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Original Article

Multifactorial analysis of corneal biomechanical stability after deep anterior lamellar keratoplasty: integration of anterior segment imaging indices and ocular response analyzer data

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Abstract: Objective: To identify independent predictors of corneal biomechanical stability after deep anterior lamellar keratoplasty (DALK) by integrating anterior segment imaging indices with Ocular Response Analyzer (ORA) data. Methods: This retrospective case-control study included 209 patients (209 eyes) with advanced-stage keratoconus who underwent DALK at HeBei Eye Hospital between January 2019 and December 2024. Patients were classified into high (n=146) and low (n=63) biomechanical stability groups based on 12-month postoperative clinical status. Preoperative findings included anterior segment imaging metrics (central corneal thickness, thinnest corneal thickness, anterior chamber depth, anterior chamber angle, maximum keratometry, central keratoconus index), ORA-derived biomechanical indices (corneal hysteresis, corneal resistance factor), and perioperative variables (residual stromal bed thickness, intraoperative complications, postoperative steroid duration). Results: Among the 209 enrolled patients, 146 (69.9%) achieved high biomechanical stability, while 63 (30.1%) were classified as having low biomechanical stability. Multivariate logistic regression identified six independent predictors of low biomechanical stability: higher maximum keratometry (odds ratio [OR]=1.164, P<0.001), wider anterior chamber angle (OR=1.099, P=0.004), greater residual stromal bed thickness (OR=1.044, P=0.011), occurrence of intraoperative complications (OR=3.401, P=0.020), lower preoperative corneal hysteresis (OR=0.727, P=0.008), and shorter duration of postoperative steroid use (OR=0.875, P=0.010). Conclusions: Six independent predictors of post-DALK biomechanical stability were identified, spanning preoperative, intraoperative, and postoperative factors. These findings may aid risk stratification, pending prospective validation.

Keywords: Deep anterior lamellar keratoplasty, corneal biomechanics, ocular response analyzer, anterior segment imaging, keratoconus

Introduction

Corneal biomechanics refers to the cornea's response to stress and its ability to return to its original shape. This property is essential for maintaining corneal structure and visual function [1]. This property is not static; surgery alters the cornea's natural biomechanical structure, which may lead to instability. Instability may manifest as alterations in shape, curvature, or refractive outcome [2]. Therefore, careful postoperative assessment of corneal biomechanics is essential to evaluate surgical success and long-term stability.

For patients with advanced keratoconus who can no longer tolerate contact lenses, deep anterior lamellar keratoplasty (DALK) has become the first-line surgical option [3]. DALK only replaces the diseased anterior stroma and preserves the patient's own healthy endothelium and Descemet's membrane. Compared to penetrating keratoplasty (PK), DALK largely eliminates the risk of endothelial rejection, offers longer graft survival, and provides a safer postoperative course with fewer vision-threatening complications [3-5]. These advantages position DALK as a superior treatment for corneal stromal diseases in eyes with healthy endothelium.

However, replacement of the anterior stromal layer creates a complex biomechanical interface between the donor graft and recipient bed.

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Thus, the postoperative biomechanical state of the cornea is not determined solely by the graft's intrinsic properties. It results from the interplay of several factors, including surgical technique, the thickness and quality of the residual host stroma, graft-host junction healing, and the integrity of the preserved posterior layers [6-8]. Understanding these multifactorial contributors is crucial, as poor biomechanical stability can compromise visual quality and lead to complications such as graft ectasia [9].

Modern anterior segment imaging devices give us useful, high-detail images for this analysis. Devices like Scheimpflug tomography (for example, Pentacam) and optical coherence tomography (OCT) can measure important indices without touching the eye. These include corneal thickness distribution, curvature, elevation, and anterior chamber dimensions [10-12]. These topographic and tomographic indices help us describe the shape of the cornea, but they only give an indirect idea of its mechanical strength. In addition, the Ocular Response Analyzer (ORA) can directly measure corneal biomechanical properties in a living eye [13, 14] The ORA is a non-contact tonometer. It uses a puff of air to flatten the cornea and then records hysteresis-based indices. The main ones are corneal hysteresis (CH) and corneal resistance factor (CRF). CH shows the cornea's viscous damping, and CRF shows its overall resistance [15, 16].

Older studies used only imaging indicators or ORA data alone to check the cornea after keratoplasty [17, 18]. But they did not look at both kinds of data together after DALK, creating a deficit in our knowledge. Other reports said that corneal biomechanics after lamellar surgery is not the same as after PK [7, 19]. Some surgical factors can modify this, but we still do not have a good model that incorporates many different kinds of data. Also, many early studies on graft biomechanics came before the new imaging and analysis methods [19]. This created a need for new studies, such as ours. We did a multifactorial analysis of corneal biomechanical stability after DALK for keratoconus. We took numbers from advanced anterior segment imaging and combined them with direct biomechanical data from ORA. The importance of discovering these factors is that it can help doctors decide the risk before surgery, make choices during surgery, and plan special care after surgery so that the graft lasts longer.

Patients and methods

Research design and case selection

This retrospective case-control study included 209 patients (209 eyes) with advanced keratoconus who underwent DALK at HeBei Eye Hospital between January 2019 and December 2024. All patients had the same surgical procedure. One experienced corneal surgeon did all the operations. Demographic information and clinical data were obtained from the electronic medical record system.

Inclusion criteria for the study were as follows: (1) Patients diagnosed explicitly with keratoconus, a diagnosis determined by both clinical evaluation and topographical analysis [20]; (2) Individuals aged from 18 to 45 years at the time of their operation; (3) Those who received a conventional DALK using the big-bubble technique; and (4) Availability of comprehensive clinical data, encompassing metrics from the ORA, tomographic assessments, and pachymetry readings. Conversely, exclusion criteria entailed: (1) Any record of previous ocular surgeries, such as interventions on the cornea, treatments for glaucoma, or refractive surgeries; (2) Cases necessitating an intraoperative switch from DALK to penetrating keratoplasty (PKP) because of a perforation in the Descemet membrane; (3) Presence of active ocular infections or significant inflammation during surgery; (4) Systemic conditions recognized to interfere with corneal healing processes, like collagen vascular diseases or poorly managed diabetes mellitus; and (5) Participants lost to follow-up prior to finishing the one-year post-surgical examination.

Surgical methods and grouping criteria

All DALK procedures were performed by a single experienced corneal surgeon [21]. First, the surgeon made a partial-thickness cut in the patient's cornea. The standard big-bubble technique was used and the cut depth was approximately 60-80% of the peripheral stromal thickness. A 30-gauge needle was then inserted into the deep stroma with the needle bevel faced down. Air was injected with force. This created a type I big bubble. The bubble separated Descemet's membrane (DM) from the stroma above it. If a big bubble did not form, manual stromal dissection was performed. The anterior stroma was then excised. Then the donor corneal graft was taken. The donor graft was 0.25 mm larger in diameter than the recipient bed. The endothelium and DM were carefully removed from the donor graft and the donor graft was fixed to the recipient bed using 16 interrupted 10-0 nylon sutures. The knots were buried inside the recipient stroma. Postoperatively, all patients received topical eye drops; the drops were tobramycin-dexamethasone (Approval No. H20073641; Hangzhou Guoguang Pharmaceutical Co., Ltd.), used four times a day. The dose was reduced over one month. Patients also got 0.1% tacrolimus (Approval No. H20133242; Zhejiang Sanshen Mandi Pharmaceutical Co., Ltd.) twice a day for one year. This was to stop immune rejection.

Patients were classified into two groups based on a standardized composite clinical assessment performed at the 12-month postoperative visit. The high biomechanical stability group (n=146) was defined by the following criteria assessed at the 12-month follow-up: (1) A clinically clear graft with no evidence of immune rejection; (2) A change in maximum keratometry (Kmax) of less than 1.0 diopter compared with the stable 3-month postoperative baseline, as measured by Pentacam HR; and (3) No requirement for any secondary surgical intervention, including re-grafting. Conversely, the low biomechanical stability group (n=63) met at least one of the following criteria: (1) Documentation of one or more episodes of graft rejection requiring intensified medical therapy; (2) Progressive corneal steepening, defined as an increase in Kmax of more than 1.0 diopter from the 3-month postoperative baseline; or (3) The necessity for a repeat keratoplasty or other surgical procedures due to biomechanical or refractive instability. This composite outcome-based classification, which integrates a quantitative biomechanical proxy (keratometry change), a biological event (rejection), and a hard clinical endpoint (re-operation), was adapted from the framework employed by Hosny et al. [22] and avoids reliance on arbitrary cut-offs from a single biomechanical measurement.

Data collection and evaluation methods

Demographic, clinical, and surgical data: Demographic, clinical, and surgical variables were retrospectively collected from medical records as possible predictors of postoperative biomechanical stability. Demographic data included the patient's age at the time of surgery and biological gender. Baseline clinical characteristics encompassed the best-corrected visual acuity (BCVA) converted to LogMAR, intraocular pressure (IOP) measured preoperatively, and the stage of keratoconus as classified by the Amsler-Krumeich system. Preoperative biometric data such as axial length were also recorded. Detailed surgical findings were extracted from operative notes, including the total recorded surgical time, the diameter of the donor button, and the occurrence of intraoperative complications. Additionally, the duration of postoperative steroid use was documented.

Anterior segment imaging and pachymetry values: Comprehensive corneal tomographic and pachymetric data were collected preoperatively using the Pentacam HR (Oculus Optikgeräte GmbH, Wetzlar, Germany) and the Tomey CASIA-2 swept-source anterior segment optical coherence tomography (SS-OCT) device (Tomey Corporation, Nagoya, Japan). The following were recorded: central corneal thickness (CCT) measured as the thickness at the corneal apex; thinnest corneal thickness (TCT) representing the minimal pachymetry value; anterior chamber depth (ACD) and anterior chamber angle (ACA) to assess anterior segment configuration. The maximum keratometry (Kmax) value was derived from the Pentacam keratometry readings. Additional tomographic indices, including central keratoconus index (CKI), was collected to capture disease severity and corneal irregularity. Intraoperatively, the residual stromal bed thickness (RST) was measured using AS-OCT immediately after stromal dissection and just before graft placement to document the thickness of the host bed (**Figure 1**). Anterior chamber width (ACW) was also recorded to complete the preoperative structural profile.

Using ocular response analyzer for corneal biomechanical assessment: At the preoperative baseline, we used the Ocular Response Analyzer (ORA; Reichert Technologies, Depew, NY, USA) to assess corneal biomechanics in live subjects. The ORA device is a non-invasive tool that uses air puffs to measure how the cornea reacts. For each study eye, at least four ORA measurements were obtained, and only measurements with a waveform score of 3.5 or above, indicating a good and symmetrical response curve, were used. From these, the measurement with the highest score was selected

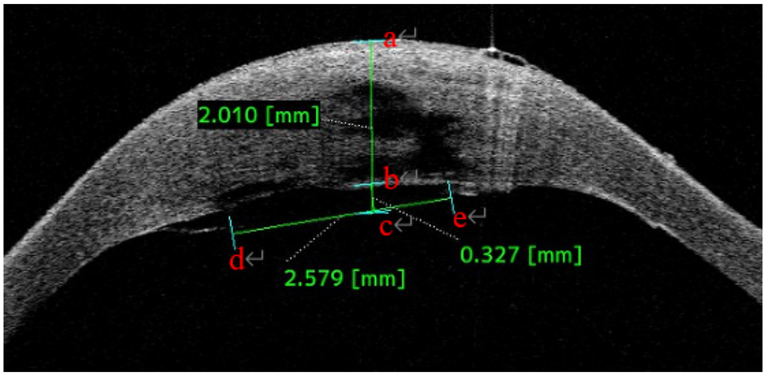

Figure 1. AS-OCT shows corneal edema and thickening, subepithelial bullae, rupture of the Descemet's membrane, and formation of a cleft in the stroma communicating with the anterior chamber during the acute phase of keratoconus.

as the representative value for that eye. The primary outcomes recorded were corneal hysteresis (CH), reflecting the cornea's viscous damping capacity, and the corneal resistance factor (CRF), indicating its overall resistance to deformation. Also, the device gave two types of intraocular pressure readings: Goldmann-correlated IOP (IOPg) and cornea-compensated IOP (IOPcc). We collected all four values (CH, CRF, IOPg, IOPcc) for analysis. These provided a full picture of the biomechanical properties of the cornea. This information could be compared with structural data from imaging of the front part of the eye.

Ethical statement

This retrospective study was conducted in full compliance with the ethical principles outlined in the Declaration of Helsinki. The research protocol, including the waiver of informed consent, was formally reviewed and approved by the Institutional Review Board and the independent Ethics Committee of HeBei Eye Hospital. The waiver of consent was granted because the study involved no more than minimal risk to the subjects, the research could not practicably be carried out without the waiver, and the waiver did not adversely affect the rights and welfare of the patients. All patient data used in this analysis were fully anonymized and de-identified prior to extraction from the electronic health record system for research purposes. Data handling and storage complied with institutional data protection policies and relevant regulations concerning patient privacy and confidentiality for retrospective data reviews.

Statistical method

Statistical analyses were performed using SPSS version 25.0 (SPSS Inc., Chicago, IL, USA) and R software package version 3.0.2 (Free Software Foundation, Inc, Boston, MA, USA). Continuous variables were expressed as mean ± standard deviation (SD) if they followed a normal distribution, or as median with interquartile range (IQR) if they did not. Normality was assessed using the Shapiro-Wilk test. Categorical variables were expressed as frequencies and percentages. Continuous variables were analyzed using unpaired t-tests for normally distributed data, while the Mann-Whitney U test was applied for non-normally distributed data. Categorical variables were compared using the chi-square test or Fisher's exact test, as appropriate. To identify independent predictors of biomechanical instability, we conducted univariate and multivariate logistic regression analyses. Odds ratios (OR) with 95% confidence intervals (CI) were calculated for each parameter as a continuous variable. Variables with a *p*-value <0.10 in the univariate analysis were entered into the multivariate logistic regression model using a stepwise forward selection method to control for potential confounding factors. The multivariate logistic regression model was designated as the primary confirmatory analysis to identify independent predictors, with univariate results serving only as screening steps. This strategy inherently controls for shared variance among predictors and provides a single, integrated model, thereby reducing the risk of false-positive findings that can arise from performing multiple independent univariate statistical tests. A two-tailed *p*-value <0.05 was considered significant. Multicollinearity among independent variables was assessed using variance inflation factors (VIF), with a VIF >10 indicating significant collinearity.

Results

Patient disposition and baseline characteristics

Demographic profiles of the two groups were largely comparable, with one notable excep-

Table 1. Demographic and baseline clinical characteristics

Indicator	High biomechanical stability (n=146)	Low biomechanical stability (n=63)	t/χ²	*P* value
Age (years)	29.93 ± 5.42	27.69 ± 4.11	3.280	0.001
Gender [n (%)]			0.341	0.559
Male	108 (73.97%)	49 (77.78%)		
Female	38 (26.03%)	14 (22.22%)		
BMI (kg/m²)	22.37 ± 2.96	22.19 ± 2.84	0.405	0.686
Smoking history [n (%)]	26 (17.81%)	14 (22.22%)	0.554	0.457
Drinking history [n (%)]	20 (13.70%)	10 (15.87%)	0.169	0.681
Laterality [n (%)]			0.002	0.962
Right eye	77 (52.74%)	33 (52.38%)		
Left eye	69 (47.26%)	30 (47.62%)		

Abbreviations: BMI, body mass index.

Table 2. Disease-related general findings

Indicator	High biomechanical stability (n=146)	Low biomechanical stability (n=63)	t/χ²	*P* value
BCVA (LogMAR)	0.46 ± 0.22	0.53 ± 0.24	1.846	0.066
IOP (mmHg)	14.27 ± 2.61	14.08 ± 2.54	0.482	0.631
Disease Severity [n (%)]			4.217	0.040
Stage III	94 (64.38%)	31 (49.21%)		
Stage IV	52 (35.62%)	32 (50.79%)		
Axial Length (mm)	23.68 ± 0.91	23.74 ± 0.88	0.441	0.659

Abbreviations: BCVA, best-corrected visual acuity; IOP, intraocular pressure.

tion: patients in the low biomechanical stability group were significantly younger (27.69 ± 4.11 years vs. 29.93 ± 5.42 years, P=0.001, **Table 1**). No other demographic differences reached statistical significance, including gender, BMI, or lifestyle factors, suggesting that age may play a distinct role in postoperative biomechanical outcomes.

Table 2 presents the disease-related general findings. The proportion of patients with stage IV keratoconus was significantly higher in the low stability group compared with the high stability group (50.79% vs. 35.62%, P=0.040). Although best-corrected visual acuity tended to be worse in the low stability group, the difference did not reach statistical significance (P=0.066). No significant differences were found in preoperative intraocular pressure or axial length between the two groups (P>0.05). These results indicate that more advanced disease severity may predispose to poorer biomechanical outcomes after DALK.

Preoperative anterior segment imaging indicators

Marked differences in anterior segment architecture emerged between the two groups (**Figure 2**). Patients who later developed biomechanical instability exhibited thinner corneas, as reflected by both central corneal thickness (506.91 ± 44.82 μm vs. 528.63 ± 41.27 μm, P<0.001) and thinnest corneal thickness (492.38 ± 43.17 μm vs. 516.42 ± 40.55 μm, P<0.001). Conversely, these same patients had deeper anterior chambers (3.59 ± 0.33 mm vs. 3.48 ± 0.31 mm, P=0.023) and wider anterior chamber angles (37.84 ± 4.96°vs. 35.17 ± 4.52°, P<0.001). Disease severity indices further distinguished the two groups: maximum keratometry and the central keratoconus index were both significantly elevated in the low stability group (58.63 ± 4.74 D vs. 55.21 ± 4.18 D, P<0.001; 1.05 ± 0.04 vs. 1.03 ± 0.04, P<0.001, respectively). Notably, residual stromal bed thickness measured during surgery was also

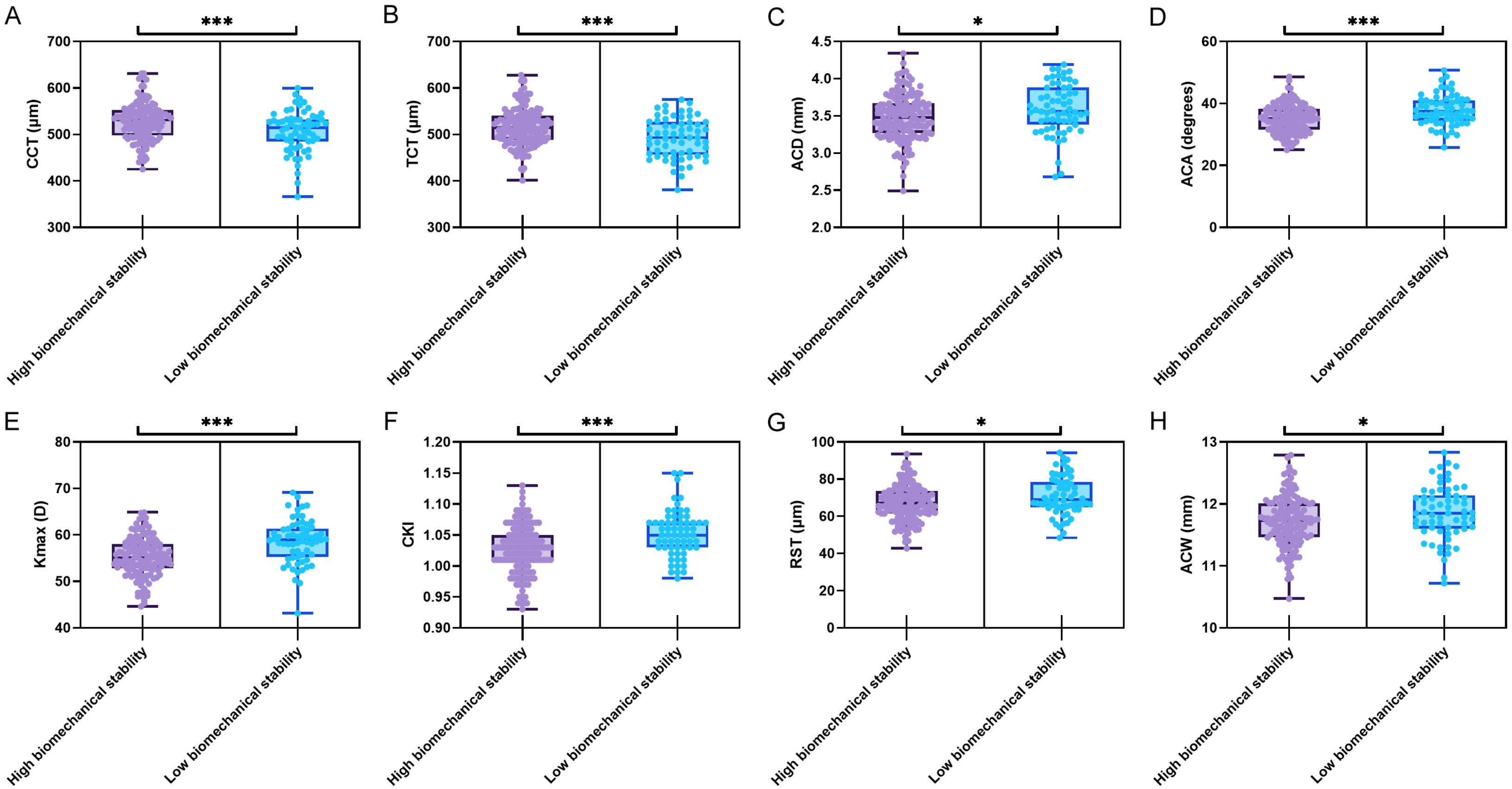

Figure 2. Preoperative anterior segment imaging findings. A. CCT (μm); B. TCT (μm); C. ACD (mm); D. ACA (degrees); E. Kmax (D); F. CKI; G. RST (μm); H. ACW (mm). Abbreviations: CCT, central corneal thickness; TCT, thinnest corneal thickness; ACD, anterior chamber depth; ACA, anterior chamber angle; Kmax, maximum keratometry reading; CKI, central keratoconus index; ACW, anterior chamber width. *P<0.05; ***P<0.001.

Table 3. Preoperative ocular response analyzer indicators

Indicator	High biomechanical stability (n=146)	Low biomechanical stability (n=63)	t	*P* value
CH (mmHg)	9.48 ± 1.29	8.81 ± 1.24	3.466	<0.001
CRF (mmHg)	9.94 ± 1.48	9.23 ± 1.41	3.221	0.001
IOPcc (mmHg)	16.38 ± 2.69	16.71 ± 2.73	0.799	0.425
IOPg (mmHg)	15.12 ± 2.61	15.04 ± 2.57	0.200	0.842

Abbreviations: CH, corneal hysteresis; CRF, corneal resistance factor; IOPcc, cornea-compensated intraocular pressure; IOPg, Goldmann-correlated intraocular pressure.

greater in the low stability group (71.07 ± 10.28 μm vs. 67.38 ± 9.46 μm, P=0.013), as was anterior chamber width (11.86 ± 0.44 mm vs.11.72 ± 0.41 mm, P=0.029). Collectively, these findings indicated a preoperative structural profile characterized by more advanced ectasia and a thicker residual stromal layer in eyes that ultimately exhibited worse biomechanical outcomes.

Preoperative corneal biomechanical indices

Table 3 presents the preoperative corneal biomechanical indices measured with the ORA, along with comparisons between the two groups. The low stability group had lower CH (8.81 ± 1.24 mmHg vs. 9.48 ± 1.29 mmHg. The difference was significant (P<0.001). The low stability group also had lower corneal resistance factor (CRF). Their CRF was 9.23 ± 1.41 mmHg. The high stability group had CRF 9.94 ± 1.48 mmHg. The difference was also significant (P=0.001). For cornea-compensated intraocular pressure (IOPcc) and Goldmann-correlated intraocular pressure (IOPg), there was no significant difference between the two groups. Both *P* values were >0.05. These findings indicate that lower preoperative corneal viscoelastic damping capacity means worse postoperative biomechanical outcomes; and also lower resistance to deformation means worse outcomes.

Perioperative and graft-related indicators

Surgical and postoperative factors also differed between the two groups (**Table 4**). Intraoperative complications occurred more frequently in the low stability group (14.29%) than in the high stability group (4.11%, P=0.020). Patients in the low stability group used steroid drops for a shorter time. Their average was 12.79 weeks. The high stability group used them for 14.03 weeks. The *P* value was 0.011. While there were significant differences for surgical duration, graft size, and anesthesia type, there were no other differences between the two groups so the likely reasons for the bad outcomes were: having problems during surgery, and not using steroids long enough after surgery. The manner in which surgery was done (such as how long it took or what size graft) did not matter.

Correlation and regression analyses

In the correlation analysis of factors associated with low biomechanical stability (**Table 5**), several indicators showed significant associations. Age, corneal thickness, corneal hysteresis, corneal resistance factor, and length of steroid use had negative correlations. On the other hand, disease severity (stage IV), anterior chamber angle, keratometry values, residual stromal bed thickness, and intraoperative complications had positive correlations and the univariate logistic regression analysis (**Table 6**) backed these findings. Younger age, more severe disease, thinner corneas, steeper keratometry, wider anterior chamber angle, thicker residual stromal bed, lower biomechanical indicators, intraoperative complications, and shorter steroid use were identified as risk factors. Prior to constructing the multivariate logistic regression model, multicollinearity among the candidate predictor variables was formally assessed using variance inflation factors (VIF). All VIF values were below 10 (range: 1.12-3.84), confirming the absence of significant collinearity. The odds ratios for anterior chamber depth (OR=3.014) and intraoperative complications (OR=3.889) indicated strong effects After adjusting for possible confounders, multivariate logistic regression (**Table 7**) found six independent predictors of low biomechanical stability. Higher maximum keratometry (OR=1.164, P<0.001), wider anterior chamber angle (OR=1.099, P=0.004), greater residual stromal bed thickness (OR=1.044, P=0.011), and intraoperative complications (OR=3.401, P=0.020) increased the risk. In contrast, higher preoperative corneal hysteresis (OR=0.727, P=0.008)

Table 4. Perioperative and graft-related indicators

Indicator	High biomechanical stability (n=146)	Low biomechanical stability (n=63)	t/χ^2	*P* value
SDur (min)	83.27 ± 15.84	79.31 ± 12.96	1.749	0.082
GSize (mm)	8.09 ± 0.43	8.12 ± 0.39	0.392	0.695
IOC [n (%)]			5.399	0.020
Yes	6 (4.11%)	9 (14.29%)		
No	140 (95.89%)	54 (85.71%)		
Anes [n (%)]			0.136	0.712
General anesthesia	54 (36.99%)	25 (39.68%)		
Local anesthesia	92 (63.01%)	38 (60.32%)		
Postop Steroid (weeks)	14.03 ± 3.37	12.79 ± 2.83	2.555	0.011

Abbreviations: SDur, surgical duration; GSize, graft size; IOC, intraoperative complications; Anes, type of anesthesia; Postop Steroid, duration of postoperative steroid use.

Table 5. Correlation analysis of preoperative, intraoperative, and postoperative variables with low biomechanical stability after DALK

Variable	rho	*P* value
Age (years)	-0.224	0.001
Disease Severity (Stage IV)	0.142	0.040
CCT (μm)	-0.211	0.002
TCT (μm)	-0.234	<0.001
ACD (mm)	0.166	0.017
ACA (degrees)	0.239	<0.001
Kmax (D)	0.338	<0.001
CKI	0.292	<0.001
RST (μm)	0.157	0.023
ACW (mm)	0.154	0.026
CH (mmHg)	-0.222	0.001
CRF (mmHg)	-0.192	0.005
IOC (Yes)	0.181	0.009
Postop Steroid (weeks)	-0.167	0.016

Abbreviations: CCT, central corneal thickness; TCT, thinnest corneal thickness; ACD, anterior chamber depth; ACA, anterior chamber angle; Kmax, maximum keratometry; CKI, central keratoconus index; RST, residual stromal bed thickness; ACW, anterior chamber width; CH, corneal hysteresis; CRF, corneal resistance factor; IOC, intraoperative complications.

and longer postoperative steroid use (OR= 0.875, P=0.010) were protective factors. These results highlight that many factors affect biomechanical outcomes after DALK surgery. Preoperative structure and biomechanics, how the surgery is done, and postoperative management all played independent roles.

Discussion

This study looked at corneal biomechanical stability after DALK. We studied a large group of patients with advanced keratoconus. We incorporated three types of data: preoperative anterior segment imaging, ORA biomechanical measurements, and perioperative clinical information. Then we found that structural, mechanical, and surgical factors all work together to determine the status of the cornea after surgery. The results showed that stability after DALK is not just from the graft itself, but it also reflects the host's disease severity, the leftover bed quality, problems during surgery, and how the patient is managed after surgery.

Age at surgery also differed significantly between groups. The low stability group had younger patients. This matches what Feizi et al. [19] found. They suggested that younger age may cause more aggressive ectasia as well as a stronger healing response after surgery. Thus, younger patients may be at higher risk of worse biomechanical outcomes. Young corneas have more biological activity. For example, they have more enzymes and more inflammation signals. This may speed up the remodeling at the graft-host interface. It may also lead to late steepening of the cornea [23-25]. Niazi et al. [6] also suggested this in their review of DALK results.

Preoperative structural indicators revealed a distinct morphological profile in eyes that later developed biomechanical instability. These patients exhibited thinner central and thinnest corneal thicknesses, steeper maximum keratometry, and more advanced disease severity, as reflected by a higher proportion of stage IV keratoconus. These observations are consistent with the finite element modeling work of Li et al. [7], who demonstrated that the biomechanical behavior of the post-DALK cornea is

Table 6. Univariate logistic regression analysis of factors associated with low biomechanical stability after DALK

Variable	Coefficient	Std Error	Wald	*P* Value	OR	CI Lower	CI Upper
Age (years)	-0.088	0.031	2.837	0.005	0.915	0.860	0.972
Disease Severity (Stage IV)	0.624	0.306	2.041	0.041	1.866	1.026	3.409
CCT (μm)	-0.012	0.004	3.218	0.001	0.988	0.980	0.995
TCT (μm)	-0.014	0.004	3.610	<0.001	0.986	0.978	0.993
ACD (mm)	1.103	0.492	2.242	0.025	3.014	1.169	8.113
ACA (degrees)	0.121	0.034	3.557	<0.001	1.129	1.058	1.210
Kmax (D)	0.184	0.04	4.630	<0.001	1.202	1.116	1.305
CKI	0.461	0.118	15.280	<0.001	1.586	1.263	1.992
RST (μm)	0.039	0.016	2.456	0.014	1.040	1.008	1.073
ACW (mm)	0.799	0.371	2.155	0.031	2.223	1.088	4.680
CH (mmHg)	-0.407	0.124	3.297	<0.001	0.665	0.518	0.843
CRF (mmHg)	-0.344	0.111	3.084	0.002	0.709	0.565	0.877
IOC (Yes)	1.358	0.551	2.465	0.014	3.889	1.339	12.095
Postop Steroid (weeks)	-0.122	0.049	2.487	0.013	0.885	0.801	0.972

Abbreviations: CCT, central corneal thickness; TCT, thinnest corneal thickness; ACD, anterior chamber depth; ACA, anterior chamber angle; Kmax, maximum keratometry; CKI, central keratoconus index; RST, residual stromal bed thickness; ACW, anterior chamber width; CH, corneal hysteresis; CRF, corneal resistance factor; IOC, intraoperative complications; OR, odds ratio; CI, confidence interval.

Table 7. Multivariate logistic regression analysis of independent predictors for low biomechanical stability after DALK

Variable	Coefficient	Std Error	Wald	*P* Value	OR	CI Lower	CI Upper
Kmax (D)	0.152	0.041	3.707	<0.001	1.164	1.074	1.262
CH (mmHg)	-0.318	0.119	2.672	0.008	0.727	0.576	0.918
ACA (degrees)	0.094	0.033	2.848	0.004	1.099	1.030	1.172
RST (μm)	0.043	0.017	2.529	0.011	1.044	1.010	1.079
IOC (Yes)	1.224	0.526	2.327	0.020	3.401	1.214	9.528
Postop Steroid (weeks)	-0.134	0.052	2.577	0.010	0.875	0.788	0.971

Abbreviations: CH, corneal hysteresis; ACA, anterior chamber angle; RST, residual stromal bed thickness; IOC, intraoperative complications; OR, odds ratio; CI, confidence interval.

heavily influenced by the preoperative ectatic status. A thinner and steeper host cornea represents a more compromised structural foundation, which, even after successful lamellar replacement, may provide insufficient mechanical support to resist long-term deformation [26-28]. Furthermore, the deeper anterior chambers and wider anterior chamber angles observed in the instability group corroborate the findings of Toprak et al. [20], who identified these tomographic features as markers of advanced ectasia, indicating a more globally altered ocular structural environment.

An intriguing finding of this study was that greater residual stromal bed thickness (RST) emerged as an independent risk factor for low biomechanical stability, which appears counterintuitive given that a thicker residual layer might be expected to confer greater structural support. To interpret this seemingly paradoxical result, the specific clinical context of advanced keratoconus surgery must be considered. In eyes with severely ectatic and fragile corneas, the surgeon may intentionally preserve a thicker residual stromal layer as a precautionary measure to avoid intraoperative complications such as microperforation or Descemet's membrane rupture. Consequently, a thicker RST in the low stability group may not reflect a robust residual bed, but rather serves as an indirect marker of a fundamentally weaker and more pathologically compromised host cornea that necessitated a more conservative dissection

[29, 30]. This interpretation aligns with the finite element analysis by Chen et al. [8], which demonstrated that the biomechanical integrity of the graft-host interface is critically dependent on the intrinsic quality and uniformity of the residual host tissue. If the preserved stromal bed is structurally inferior, even a greater absolute thickness may be insufficient to resist long-term biomechanical deformation, predisposing the eye to postoperative instability.

The preoperative biomechanical profile, as assessed by the ORA, was also a powerful determinant. Patients with lower CH and CRF were at substantially higher risk of postoperative instability. These findings are in agreement with the work of Greenstein et al. [16], who established CH as a sensitive indicator of corneal viscoelasticity and overall structural integrity. A low preoperative CH reflects a cornea with diminished capacity to dissipate mechanical energy, a property that likely persists even after stromal replacement, contributing to an ongoing vulnerability to deformation. Ramirez-Miranda et al. [15] emphasized that such baseline biomechanical weakness may limit the cornea's ability to maintain its curvature and refractive stability after any surgical intervention.

Perioperative and postoperative factors added further layers of complexity. The occurrence of intraoperative complications, such as microperforations or the need for manual dissection, was a strong independent predictor of a poor biomechanical outcomes. This finding was supported by Akdemir et al. [18], who compared big-bubble versus manual lamellar dissection in DALK and reported that technically challenging cases with intraoperative disruptions were associated with greater postoperative topographic changes and irregular astigmatism. Such complications likely create an irregular graft-host interface, induce aberrant wound healing with excessive fibrosis or inadequate tissue apposition, and ultimately compromise the mechanical integrity of the surgical construct.

The duration of postoperative steroid use emerged as a protective factor in the multivariate model, with longer steroid use associated with a lower risk of biomechanical instability. This result highlights the critical role of modulating the postoperative inflammatory response in preserving graft stability. Aldebasi et al. [5] noted that effective control of inflammation is essential for proper graft-host integration and the prevention of rejection episodes, which themselves can trigger biomechanical deterioration. Prolonged steroid use may mitigate the fibrotic and remodeling processes that can lead to interface irregularities and progressive steepening, underscoring the importance of individualized anti-inflammatory regimens [31, 32].

From a clinical perspective, our analysis provides a framework. Clinicians can use it to assess risk before surgery. They can also plan care after surgery. We found that independent predictors included high preoperative Kmax, wide anterior chamber angle, low CH, thick RST, problems during surgery, and short steroid use. These factors are useful for clinicians. Before surgery, patients with severe ectasia and poor biomechanical indicators may need more follow-up, or doctors may think about extra treatments. For example, they could do cross-linking in the leftover stromal bed. In addition to taking care of these factors, the use of steroids for a longer time after surgery seems protective. So a longer anti-inflammatory treatment may help high-risk patients. This is not a one-size-fits-all plan anymore. Instead, a risk-based strategy may improve long-term graft survival and vision results.

Several limitations should be acknowledged. Our study was retrospective and single-center, which may have introduced selection biasIt also limited how much we can generalize the results. We used strict inclusion criteria and multivariate models to control confounders. But some unmeasured variables may still have affected outcomes: for example, small differences in surgical technique, or how well patients used their eye drops after surgery. Second, the study design was limited to the analysis of preoperative ORA indicators as predictors of a composite 12-month clinical outcome; systematic, serial postoperative biomechanical measurements at multiple time points were not collected. Consequently, we were unable to observe the dynamic temporal evolution of corneal hysteresis, corneal resistance factor, and related metrics during the critical period of graft-host biomechanical integration. This represents an important direction for future prospective studies, which should incorporate scheduled ORA assessments at multiple postoperative intervals (e.g., 1, 3, 6, and 12 months) to delineate the time-dependent trajectory of biomechanical remodeling after DALK and to identify critical windows during which early biomechanical deterioration may be detected. We used CH and CRF as biomechanical markers. These are well-validated but they do not fully show the complex, anisotropic mechanical properties of the cornea. Future studies should be prospective and include multiple centers. We should also do longitudinal biomechanical profiling and use advanced imaging like Brillouin microscopy or optical coherence elastography. This would help us understand the dynamic remodeling after DALK and confirm the risk factors found by this study.

Conclusion

This study demonstrated that corneal biomechanical stability after DALK is influenced by multiple factors working together. They include how severe the disease is before surgery, the cornea's own weak biomechanical properties, surgical events, and how inflammation is controlled after surgery. Our analysis found several independent predictors of instability. These were high preoperative Kmax, wide anterior chamber angle, low corneal hysteresis, thick residual stromal bed, intraoperative complications, and shorter steroid use. Based on these findings, we propose a shift in clinical strategy: before surgery, we risk should be evaluated in a stratified way. After surgery, we should make personalized plans for each patient. This may help improve long-term graft survival and functional results.

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Disclosure of conflict of interest

None.

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