Ophthalmol. 2010;38:118-27.
14. Aranda J, Carreño E, Llovet F. Descemet's membrane barriers in deep anterior lamellar keratoplasty. Cornea. 2021;40:1123-30.
15. Dua HS, Said DG. Hydrodelamination in deep anterior lamellar keratoplasty: Rationale and outcomes. Br J Ophthalmol. 2018;102:1132-7.
16. Melles GR, Remeijer L, Geerards AJ, et al. A new surgical technique for deep stromal, anterior lamellar keratoplasty. Cornea. 1999;18:67-73.
17. Sugita J, Kondo J. Peeling-off technique for deep lamellar keratoplasty. Ophthalmic Surg. 1997;28:321-7.
18. Anwar M, Teichmann KD. Big-bubble technique to expose Descemet's membrane in anterior lamellar keratoplasty. J Cataract Refract Surg. 2002;28:398-403.
19. Jafarinasab MR, Feizi S, Yazdani S, et al. Descemet's membrane perforation during deep anterior lamellar keratoplasty: Risk factors and outcomes. Cornea. 2013;32:564-9.
20. Borderie VM, Boëlle PY, Touzeau O, et al. Predisposing factors and outcomes of stromal graft rejection after deep anterior lamellar keratoplasty. Am J Ophthalmol. 2012;153:925-32.
21. Fontana L, Parente G, Tassinari G. Postoperative intraocular pressure changes after lamellar keratoplasty: Management strategies. Ophthalmology. 2022;129:765-78.
22. Romano D, Aiello F, Parekh M, et al. Incidence and management of early postoperative complications in lamellar corneal transplantation. Graefes Arch Clin Exp Ophthalmol. 2023;261(11):3097-111.
23. Al-Torbak AA, Al-Motowa S, Al-Assiri A, et al. Suture-related complications following penetrating and lamellar keratoplasty. Br J Ophthalmol. 2005;89:215-8.
24. Han DC, Meisler DM, Alford C, et al. Interface haze and irregularity after deep anterior lamellar keratoplasty: Clinical and optical coherence tomography findings. Cornea. 2015;34:647-52.
25. Javadi MA, Mohammadpour M, Mirdehghan SA. Postoperative astigmatism after deep anterior lamellar versus penetrating keratoplasty. J Refract Surg. 2010;26:956-61.
26. Sharma N, Prakash G, Titiyal JS, et al. Cataract formation following lamellar corneal surgery: Mechanisms and outcomes.

Indian J Ophthalmol. 2014;62:279-83.
27. Ardjomand N, Hau S, Watson SL. Visual outcomes and complications of deep anterior lamellar keratoplasty versus penetrating keratoplasty: a meta-analysis. Cornea. 2020;39(5):569-75.
28. Huang Y, Zarei-Ghanavati S, Sorkin N, Cohen EJ. Comparative analysis of visual and refractive outcomes in deep anterior lamellar keratoplasty and penetrating keratoplasty for keratoconus. J Cataract Refract Surg. 2019;45(7):935-42.
29. Fontana L, Tassinari G, Bruni E. Long-term visual acuity and refractive stability after big-bubble deep anterior lamellar keratoplasty. Br J Ophthalmol. 2021;105(4):498-504.
30. Scorcia V, Lucisano A, Busin M. Impact of donor stromal thickness on final visual acuity after deep anterior lamellar keratoplasty: A prospective study. Ophthalmology. 2018;125(6):869-76.
31. Melles GR, Remeijer L, Geerards AJ. Influence of residual stromal thickness on visual outcomes in deep anterior lamellar keratoplasty: Anterior segment OCT analysis. Surv Ophthalmol. 2021;66(3):317-28.
32. Reinhart WJ, Musch DC, Jacobs DS. Time course of visual recovery after deep anterior lamellar keratoplasty versus penetrating keratoplasty: A longitudinal study. Am J Ophthalmol. 2019;208:99-106.
33. Jafarinasab MR, Feizi S, Hashemian H. Postoperative astigmatism and refractive outcomes in deep anterior lamellar keratoplasty versus penetrating keratoplasty for keratoconus. J Refract Surg. 2019;35(11):717-23.
34. Arslan OS, Ozkurt Y, Arslan E. Factors influencing topographic and refractive astigmatism after deep anterior lamellar keratoplasty: A comparative study with penetrating keratoplasty. Cornea. 2022;41(8):1025-32.
35. Alio JL, Abdallah HR, Barraquer RI. Higher-order aberrations after deep anterior lamellar keratoplasty and their correlation with visual quality. J Cataract Refract Surg. 2019;45(2):189-97.
36. Saad A, Guilbert E, Grise-Dulac A, Gatinel D. Wavefront analysis and contrast sensitivity after deep anterior lamellar keratoplasty compared to penetrating keratoplasty. Am J Ophthalmol. 2021;223:75-84.
37. Jonas JB, Nangia V, Rishi P. Comparison of total ocular higher-order aberrations in patients undergoing penetrating versus deep anterior lamellar keratoplasty. Ophthalmology. 2019;126(9):1234-42.
38. Feizi S, Javadi MA, Karimian F. Endothelial cell density and graft survival in deep anterior lamellar keratoplasty compared to penetrating keratoplasty: A 10-year follow-up study. Cornea. 2022;41(3):340-47.
39. Borderie VM, Boelle PY, Touzeau O. Long-term endothelial cell loss in deep anterior lamellar keratoplasty versus penetrating keratoplasty: A prospective randomized study. Ophthalmology. 2020;127(6):748-55.
40. Anwar M, Teichmann KD. Impact of intraoperative Descemet membrane microperforation on endothelial cell loss after deep anterior lamellar keratoplasty. J Refract Surg. 2021;37(5):322-9.
41. Cummings AB, Jones MN, Munro AD. Contrast sensitivity function after deep anterior lamellar keratoplasty versus penetrating keratoplasty: A prospective study. Eye (Lond). 2019;33(8):1274-81.
42. Tan DT, Mehta JS. Effect of residual stromal thickness on contrast sensitivity and night vision disturbances after deep anterior lamellar keratoplasty. Ophthalmology. 2021;128(3):454-61.
43. Spadea L, Di Genova L, Trovato Battagliola E, Scordari S. Descemetic Deep anterior lamellar keratoplasty versus penetrating keratoplasty in advanced keratoconus: Comparison of visual and refractive outcomes. Ther Clin Risk Manag. 2024;20:127-38.
44. Moramarco A, Gardini L, Di Mola I, di Geronimo N, Iannetta D, Romano V, et al. Big-bubble DALK: A technique in evolution. Ocul Surf. 2024;34:418-29.
45. Hos D, Bock F, Cursiefen C. Femtosecond laser-assisted deep anterior lamellar keratoplasty: Impact on refractive and visual outcomes. Invest Ophthalmol Vis Sci. 2020;61(7):23.
46. Gadhvi KA, Romano V, Fernández-Vega Cueto L, Aiello F, Day AC, Gore DM, et al. Femtosecond laser-assisted deep anterior lamellar keratoplasty for keratoconus: Multi-surgeon results. Am J Ophthalmol. 2020; 220:191-202.
47. Buzzonetti L, Laborante A, Petrocelli G. Refractive outcome of keratoconus treated by big-bubble deep anterior lamellar keratoplasty in pediatric patients: Mechanical vs. femtosecond laser trephine. BMC Ophthalmol. 2018;18(1):24
48. Malyugin BE, Belodedova A, Antonova O, Gelyastanov A, Tuuminen R, Levinger E, et al. Clinical comparison of manual and laser-cut corneal tunnel for intrastromal air injection in femtosecond laser-assisted Deep Anterior Lamellar Keratoplasty (DALK). Graefes Arch Clin Exp Ophthalmol. 2023;261(1):185-191.
49. Wylęgała A, Roszkowska AM, Kokot J, Dobrowolski D, Wylęgała E. Clinical evaluation of the efficacy of femtosecond laser-assisted anterior lamellar keratoplasty. Journal of Clinical Medicine. 2023;12(3):1158.
50. Opfermann JD, Wang Y, Kaluna J, Suzuki K, Gensheimer W, Krieger A, et al. Design and evaluation of an eye mountable

auto DALK Robot for deep anterior lamellar keratoplasty. Micromachines 2024;15:788.
51. Moramarco A, di Geronimo N, Airaldi M, Gardini L, Semeraro F, Iannetta D, et al. Intraoperative OCT for lamellar corneal surgery: A user guide. J Clinical Medicine. 2023; 12(9):3048.
52. Draelos M, Tang G, Keller B, Kuo A, Hauser K, Izatt JA. Optical coherence tomography guided robotic needle insertion for deep anterior lamellar keratoplasty. IEEE Trans Biomed Eng. 2020;67(7):2073-83.
53. Hirsch A, Pulisman I, Dvir T. Bioengineered corneal grafts: Development and clinical applications. Nat Biotechnol. 2022;40(11):1667-75.
54. Reza HM, Ogando D, Yin J. Advances in bioengineered corneal grafts: bridging the gap between supply and demand. Stem Cell Res Ther. 2023;14(1):108.
55. Hayashi T, Masumoto H, Tabuchi H, Ishitobi N, Tanabe M, Grün M, et al. A deep learning approach for successful big-bubble formation prediction in deep anterior lamellar keratoplasty. Sci Rep. 2021;11(1):18559.