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ORIGINAL RESEARCH

Corneal Biomechanics Before and After Descemet Membrane Endothelial Keratoplasty in Patients with Fuchs Endothelial Corneal Dystrophy

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Purpose: Descemet Membrane Endothelial Keratoplasty (DMEK) is a surgical intervention for restoring endothelial function in Fuchs endothelial corneal dystrophy (FECD). However, changes in corneal biomechanical properties assessed using dynamic Scheimpflug analyzer (DSA) remain limited. This study aimed to assess alterations in corneal biomechanical parameters before and after surgery in patients with FECD using DSA.

Patients and Methods: This prospective study included 24 FECD patients. Demographic data, visual acuity, central corneal thickness (CCT), endothelial cell count, intraocular pressure (IOP), stress strain index (SSI) and others DSA parameters were evaluated. Measurements were obtained preoperatively and at 1, 3, and 6 months after surgery. Repeated measures analysis of variance and pairwise correlations were used to assess differences and associations.

Results: Significant postoperative alterations were observed in multiple corneal biomechanical parameters. CCT, ARTh, A1 length, A1 DefA and SPA showed significant reductions over time. Conversely, the DefA max, maximum inverse radius, DA ratio, integrated radius and CBI significantly increased during follow-up. While, SSI remained stable at all time points. These findings demonstrate a biomechanical transformation following DMEK from 1 to 6 months postoperatively, reflecting the transition from a swollen, thickened cornea to a thinner, clearer cornea in the postoperative state.

Conclusion: DMEK resulted in reduced corneal thickness and significant changes in several corneal biomechanical parameters. However, the stability of SSI, which is independent of CCT and bIOP, suggests that intrinsic corneal stiffness remains unchanged despite postoperative remodeling. The observed biomechanical alterations may provide useful markers for monitoring corneal recovery following DMEK.

Plain Language Summary: Fuchs Endothelial Corneal Dystrophy (FECD) is a common condition that affects the back layer of the cornea. In FECD, the cells that keep the cornea healthy gradually die, causing swelling, blurred vision, and glare. Descemet Membrane Endothelial Keratoplasty (DMEK) can replace the damaged cells and restore vision. However, DMEK's effect on cornea strength and how it responds to pressure remains unclear.

In this study, we followed 24 patients with FECD who underwent DMEK surgery. We measured how their corneas responded to small air pulses using a special imaging tool called a Dynamic Scheimpflug Analyzer. We also measured corneal thickness, eye pressure, and vision before surgery and 1, 3, and 6 months afterward.

We found that DMEK improved vision and reduced corneal swelling in all patients. Many of the cornea's mechanical properties changed after surgery, mostly because the cornea became thinner and less swollen. Importantly, the stress–strain index, which reflects the cornea's true stiffness, did not change. This means that DMEK restores corneal shape and function without altering the tissue's natural strength.

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These results show that DMEK effectively improves vision and corneal health. Measuring corneal properties after surgery can help doctors monitor recovery and understand how the cornea adapts. This research also highlights which measurements reflect real tissue changes and which are influenced by swelling, guiding future studies and patient care.

Keywords: corneal stiffness, corneal remodeling, Fuchs endothelial corneal dystrophy, Corvis ST, corneal edema, dynamic Scheimpflug analysis, descemet membrane endothelial keratoplasty, stress–strain index

Introduction

Fuchs Endothelial Corneal Dystrophy (FECD) is the most common bilateral disorder of the corneal endothelium.[1] The pathophysiology of FECD is characterized by the progressive loss of endothelial cells and the development of focal posterior excrescences on the Descemet membrane, known as “guttae”.[2] These alterations can affect the corneal stroma, extending from the central region toward the periphery.[3]

Early investigations into these alterations utilized the Ocular Response Analyzer (ORA) to measure corneal hysteresis (CH) and the corneal resistance factor (CRF).[4–8] However, findings have been inconsistent: while three studies reported reduced CH and CRF in FECD patients,[5–7] another observed increased values six months following Descemet membrane endothelial keratoplasty (DMEK).[7]

This variability highlights the limitations of CH as a surrogate for corneal biomechanical integrity. The cornea exhibits complex, nonlinear stress–strain behavior; its response to loading and unloading is distinct and influenced by a multifactorial interplay of stromal constituents. CH and CRF are significantly confounded by central corneal thickness (CCT) and intraocular pressure (IOP), which complicates the isolation of intrinsic material properties, particularly in eyes undergoing surgical remodeling.[9]

To overcome these limitations, the Dynamic Scheimpflug analyzer (DSA) has emerged as a more robust assessment tool. Unlike air-pulse systems that rely on pressure differentials, the DSA uses high-speed imaging to capture the real-time corneal configuration during applanation. Crucially, it yields the stress–strain index (SSI), a parameter derived to evaluate corneal stiffness independently of IOP and CCT.[4,10]

Despite the theoretical advantages of the SSI, evidence regarding its utility in post-DMEK longitudinal cohorts remained limited. Previous literatures were restricted by short follow-up durations (≤6 months), failing to capture the full trajectory of biomechanical recovery.[4,10] This study addresses this knowledge gap by prospectively evaluating longitudinal changes in biomechanical properties over a 6-month period following DMEK. The primary objective was to determine whether postoperative changes in corneal biomechanics in FECD can serve as a novel biomarker to optimize the timing of Descemet membrane endothelial keratoplasty (DMEK).

Materials and Methods

This prospective study was conducted at the Department of Ophthalmology, Faculty of Medicine, Chulalongkorn University. The study was adhered to the principles of the Declaration of Helsinki and approved by the Institutional Review Board of the Faculty of Medicine, Chulalongkorn University (No. 808/62) and registered with the Thai Clinical Trial Registry (TCTR ID: TCTR20191124002).

Twenty-four patients with FECD scheduled for DMEK were enrolled. Eligibility criteria included an age of 18 years or older and the presence of visually significant FECD. Exclusion criteria were applied to eyes with ocular comorbidities, such as glaucoma, uveitis, or retinal disorders. Furthermore, patients were excluded if there was a history of prior ocular surgery—with the exception of uncomplicated cataract surgery performed at least 3 months prior—keratoconus, subclinical keratoconus, corneal ectasia, or contact lens use. In bilateral cases, the eye with more advanced disease was selected for analysis. Written informed consent was obtained from all participants.

DMEK was performed using standard techniques under retrobulbar anesthesia with 2% lidocaine. The anterior chamber was maintained with ophthalmic viscosurgical devices, and Descemet membrane was scored over an 8.0–9.0-mm diameter via a 2.75-mm temporal incision. The graft (7.0–8.0 mm) was prepared, loaded into a modified

Jones tube, and injected into the anterior chamber. After positioning with an unfolding technique, 20% sulfur hexafluoride gas was injected to stabilize the graft.[11]

Ophthalmic examinations, including specular microscopy (CEM-530, Nidek, Japan), non-contact tonometry (NT-530/510, Nidek, Japan), corneal biomechanical assessment using DSA (Corvis ST: Oculus Optikgerate GmbH, Wetzlar, Germany), and corneal tomography using a rotating Scheimpflug camera (Pentacam: Oculus Optikgerate GmbH, Wetzlar, Germany), were performed by a single experienced technician. Measurements were repeated at least three times to meet the quality criteria, and only qualified images were included in the analysis. The Corvis ST is a non-contact tonometer that evaluates the dynamic corneal response (DCR) to an air pulse using an ultra-high-speed Scheimpflug camera to capture 4330 images over an 8-mm central cornea zone along a single horizontal meridian. Data were analyzed using software version 1.3r1538. All parameters were assessed preoperatively and at 1, 3, and 6 months after DMEK graft was attached. Measurements were performed only after full graft adherence was confirmed. In cases requiring rebubbling, data were collected after complete graft attachment was confirmed.

Data collected include demographic characteristics, uncorrected visual acuity (UCVA), best-corrected visual acuity (BCVA), central corneal thickness (CCT), and Ambrosio Relational Thickness to the horizontal profile (ARTh), measured using a Pentacam. Endothelial cell count (ECC) was assessed using specular microscopy, and intraocular pressure (IOP) was measured using automated tonometry. Endothelial cell count of donor graft was also recorded. The percent of endothelial cell loss (ECL) was calculated with the following formula: ECL = ((baseline donor ECC – post-op ECC) / baseline donor ECC) x 100.

Corneal biomechanical parameters were obtained using the Corvis ST (DSA), including non-contact IOP (nct IOP), biomechanically corrected IOP (bIOP), A1 length, A2 length, A1 velocity, A2 velocity, peak distance (PD), A1 deflection amplitude (A1 DefA), maximum deflection amplitude (DefA max), deformation amplitude ratio at 2 mm (DA ratio), maximum inverse radius, integrated radius, stiffness parameter at first applanation (SPA1), SSI, and the Corvis Biomechanical Index (CBI). Descriptions of all parameters are provided in Table 1.

Table 1 Description of All Parameters

	Definition
Static parameters	
Parameters measured by Pentacam	
Central corneal thickness (CCT)	Automatically calculated from the optical pachymetry data at the corneal apex
Ambrosio relational thickness horizontal (ARTh)	Calculated by dividing the thinnest corneal thickness by the maximum pachymetric progression index (PPImax.) along the horizontal axis
Corneal biomechanic parameters measured by Corvis ST	
Biomechanical-corrected IOP (bIOP)	An estimate of the intraocular pressure that accounts for the influence of corneal biomechanical properties
Deformation-related parameters	
Corneal biomechanic parameters measured by Corvis ST	
Non-contact IOP (nct IOP)	An intraocular pressure that measures by using a puff of air to momentarily flatten the cornea and an ultra-fast camera to track the deformation
A1 Length (mm.)	Lengths of flattened cornea during at 1st applanation (inward movement)
A2 Length (mm.)	Lengths of flattened cornea during at 2nd applanation (outward movement)
A1 Velocity (m/s)	Corneal velocity (maximum) at 1st applanation

(*Continued*)

Table 1 (Continued).

	Definition
A2 Velocity (m/s)	Corneal velocity (maximum) at 2nd applanation
Peak distance (PD) (mm.)	Distance between humps of cornea during maximum inward movement
Maximum deflection amplitude (DefA max) (mm.)	The maximum outward displacement of the corneal apex during an air puff test, calculated by subtracting the whole-eye movement from the total deformation amplitude
A1 Deflection amplitude (A1 DefA) (mm.)	The displacement of the central point (apex) of the cornea relative to its original, undeformed position at the A1 moment, after correcting for any overall eye movement
Deformation amplitude at 2 millimeters from apex (DA ratio) (mm.)	Calculated as the ratio of the deformation amplitude at the peripheral cornea (measured at 2 mm from the apex) to the deformation amplitude at the apex
Max inverse radius ($mm.^{-1}$)	The inverse radius of curvature at highest concavity
Integrated inverse Radius ($mm.^{2}$)	Area under inverse radius curve
Stiffness-related parameters	
Corneal biomechanic parameters measured by Corvis ST	
Corvis Biomechanical Index (CBI)	A composite diagnostic parameter calculated by the Corvis ST that combines corneal deformation parameters and thickness profiles to detect corneal ectasia (such as keratoconus).
Corneal stiffness parameter at the first applanation (SPA1) (mmHg/mm.)	The load at applanation divided by displacement from undeformed to A1
Corneal stress-strain index (SSI)	Stress-strain curves describe the intrinsic elastic properties of the cornea

Statistical analyses were performed using SPSS version 24.0 (IBM Corp., Armonk, NY, USA). Descriptive data are presented as mean ± standard deviation (SD). The primary outcome of the study was the stress–strain index (SSI), while other biomechanical parameters were considered secondary endpoints. Changes in these parameters over time were analyzed using repeated-measures analysis of variance (ANOVA). The assumption of sphericity was assessed using Mauchly's test. Post-hoc pairwise comparisons were performed with Bonferroni adjustment for multiple comparisons. Missing data were handled using last observation carried forward (LOCF) imputation. Sample size was calculated using G*Power software, assuming a moderate effect size (0.3), power of 80%, and an alpha level of 0.05.

Results

A total of 24 patients diagnosed with FECD participated in this study. The mean age was 64.8 ± 9.2 years, and 80% of participants were women. Baseline characteristics were presented in Table 2. All patients were pseudophakic. The mean ECC of donor graft before surgery was 2838 ± 217 cell/mm2.The mean ECC at 1, 3, and 6 months postoperatively were 2168 ± 533, 2084 ± 547, and 2018 ± 521 cells/mm^{2}, respectively. Corresponding endothelial cell loss (ECL) rates were 0.25%, 0.29%, and 0.30%. Other results were presented in Figure 1–3. Regarding the group of static parameters, mean

Table 2 Baseline Characteristics

Characteristic	**N=24**
Age, y	64.1 (range 50–82)
Female sex	19 (86.3%)
Right eye	11 (45.8%)

(*Continued*)

Table 2 (Continued).

Characteristic	**N=24**
Modified Krachmer grading	
Grade 1	0
Grade 2	0
Grade 3	0
Grade 4	0
Grade 5	2 (8%)
Grade 6	22 (92%)
Rebubbling	11 (45.8%)

CCT decreased significantly at all postoperative time points compared with preoperative values ($p < 0.05$), decreasing from 638 ± 68 µm preoperatively to 560 ± 46, 537 ± 40, and 535 ± 40 µm at 1, 3, and 6 months after surgery, respectively. This reduction is correlated with the mean ARTh index, which decreased from 704 ± 406 preoperatively to 407 ± 137 ($p = 0.001$), 431 ± 175 ($p = 0.003$), and 471 ± 163 ($p = 0.012$) at 1, 3, and 6 months after surgery, respectively. bIOP at 3 and 6 months postoperatively were significantly higher than preoperative values (Table 3).

In terms of deformation-related parameters, no significant differences were observed in IOP and nct IOP between pre- and postoperative measurements at all time points. However, SPA1 significantly decreased after DMEK. Preoperative A1

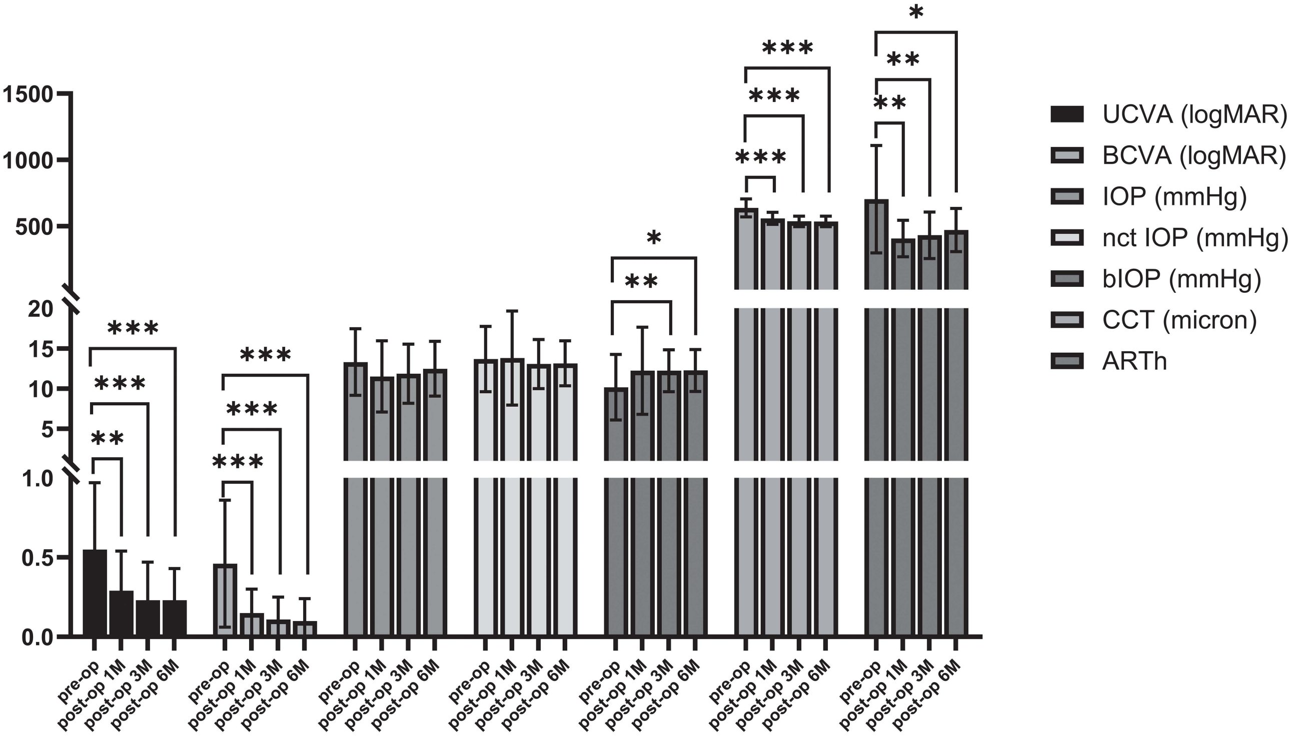

Figure 1 Changes in visual acuity, intraocular pressure, central corneal thickness, and Ambrósio relational thickness before and after descemet membrane endothelial keratoplasty Surgery (1, 3, and 6 Months).

Notes: P value was calculated using repeated measures ANOVA and pairwise correlation. *$p<0.05$, ** $p<0.01$, *** $p<0.001$.

Abbreviations: UCVA, uncorrected visual acuity; BCVA, best corrected visual acuity; IOP intraocular pressure; nct IOP, non-contact intraocular pressure; bIOP, biomechanical-corrected intraocular pressure; CCT, central corneal thickness; ARTh, Ambrosio relational thickness horizontal.

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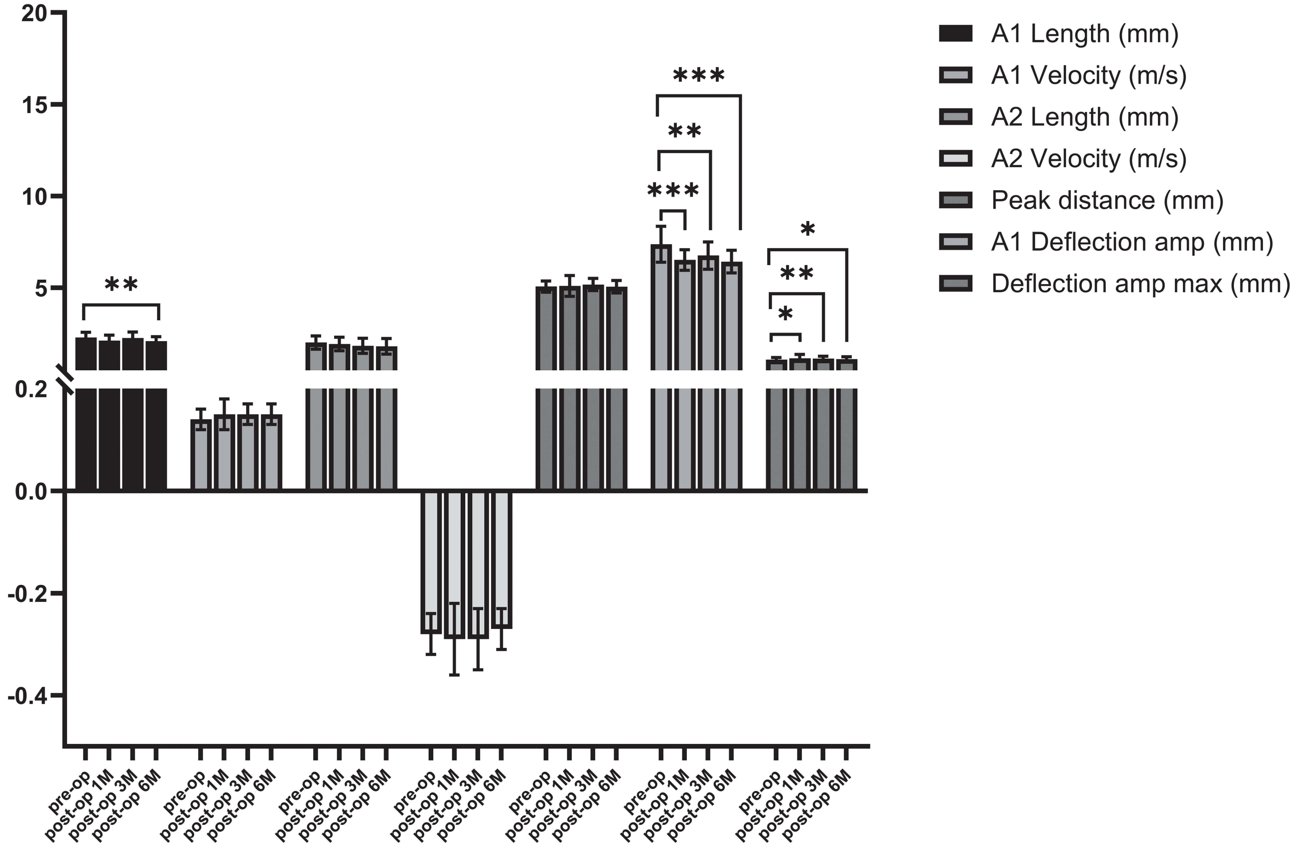

Figure 2 Changes in Corneal Biomechanical Parameters Before and After DMEK Surgery at 1, 3, and 6 Months.
Notes: P value was calculated using repeated measures ANOVA and pairwise correlation. *p<0.05, ** p<0.01, *** p<0.001.
Abbreviations: A1 deflection amp, A1 deflection amplitude; deflection amp max, maximum deflection amplitude.

length was greater in the swollen cornea (2.30 ± 0.28 mm) than in the postoperative cornea at 1, 3, and 6 months (2.13 ± 0.29 mm, 2.26 ± 0.34 mm, and 2.09 ± 0.25 mm, respectively). The reduction in the A1 length was statistically significant between preoperative and 6-month postoperative measurements ($p = 0.004$). However, no significant differences were observed in A2 length or in A1 and A2 velocities after surgery. A1 DefA was significantly greater in swollen FECD corneas (7.38 ± 0.98 mm) than in postoperative corneas (6.52 ± 0.56 mm, $p < 0.001$; 6.76 ± 0.75 mm, $p = 0.003$; and 6.43 ± 0.62 mm, $p < 0.001$ at 1, 3, and 6 months, respectively). DefA max was significantly higher at 1 (1.16 ± 0.21 mm), 3 (1.14 ± 0.14 mm), and 6 months (1.12 ± 0.13 mm) postoperatively than at preoperative assessment (1.09 ± 0.11 mm) with p-values of 0.014, 0.007, and 0.028, respectively. The DA ratio increased significantly in post-DMEK corneas (4.36 ± 0.59 mm, 4.83 ± 0.50 mm, 4.87 ± 0.90 mm at 1, 3, and 6 months, respectively) compared with the preoperative value (4.16 ± 0.46 mm), with p-values of 0.002, < 0.001, and 0.02, respectively. During peak corneal inflation in response to the air pulse, the maximum inverse radius and integrated radius were significantly higher post-DMEK than preoperatively. Maximum inverse radius increased from 0.15 ± 0.02 mm^{-1} preoperatively to 0.16 ± 0.01 mm^{-1} ($p = 0.006$), 0.17 ± 0.01 mm^{-1} ($p = 0.002$), and 0.17 ± 0.01 mm^{-1} ($p = 0.001$) at 1, 3, and 6 months after surgery, respectively. Similarly, the integrated radius exhibited a significant difference, with values of 8.31 ± 1.22 mm^{-1} preoperatively and 8.89 ± 1.38 mm^{-1} ($p = 0.041$), 9.32 ± 0.93 mm^{-1} ($p < 0.001$), and 9.51 ± 1.00 mm^{-1} ($p < 0.001$) at 1, 3, and 6 months after surgery, respectively. However, PD showed no significant changes after surgery, with a preoperative value of 5.07 ± 0.31 mm and postoperative values of 5.11 ± 0.31, 5.18 ± 0.33 and 5.06 ± 0.34 at 1, 3 and 6 months, respectively.

Regarding the stiffness-related parameters, preoperative SPA1 (105.38 ± 18.29) was significantly higher than postoperative values at 1, 3, and 6 months (89.42 ± 24.52, $p < 0.001$; 91.03 ± 21.46, $p = 0.001$; 91.14 ± 19.43, $p = 0.002$; respectively). In contrast, SSI remained stable throughout the follow-up period; starting from a preoperative baseline of 1.039 ± 0.059, no significant changes were observed at 1, 3, or 6 months 0.990 ± 0.080, 1.054 ± 0.053, and 1.064 ± 0.055,

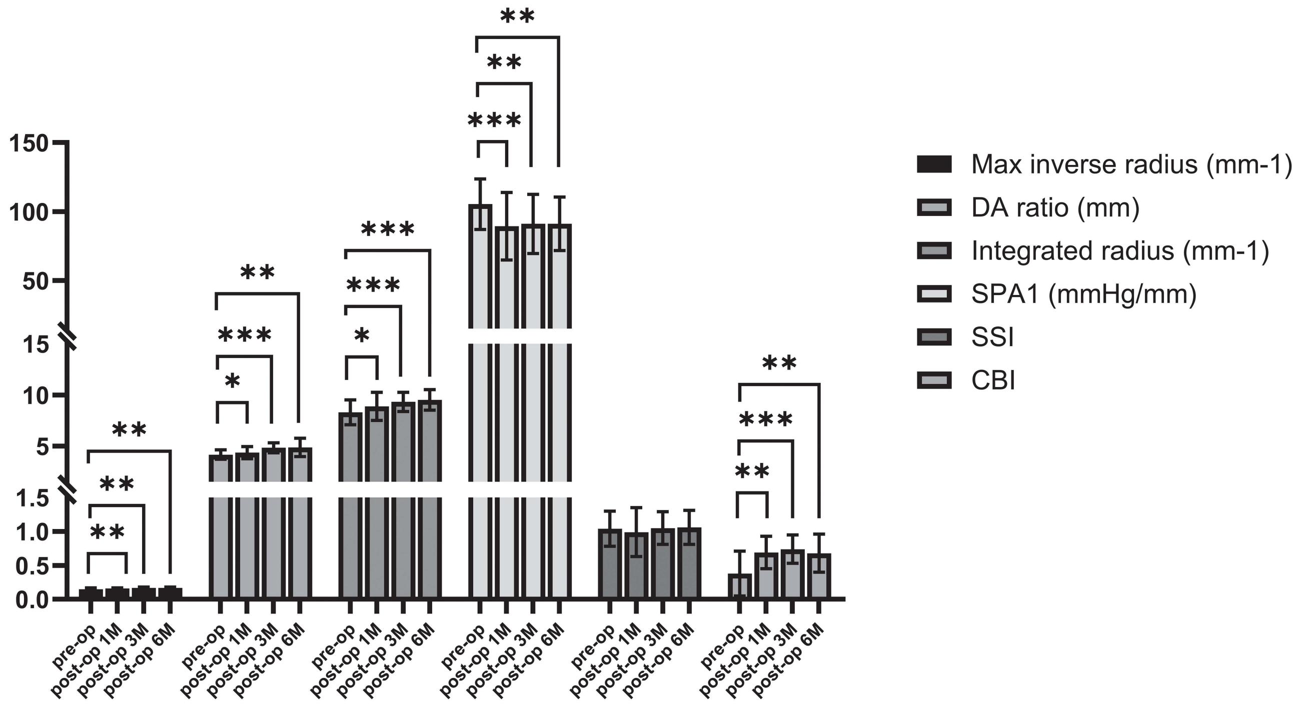

Figure 3 Changes in Corneal Biomechanical Parameters Before and After DMEK Surgery at 1, 3, and 6 Months.

Notes: P value was calculated using repeated measures ANOVA and pairwise correlation. *p<0.05, ** p<0.01, *** p<0.001.

Abbreviations: DA ratio, deformation amplitude at 2 millimeters from apex; SPA1, corneal stiffness parameter at the first applanation; SSI, corneal stress-strain index; CBI, corvis biomechanic index.

respectively). Preoperative CBI (0.38 ± 0.33) was significantly lower than postoperative values at 1, 3, and 6 months (0.69 ± 0.24, p=0.001; 0.74 ±0.21, p<0.001; 0.68 ±0.28, p=0.004, respectively). All biomechanical parameters are provided in Table 4.

No cases of primary graft failure were observed. Eleven patients (46%) experienced early postoperative graft detachment during the early postoperative period, necessitating rebubbling procedures. However, subgroup analysis comparing biomechanical parameters between rebubbling and non-rebubbling eyes was precluded by limited statistical power.

Table 3 Comparison of Clinical Parameters Before and After Descemet Membrane Endothelial Keratoplasty at 1, 3, and 6 months

UCVA		**Mean Difference**	**SD.**	**95% CI**		**p value**
				Lower Bound	**Upper Bound**	
pre-op	post-op 1 M	0.262	0.077	0.104	0.421	0.002
	post-op 3 M	0.321	0.072	0.172	0.470	<0.001
	post-op 6 M	0.321	0.075	0.165	0.476	<0.001
BCVA						
pre-op	post-op 1 M	0.308	0.075	0.153	0.464	<0.001
	post-op 3 M	0.353	0.083	0.181	0.524	<0.001
	post-op 6 M	0.363	0.082	0.192	0.533	<0.001
IOP						
pre-op	post-op 1 M	1.792	0.921	−0.114	3.697	0.064
	post-op 3 M	1.450	0.821	−0.249	3.149	0.091
	post-op 6 M	0.833	0.939	−1.109	2.776	0.384

(*Continued*)

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Table 3 (Continued).

UCVA		**Mean Difference**	**SD.**	**95% CI**		**p value**
				Lower Bound	**Upper Bound**	
Nct IOP (corvis)						
pre-op	post-op 1 M	−0.125	1.103	−2.408	2.158	0.911
	post-op 3 M	0.625	0.726	−0.877	2.127	0.398
	post-op 6 M	0.542	0.802	−1.117	2.201	0.506
bIOP						
pre-op	post-op 1 M	−2.067	1.128	−4.400	0.267	0.080
	post-op 3 M	−2.067	0.706	−3.526	−0.607	0.008
	post-op 6 M	−2.1	0.858	−3.874	−0.326	0.022

Abbreviations: UCVA, uncorrected visual acuity; BCVA, best corrected visual acuity; IOP intraocular pressure; Nct IOP, non-contact intraocular pressure; bIOP, biomechanical-corrected intraocular pressure; SD, standard deviation.

Table 4 Comparison of Corneal Thickness, Ambrósio Relational Thickness and Biomechanical Parameters Before and After Descemet Membrane Endothelial Keratoplasty at 1, 3, and 6 months

CCT		**Mean Difference**	**SD.**	**95% CI**		**p value**
				Lower Bound	**Upper Bound**	
pre-op	post-op 1 M	78.583	12.308	53.122	104.045	<0.001
	post-op 3 M	101.167	14.516	71.139	131.194	<0.001
	post-op 6 M	102.5	15.039	71.389	133.611	<0.001
ARTh						
pre-op	post-op 1 M	297.213	80.438	130.814	463.611	0.001
	post-op 3 M	272.492	82.773	101.262	443.721	0.003
	post-op 6 M	232.542	85.039	56.625	408.459	0.012
A1 length						
pre-op	post-op 1 M	0.177	0.089	−0.007	0.360	0.058
	post-op 3 M	0.043	0.087	−0.137	0.223	0.626
	post-op 6 M	0.217	0.069	0.075	0.359	0.004
A1 velocity						
pre-op	post-op 1 M	−0.006	0.007	−0.021	0.009	0.427
	post-op 3 M	−0.011	0.005	−0.023	0.000	0.052
	post-op 6 M	−0.007	0.006	−0.019	0.005	0.231
A2 length						
pre-op	post-op 1 M	0.076	0.095	−0.120	0.273	0.431
	post-op 3 M	0.174	0.123	−0.080	0.428	0.169
	post-op 6 M	0.204	0.118	−0.039	0.448	0.096

(*Continued*)

Table 4 (Continued).

CCT		Mean Difference	SD.	95% CI		p value
				Lower Bound	Upper Bound	
A2 velocity						
pre-op	post-op 1 M	0.013	0.016	−0.020	0.046	0.424
	post-op 3 M	0.008	0.014	−0.020	0.036	0.569
	post-op 6 M	−0.013	0.012	−0.038	0.011	0.278
Peak distance						
pre-op	post-op 1 M	−0.039	0.106	−0.258	0.180	0.715
	post-op 3 M	−0.106	0.078	−0.267	0.054	0.184
	post-op 6 M	0.006	0.074	−0.147	0.159	0.938
Maximum deflection amplitude						
pre-op	post-op 1 M	−0.069	0.040	0.099	−0.151	0.014
	post-op 3 M	−0.051	0.028	0.084	−0.109	0.007
	post-op 6 M	−0.028	0.027	0.318	−0.083	0.028
A1 Deflection amplitude						
pre-op	post-op 1 M	0.863	0.209	0.430	1.295	<0.001
	post-op 3 M	0.615	0.184	0.234	0.997	0.003
	post-op 6 M	0.953	0.181	0.578	1.328	<0.001
Max inverse radius						
pre-op	post-op 1 M	−0.012	0.004	−0.020	−0.004	0.006
	post-op 3 M	−0.015	0.004	−0.024	−0.006	0.002
	post-op 6 M	−0.019	0.005	−0.029	−0.009	0.001
DA ratio						
pre-op	post-op 1 M	−0.2	0.080	−0.366	−0.034	0.020
	post-op 3 M	−0.671	0.106	−0.890	−0.451	<0.001
	post-op 6 M	−0.704	0.198	−1.114	−0.294	0.002
Integrated radius						
pre-op	post-op 1 M	−0.583	0.269	−1.139	−0.027	0.041
	post-op 3 M	−1.008	0.246	−1.517	−0.500	<0.001
	post-op 6 M	−1.204	0.228	−1.676	−0.733	<0.001
SPA1						
pre-op	post-op 1 M	15.958	3.916	7.858	24.059	<0.001
	post-op 3 M	14.350	3.920	6.241	22.459	0.001
	post-op 6 M	14.242	4.025	5.915	22.568	0.002
SSI						
pre-op	post-op 1 M	0.049	0.079	−0.116	0.213	0.545
	post-op 3 M	−0.015	0.054	−0.128	0.098	0.784
	post-op 6 M	−0.025	0.050	−0.130	0.080	0.623

(*Continued*)

Table 4 (Continued).

CCT		Mean Difference	SD.	95% CI		p value
				Lower Bound	Upper Bound	
CBI						
pre-op	post-op 1 M	−0.314	0.075	−0.472	−0.156	0.001
	post-op 3 M	−0.367	0.078	−0.530	−0.203	<0.001
	post-op 6 M	−0.303	0.092	−0.496	−0.109	0.004

Abbreviations: CCT, central corneal thickness; ARTh, Ambrosio relational thickness horizontal; A1 length, lengths of flattened cornea during at 1st applanation; A1 velocity, corneal velocity (maximum) at 1st applanation; A2 length, lengths of flattened cornea during at 2nd applanation; A2 velocity, corneal velocity (maximum) at 2nd applanation; peak distance, distance between humps of cornea during maximum inward movement; maximum deflection amplitude; the maximum outward displacement of the corneal apex during an air puff test, calculated by subtracting the whole-eye movement from the total deformation amplitude; A1 Deflection amplitude, displacement of the central point (apex) of the cornea relative to its original, undeformed position at the A1 moment; Max inverse radius, inverse radius of curvature at highest concavity; DA ratio, deformation amplitude ratio; Integrated radius, area under inverse radius curve; SPA1, corneal stiffness parameter at the first applanation; SSI, stress-strain index; CBI, corvis biomechanic index; SD, standard deviation.

Discussion

Corneal biomechanical changes often precede morphological alterations in diseases such as keratoconus, corneal ectasia,[12] post-refractive surgery,[13] and corneal edema in FECD.[4] Therefore, corneal biomechanical parameters can be used as biomarkers to detect and monitor disease progression. In this study, significant differences in corneal physiological and biomechanical properties were observed using DSA (Corvis ST) in patients with FECD who had undergone DMEK. As expected, corneal ECC increased following DMEK, and this improvement was sustained for up to 6 months. Restoration of graft function led to reduced corneal swelling and CCT and altered some biomechanical parameters, contributing to visual improvement. These findings highlight the reproducibility and effectiveness of DMEK as a standard treatment for FECD.

Eleven DCR parameters from Corvis ST and ARTh from Pentacam demonstrated significant changes after DMEK. Although the SSI, which was obtained from Corivs ST, did not change significantly, it was considered because of its clinical relevance. Parameters were categorized into three groups as in Table 1: (1) static parameters; (2) deformation-related indices during loading; (3) stiffness-related parameters.

CCT significantly affects uncorrected IOP measured by Corvis and non-contact tonometry, but not bIOP.[14] Similarly, both ORA-derived corneal-compensated IOP and Goldmann IOP correlate strongly with CCT, whereas bIOP does not.[15] Corneal edema has been shown to cause IOP overestimation; thus, reductions in corneal thickness and edema generally lead to lower IOP readings.[16] In our study, both IOP and nct IOP (Corvis) demonstrated a nonsignificant decrease following DMEK. Although previous studies have reported no correlation between CCT and bIOP[15] corneal-compensated IOP measured by ORA increased in the presence of corneal edema.[16] In contrast, we observed a significant increase in bIOP after DMEK, with a decrease in CCT and resolution of corneal edema. Elevated bIOP may reflect true IOP and could be influenced by postoperative inflammation or prolonged use of steroid eye drops after corneal transplantation.

CCT significantly decreased 1 month after DMEK and remained stable from 3 months to at least 6 months. The new endothelial graft restored the hydration of the corneal stroma via its pump function, resulting in improved corneal clarity.[17] Consequently, both the UCVA and BCVA significantly improved from 1 month postoperatively. Changes in CCT were associated with alterations in other DCR parameters, as discussed below.

ARTh levels significantly decreased at all postoperative time points. The postoperative decrease in ARTh observed in this study indicates that the cornea is thinner or less swollen, with thickness increasing rapidly toward the periphery.[18] This finding correlates with the reduction in CCT after DMEK and suggests that ARTh can be used to assess changes in thin, ectatic corneas, monitor thick, swollen corneas, and evaluate overall endothelial pump function.

In this study, several deformation-related corneal shape parameters changed significantly after surgery, including the maximum inverse radius, DA ratio, integrated radius, A1 length, A1 DefA, and DefA max. Among these, the DA ratio showed a significant postoperative increase, reflecting reduced corneal resistance to deformation; however, this parameter is influenced by both CCT and bIOP.[19] Therefore, the DA ratio alone may not reliably represent true corneal biomechanical resistance.

Previous studies demonstrated a negative correlation between DA ratio and both CCT and bIOP.[19] In our study, CCT decreased significantly after DMEK, whereas bIOP increased. The observed increase in the DA ratio was consistent with the reduction in CCT but did not align with the expected negative correlation with bIOP, as previously reported.[19] This discrepancy may be explained by the stronger negative correlation of DA ratio with CCT (standardized coefficient = –0.751) compared with bIOP (standardized coefficient = –0.560).[19] Consequently, postoperative changes in DA ratio were likely driven predominantly by the reduction in CCT rather than by increased bIOP.

Furthermore, both the maximum and integrated inverse radii significantly increased after surgery. These parameters directly reflect corneal shape and may serve as indicators of corneal stiffness, as a lower concave curvature is associated with a stiffer corneal response.[20] However, both parameters demonstrated a negative correlation with changes in CCT and bIOP, with CCT showing a stronger standardized coefficient than bIOP.[19] Thus, the postoperative increase in maximum and integrated inverse radii appears to be primarily driven by the reduction in CCT, despite a concurrent increase in bIOP.

A1 DefA was significantly reduced at all postoperative time points, whereas DefA max increased following DMEK. Both parameters reflect corneal elastic behavior, as they quantify corneal deformation in response to an external air-puff load.[21] However, these deformation metrics are influenced by CCT and bIOP.[22] Previous studies reported a positive association between bIOP and A1 DefA, but a negative relationship between bIOP and DefA max in both thinner (CCT ≤ 550 µm) and thicker (CCT > 550 µm) corneas.[22] In our study, postoperative bIOP increased, A1 DefA decreased, and DefA max increased, consistent with the findings of Esteban et al, who observed significant postoperative increases in both DefA max and bIOP after DMEK[10] A1 DefA, however, was not assessed in their study.

Moreover, a biomechanically weaker cornea exhibits greater deformability, reaches the first applanation (A1) earlier, and is characterized by shorter A1 length and higher A1 velocity.[23] In our study, A1 length significantly reduced at 6 months postoperatively, which may indicate decreased corneal rigidity. In contrast, A1 velocity, A2 length, and A2 velocity showed no significant postoperative changes.

In this study, the postoperative increases in DefA max, maximum inverse radius, integrated radius, and DA ratio, along with the reduction in A1 length, suggest that the cornea is apparent softening on deformation metrics which was dominated by CCT. Conversely, the observed increase in A1 DefA levels could indicate increased corneal stiffness following DMEK. These seemingly contradictory findings are likely influenced by alterations in stromal hydration. The hydration state of the corneal stroma is a key determinant of biomechanical behavior; excessive hydration increases collagen fibril diameter and modifies interfibrillar spacing, thereby altering the viscoelastic properties of the tissue.[6]

Furthermore, these deformation parameters are affected by both CCT and bIOP, further complicating the interpretation of postoperative biomechanical changes. Therefore, a definitive conclusion regarding whether the cornea becomes stiffer or weaker after DMEK cannot be established. Nonetheless, this study demonstrates that several deformation-based metrics reflecting corneal behavior during the loading phase undergo significant postoperative changes.

In the third group, parameters related to corneal stiffness and integrated parameters included SPA1, CBI, and SSI. Higher SPA1 values indicate greater corneal stiffness.[24] CBI was developed to distinguish keratoconus from normal corneas by integrating multiple DCR parameters, achieving an area under the receiver operating characteristic curve exceeding 0.98; higher CBI values indicate reduced corneal biomechanical strength.[20] In this study, SPA1 significantly decreased 1 month after surgery, whereas CBI significantly increased, suggesting reduced corneal stiffness postoperatively. These changes correspond with alterations in DefA max, maximum inverse radius, integrated radius, and DA ratio. In contrast, SSI remained stable throughout follow-up. This apparent discrepancy may be explained by the positive correlation of SPA1 with CCT and bIOP,[19] whereas CBI is negatively correlated with CCT. Consequently, assessing changes in these two corneal biomechanical parameters after DMEK might be unreliable, as both CCT and bIOP were significantly altered after surgery. In contrast, SSI, which measures stiffness and resistance to deformation under stress, is not associated with CCT or IOP.[25]

In this study, all patient developed advanced stage of FECD. More advanced disease stages may be associated with greater structural alterations, which could not only affect baseline biomechanical properties but also influence the magnitude of

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postoperative change following surgery. Postoperative changes across the three parameter groups indicated that most metrics reflected a softer cornea than the preoperative edematous state, consistent with previous observations in FECD corneas. Exceptions include bIOP and A1 DefA, which indicated a stiffer cornea. These results are consistent with the findings of Esteban et al,[10] which demonstrated that FECD corneas become less stiff after DMEK In their study, bIOP significantly increased after DMEK; however, A1 DefA and SSI were not evaluated. In contrast, our study uniquely demonstrates that the SSI—a parameter resilient to confounding by CCT and IOP—remained stable throughout the follow-up period.

DMEK offers advantages over other endothelial keratoplasty techniques by restoring near-normal corneal anatomy through selective replacement of Descemet's membrane and endothelium, resulting in improved visual outcomes and faster recovery. Postoperatively, restoration of endothelial function leads to normalization of stromal hydration, which influences corneal biomechanics. As a result, deformation-based indices reflect geometric changes rather than true alterations in corneal stiffness, while intrinsic stiffness (eg., SSI) remains relatively stable, with values approaching those of normal corneas. This is consistent with previously reported findings.[26] Furthermore, no significant changes in biomechanical parameters were observed between the 3- and 6-month postoperative intervals, suggesting an early stabilization of the corneal biomechanical profile.

Understanding the pathophysiology of FECD, particularly its genetic basis, imaging characteristics, and the biomechanical properties of the diseased tissue, is critical for improving its diagnosis. Alterations in some corneal biomechanical parameters may serve as early indicators of subclinical corneal edema; however, further studies are warranted to validate these observations.

Future studies are warranted to evaluate the potential of this parameter as a predictive marker for surgical outcomes. In particular, longer-term follow-up beyond 12 months, as well as inclusion of comparative cohorts (eg., FECD without surgery, DSEK, and healthy controls), would provide more comprehensive insight. Additionally, multivariable modeling approaches may help to disentangle the relative contributions of corneal thickness (CCT), biomechanically corrected intraocular pressure (bIOP), and intrinsic stiffness parameters, thereby improving the interpretation and clinical applicability of corneal biomechanical assessments.

This study has a few limitations. First, the sample size was relatively small (24 eyes), which may limit the generalizability of the findings and reduce the statistical power to detect subtle biomechanical changes. Second, the follow-up period was limited to 6 months, preventing assessment of long-term biomechanical remodeling of the cornea after DMEK. Third, the corneal hydration status, postoperative steroid use, and subclinical inflammation may have affected parameters such as bIOP and deformation metrics, making it difficult to distinguish true biomechanical alterations from physiological fluctuations. Fourth, the absence of a control group (such as untreated FECD or normal corneas) precluded direct comparison. Finally, multiple comparisons across many parameters increase the risk of type I error, especially without correction.

Conclusion

DMEK effectively restores corneal clarity and improves visual outcomes in patients with FECD by reestablishing endothelial pump function and reducing corneal edema. Although several corneal biomechanical parameters demonstrated significant postoperative changes, these alterations were largely influenced by variations in corneal thickness and IOP. Notably, the SSI, which reflects the intrinsic material stiffness of the cornea and is independent of CCT and bIOP, remained unchanged throughout follow-up, suggesting that DMEK did not alter the fundamental biomechanical properties of the corneal tissue. These findings emphasize that, while corneal biomechanics may provide useful adjunctive information for monitoring disease and surgical outcomes, further studies are required to determine their role as reliable biomarkers for detecting early or subclinical corneal edema in FECD.

Abbreviations

FECD, Fuchs Endothelial Corneal Dystrophy; DMEK, Descemet Membrane Endothelial Keratoplasty; UCVA, Uncorrected visual acuity; BCVA, Best-corrected visual acuity; IOP, Intraocular pressure; nct IOP, Non-contact intraocular pressure; bIOP, Biomechanical-corrected intraocular pressure; CCT, Central corneal thickness; ECC, Endothelial cell count; DA ratio, Deformation amplitude at 2 millimeters from apex; ARTh, Ambrosio relational thickness horizontal; SPA1, Stiffness parameters at first applanation; CRF, Corneal resistance factor; DSA, Dynamic Scheimpflug analyzer; SSI, Stress–strain index; AC, Anterior chamber; PD, Peak distance; DefA max, Maximum deflection amplitude; CBI, Corvis biomechanical index; DCR, Dynamic corneal response; A1 DefA, A1 deflection amplitude; ORA, The Ocular Response Analyzer.

Data Sharing Statement

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request. All data shared will be de-identified to protect participant confidentiality. Data will be made available for a period of one year following publication and will be provided via direct Email to the corresponding author.

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Disclosure

The authors report no conflicts of interest in this work.

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