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A novel corneal indentation device for comparison of corneal tangent modulus before and after FS-LASIK in vivo

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Abstract

Background: Corneal refractive laser surgery is widely used to correct myopia and astigmatism due to its safety and effectiveness. However, postoperative changes in corneal biomechanics, such as corneal ectasia, can occur, necessitating a deeper understanding of these changes. Finite Element Analysis has shown promise in predicting surgical outcomes based on corneal biomechanics. Devices like the Ocular Response Analyser (ORA) and Corvis ST provide noninvasive ways to measure corneal biomechanics, aiding in the assessment of corneal behavior post-surgery. Young's modulus and tangent modulus are crucial parameters for describing corneal elasticity, but there is limited data on the changes in tangent modulus following Femtosecond Laser-Assisted LASIK (FS-LASIK) in humans. This study aimed to investigate the effect of FS-LASIK on the corneal tangent modulus using a novel corneal indentation device (CID). The study sought to explore changes in corneal tangent modulus after FS-LASIK, taking into account central corneal thickness (CCT) and corneal radius, to enhance our understanding of the biomechanical changes induced by this surgical procedure.

Results: Sixty-six patients (66 eyes) underwent FS-LASIK, resulting in significant changes in CCT, corneal radius, and Goldmann intraocular pressure (GAT IOP) 6 months post-surgery (ΔCCT = − 88 ± 31 μm, Δcorneal radius = 0.81 ± 0.30 mm, ΔGAT IOP = − 3.2 ± 2.4 mmHg, $p < 0.001$) 6 months after surgery. However, corneal stiffness did not significantly change ($\Delta = -0.002 \pm 0.011$, $p < 0.2$). The corneal tangent modulus showed a significant increase post-surgery ($\Delta = 0.263 \pm 0.146$, $p < 0.001$), exhibiting a negative correlation with CCT ($r = -0.68$, $P < 0.001$) and a positive correlation with corneal radius ($r = 0.71$, $P < 0.001$). For each 1 mm increase in corneal radius, there was a 0.23 MPa increase in corneal modulus, and for every 100 μm reduction in corneal thickness, there was a 0.14 MPa increase in corneal modulus.

Conclusions: The corneal tangent modulus, influenced by corneal radius and CCT, increased significantly following FS-LASIK. This study highlights the biomechanical changes induced by FS-LASIK, with implications for understanding corneal behavior post-surgery and its potential impact on patient outcomes.

Keywords: Corneal tangent modulus, Corneal biomechanics, Corneal stiffness, Femtosecond Laser-Assisted LASIK, Clinical trial

Background

Corneal refractive laser surgery is considered to be a safe, effective and predictable surgical procedure for the treatment of myopia and astigmatism [1]. However, postoperative corneal remodelling changes the biomechanics of the cornea [2] and corneal ectasia can occur after surgery [3]. With the application of Finite Element Analysis in the clinic, researchers have found that corneal biomechanics might be used to predict the surgical outcome of corneal refractive surgery [4]. Therefore, changes in corneal biomechanics after refractive surgery have attracted increasing attention from refractive surgeons.

The Ocular Response Analyser (ORA) and Corvis ST are two noninvasive clinical devices for corneal biomechanics measurement. The ORA utilizes an air pulse to deform the cornea and monitor the deformation using the reflection of the infrared beam, [5] while the Corvis ST records corneal deformation using Scheimpflug visualization technology, which allows a more detailed evaluation. CH and CRF are calculated from the two independent eye pressure values obtained during the two applanation processes. CH reflects corneal viscous resistance, and CRF represents the overall ability of the cornea to resist external forces. Many studies have utilized the ORA to compare corneal biomechanical changes before and after surgery, showing a decrease in CH and CRF after surgery [6]. However, the relationship between CH and CRF and the standard mechanical properties of elastic materials remains unclear [7, 8].

Young's modulus, the ratio of stress to strain [9], is the standard terminology describing the mechanical behavior of materials. It remains constant in a perfectly elastic material. The cornea is a biological tissue with nonlinear elastic behavior due to its viscoelastic property. To overcome this problem, the tangent modulus [10], which is an instantaneous slope at a specific stress, is used to represent the elastic properties of the cornea. A novel corneal indentation device [11] has been developed to measure the tangent modulus of the cornea in clinical practice. This device has been validated with a universal testing machine by using porcine eyes ex vivo [12] and rabbit eyes in vivo [13]. A repeatability test on human subjects was also established [14].

Animal experiments ex vivo revealed that the elastic moduli of the cornea increased 1 month after LASIK [15]. However, little is known about the corneal tangent modulus changes after FS-LASIK in human eyes. Therefore, the aim of this study was to compare the corneal tangent modulus in vivo before and after FS-LASIK.

Results

A total of 66 eyes were included in this study, including 36 female patients (54.5%) and 30 male patients (45.5%). A total of 66 subjects were included in this study, with one eye randomly selected from each subject, resulting in 66 eyes being analysed. The mean age of the patients was 25.09 ± 5.39 years, the mean spherical refraction was -4.77 ± 2.03 D, the average cylinder refraction was -0.72 ± 0.81 D, and the average spherical equivalent (SE) was -5.13 ± 2.15 D. CCT significantly decreased by 88 ± 31 μm, and GAT-IOP decreased by 3.17 ± 2.4 mmHg after surgery. The mean R significantly increased by 0.81 ± 0.3 mm, and the corneal tangent modulus increased by 0.26 ± 0.15 MPa postoperatively, which was 53% higher than that before surgery. The corneal biomechanical parameters are shown in Table 1. The

Table 1 Preoperative and postoperative findings in corneal biomechanical parameters

	GAT IOP (mmHg)	Mean R (mm)	CCT (μm)	Stiffness (N/mm)	Modulus (MPa)
Preoperative	14.75 ± 2.87	7.7 ± 0.27	534 ± 32	0.078 ± 0.01	0.49 ± 0.07
Postoperative	11.58 ± 2.17	8.5 ± 0.37	446 ± 41	0.075 ± 0.00	0.75 ± 0.13
P	< 0.001	< 0.001	< 0.001	0.145	< 0.001
△	− 3.17 ± 2.4	0.81 ± 0.3	− 88 ± 31	− 0.002 ± 0.01	0.26 ± 0.15

GAT-IOP Goldmann applanation tonometer intraocular pressure, *Mean R* Mean central corneal radius, *CCT* Central corneal thickness

relationship among postoperative changes in GAT-IOP, alterations in corneal curvature, and corneal ablation thickness indicates that GAT-IOP tends to decrease with a reduction in CCT (Fig. 1).

Bivariate correlation analyses indicated that the corneal tangent modulus was positively associated with the mean R ($R^2 = 0.12$, $P < 0.01$) and negatively associated with the CCT ($R^2 = 0.12$, $P < 0.01$) before surgery. The postoperative corneal tangent modulus was positively associated with the postoperative mean R ($R^2 = 0.35$, $P < 0.01$) and negatively associated with the postoperative CCT ($R^2 = 0.31$, $P < 0.01$) (Table 2). The distribution and correlation between the mean R, CCT and corneal tangent modulus are shown in Fig. 2, which revealed a stronger correlation after surgery.

The △corneal tangent modulus was negatively correlated with △CCT ($R^2 = 0.46$, $P < 0.01$) and positively correlated with △mean R ($R^2 = 0.51$, $P < 0.01$) (Table 3). Setting the △corneal tangent modulus as a dependent variable in the stepwise multiple regression analysis (Table 4), △CCT and △mean R were significantly associated with the change in corneal tangent modulus ($P < 0.01$, adjusted $R^2 = 0.529$). The coefficient was − 1.44 for △CCT and 0.23 for mean R, indicating that for every 1 mm increase in corneal radius, the corneal modulus increased by 0.23 MPa; for every 100 μm reduction in corneal thickness, the corneal modulus increased by 0.14 MPa.

Discussion

The Corvis ST and ORA have been widely used to study the biomechanical properties of the cornea, particularly in refractive surgery for myopia treatment. Corneal refractive surgery achieves myopia correction by thinning the cornea and flattening the anterior curvature [1]. However, corneal thinning, tissue remodelling, and scarring during repair can alter corneal biomechanics [2, 23], potentially leading to severe complications such as keratoconus or corneal ectasia. [3, 24]

Corvis ST captures dynamic corneal deformation in response to an air puff, providing parameters such as deformation amplitude (DA), stiffness parameter at first applanation (SP-A1), and integrated radius. These parameters have demonstrated sensitivity to biomechanical changes induced by different refractive surgeries and crosslinking treatments [25, 26]. For instance, studies have shown that keratoconus eyes exhibit lower SP-A1 values, indicating reduced stiffness compared to post-refractive surgery corneas [27, 28]. However, Corvis ST parameters are influenced by corneal thickness and anterior curvature, which can confound results in post-surgical or pathological corneas. [29]

Table 2 Pearson correlation coefficients between corneal modulus and CCT, mean R before and after surgery

	Preoperative modulus	Postoperative modulus
Mean R		
r	0.347**	0.588**
R^2	0.12**	0.35**
CCT		
r	− 0.344**	− 0.554**
R^2	0.12**	0.31**

** P < 0.01, *Mean R* Mean central corneal radius, *CCT* Central corneal thickness

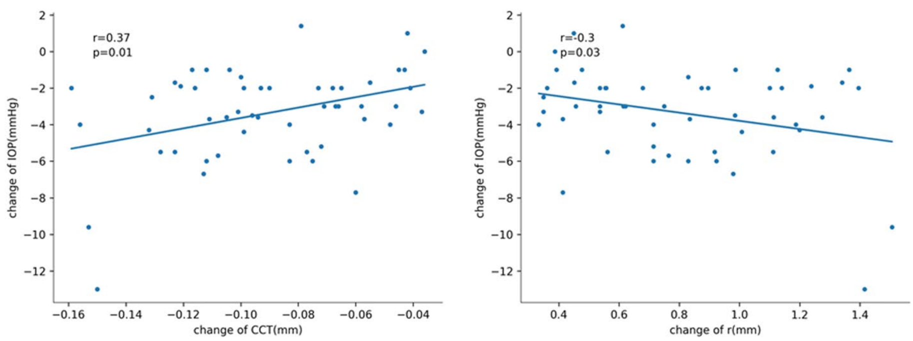

Fig. 1 Association Between GAT-IOP Reduction, Corneal Ablation Thickness, and Changes in Corneal Curvature

Table 3 Pearson correlation coefficients between △corneal modulus and △CCT, △mean R

	△corneal modulus	P
△mean R		
r	0.71	< 0.001
R^2	0.51	
△CCT		
r	− 0.68	< 0.001
R^2	0.46	

Mean R Mean central corneal radius, *CCT* Central corneal thickness

Table 4 Multiple liner regression analysis with △corneal modulus with △mean R and △CCT as independent variables

	Coefficient	SE	P
△mean R	0.229	0.066	0.001
△CCT	− 1.435	0.632	0.027

SE Spherical equivalent, *Mean R* Mean central corneal radius, *CCT* Central corneal thickness

In vitro experiments [30, 31] and mathematical models [32] have demonstrated that the cornea exhibits both elastic and viscoelastic properties. Elastic properties describe the immediate deformation response to the application of an external stress, while

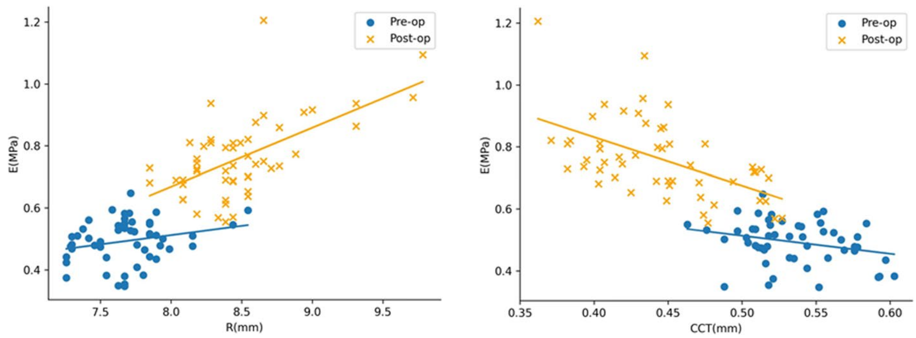

Fig. 2 Distribution and Correlation of CCT, Mean R, and Corneal Modulus. The distribution and correlation between CCT, mean R, and corneal modulus indicated a stronger positive correlation between mean R and corneal modulus and a stronger negative correlation between CCT and corneal modulus

viscoelastic properties describe the subsequent dynamic deformation response of the cornea [33]. The elastic modulus is a mechanical property that describes the stiffness of a material, and the higher the elastic modulus is, the stiffer the material is. Stiffness is a property of a structure or component of a structure and is an extensive property of the solid body that is dependent on the material, its shape, and boundary conditions.

ORA evaluates corneal biomechanical properties using viscoelastic parameters, primarily corneal hysteresis (CH) and corneal resistance factor (CRF). CH and CRF decrease following refractive surgery, reflecting global changes in corneal viscoelasticity [34, 35]. However, there is no direct correlation between CH/CRF and standard mechanical properties such as the elastic modulus, as CH and CRF describe energy absorption and damping rather than intrinsic material stiffness [7, 8]. ORA is less sensitive to localized biomechanical changes compared to Corvis ST, and its parameters are similarly influenced by intraocular pressure (IOP) and corneal thickness [36–38].

CID provides a novel approach by directly quantifying the tangent modulus, which represents the elastic stiffness of the corneal stroma under static loading conditions. Unlike Corvis ST, which focuses on dynamic deformation, and ORA, which emphasizes viscoelastic responses, CID isolates intrinsic stiffness, offering localized and static measurements. However, CID measurements are not immune to external influences. Elevated IOP may result in higher stiffness measurements due to increased resistance to indentation, whereas thicker corneas may yield higher tangent modulus values because of greater structural support. These dependencies necessitate careful interpretation of CID results alongside anatomical parameters such as IOP and corneal thickness to ensure accuracy.

The complementary roles of these devices provide a more comprehensive understanding of corneal biomechanics. Corvis ST excels in capturing dynamic deformation responses, ORA offers insights into global viscoelastic behavior, and CID focuses on localized stiffness. By integrating CID data with Corvis ST and ORA, future studies could enhance diagnostic accuracy and treatment planning for conditions such as keratoconus, corneal ectasia, and biomechanical instability following refractive surgery. Additionally, multimodal approaches incorporating CID measurements with advanced imaging techniques, such as polarization-sensitive OCT or Brillouin microscopy, hold

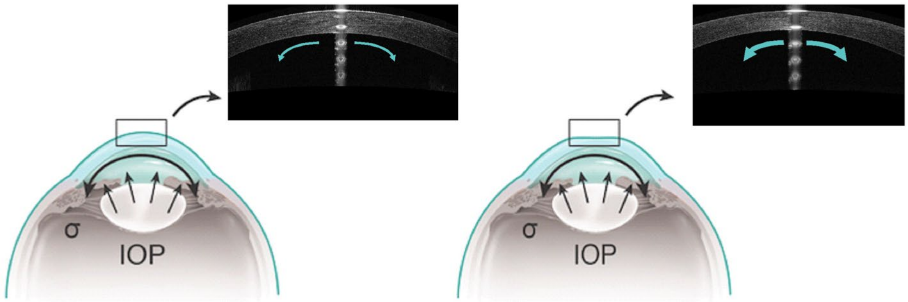

Fig. 3 Corneal Tangential Tensile Stress after FS-LASIK

promise for mapping regional biomechanical variations, enabling more precise and personalized surgical interventions.

This study revealed that corneal stiffness had no significant change after FS-LASIK, while the corneal tangent modulus significantly increased by 53% postoperatively. The increase in corneal modulus was significantly associated with changes in central corneal thickness and radius of corneal curvature. For every 1 mm increase in corneal curvature, the corneal modulus increased by 0.23 MPa; for every 100 μm reduction in corneal thickness, the corneal modulus increased by 0.14 MPa. Xu et al. found that the modulus was negatively related to the CCT in a study of the application of CID in glaucoma, which is consistent with the findings of this study [39, 40].

The cornea is composed of hundreds of lamellar layers [41] and there is cohesive force between layers. Once the cornea is incised or gasified by a laser, the tension in the affected lamellar layers is immediately reduced [42]. Loss of lamellar tension leads to redistribution of interlamellar water, causing peripheral corneal edema, which is the reason why some patients tend to be overcorrected in the early postoperative period [43]. After FS-LASIK surgery in myopia, the central cornea becomes thinner. Under the same intraocular pressure, the cornea expands outwards but cannot return to its original shape, manifested as a flattening of the central cornea and an increase in the radius of cornea curvature (Fig. 3). When a spherical shell is pressurized, the tangential tensile stress in the membrane σ_s is described by the Law of Laplace [44]: $\sigma_s = \frac{R}{2t} IOP$, where t is the corneal thickness and R is the radius of curvature. Corneal tangential tensile stress increased at a relatively stable IOP when corneal thickness decreased and radius of curvature increased after FS-LASIK. The elastic modulus is believed to have a positive correlation with tangential tensile stress, so the corneal tangent modulus increased after surgery.

In vitro animal experiments have found that the change in corneal modulus after LASIK was related to postoperative recovery time and depth of cut. Fang et al. used strip experiments to find that the corneal elastic modulus of porcine eyes decreased immediately after LASIK [45]. However, the corneal elastic modulus significantly increased with self-repair and remodelling of the cornea after surgery. They found that the corneal modulus increased by 51% 1 month after LASIK in rabbit eyes, with only 30% of the remaining corneal stroma [15]. This may be related to postoperative corneal remodelling and scar formation. It is generally believed that tissue repair and remodelling begin

48 h after injury and reach a peak of reparation between days and months after injury [46]. Many studies have pointed out that corneal refractive surgery disrupts the balance of the original corneal extracellular matrix and metalloproteinases, [47, 48] thus, the components of corneal material might change after surgery. Moreover, postoperative corneal scar formation is also likely to affect corneal biomechanics. The increase in the postoperative corneal elastic modulus reflects the adaptation of biological tissues to the new physiological environment. The higher the postoperative modulus is, the stiffer the cornea, which guarantees refractive stability and long-term safety of corneal tissue after corneal refractive surgery in low and moderate myopia.

It has been widely accepted that corneal ectasia [24] after corneal refractive surgery is associated with disruption of the integrity of corneal biomechanics. We speculate that the cornea becomes stiffer due to the higher postoperative modulus, which means that the cornea becomes less compliant and less susceptible to deformation. On the other hand, the increase in the corneal modulus may have a limited value. When the postoperative corneal modulus rises beyond its limit, the cornea cannot continue to maintain the normal shape of the eyeball. The cornea expands under fluctuations in intraocular pressure and results in cornea ectasia. The increase in the corneal modulus is proportional to the depth of ablation. The larger the depth of ablation is, the more the corneal modulus increases. Therefore, minimizing the depth of corneal ablation during refractive surgery is particularly important to prevent postoperative corneal ectasia. Regarding the safety range of corneal ablation, the current research conclusions are inconsistent. It is generally believed that the residual corneal stroma thickness of femtosecond-assisted excimer laser surgery needs to be greater than 250 μm. [48] Subsequent research in our group will establish a postoperative iatrogenic keratoma animal model to explore the "limit value" of the increase in corneal tangent modulus, thereby obtaining the percentage of the modulus rise limit and calculating the corneal ablation by the modulus change model. The safe range is expected to provide a more personalized ablation mode for corneal refractive surgery.

There were several limitations of the current study. First, the main limitation of our study is that we only looked at the modulus changes at 6 months after FS-LASIK. Further investigation of the corneal tangent modulus after the first and three months and over the span of 6 months is needed to confirm our concern that corneal healing and remodelling play an important role in increasing the corneal tangent modulus after surgery.

Second, the CID measurement is a contact test that requires good patient compliance. Improper operation could potentially cause transient injuries to the corneal epithelium, emphasizing the need for careful handling during the measurement process. Additionally, while the testing environment was temperature-controlled (22–24 °C) to minimize variability, humidity levels were not specifically monitored or controlled due to the limitations of the central air conditioning system. Although corneal biomechanical parameters such as tangent modulus and stiffness are primarily determined by the structural properties of the stromal collagen matrix, variations in humidity could indirectly affect corneal hydration, potentially introducing minor variability under extreme environmental conditions. Future studies should include both temperature and humidity monitoring to create a fully standardized testing environment, further improving the reproducibility and reliability of biomechanical assessments.

Third, the CID does not automatically calibrate the corneal center. During the measurement process, we asked the subject to look directly at the external target in front and measured several times to reduce the deviation of the measurement position, but there may still be some errors when aligning the center of the cornea [49]. Additionally, for the measurement of central corneal thickness, a trained doctor guided the subjects to look at the target in front of them for multiple measurements to reduce human error, but there may still be a bias in the measurement position.

Fourth, the composition and structural complexity of the cornea determine the specificity of the corneal tissue. The biomechanics of the various layers of the cornea are different, and the biomechanics of the scar tissue after excimer laser treatment are not yet fully understood. The CID assumes that the corneal tissue behaves as an isotropic material, obtaining an overall average tangent modulus of the central cornea. This isotropic assumption simplifies the inherently complex and anisotropic nature of the cornea, which is composed of lamellar collagen fibrils organized in directional patterns that confer different biomechanical properties along various axes.

This assumption may result in overestimation or underestimation of stiffness under certain directional stresses, particularly in cases such as keratoconus, post-surgical ectasia, or corneal grafts, where anisotropic properties are clinically significant. Consequently, while the CID provides valuable overall stiffness metrics, these results must be interpreted with caution in scenarios where directional biomechanical variations are critical for clinical decision-making. For instance, isotropic assumptions might fail to capture regional stiffness differences that influence refractive surgery outcomes, the effectiveness of crosslinking treatments in keratoconus, or biomechanical stability after corneal transplantations.

Future studies should prioritize developing anisotropic models of corneal biomechanics to account for regional stiffness variations and directional properties. Advanced imaging technologies, such as polarization-sensitive OCT (PS-OCT), Brillouin microscopy, or second-harmonic generation (SHG) imaging, can generate high-resolution maps of collagen fibril orientation and elasticity, enabling a more precise understanding of the corneal structure. Additionally, integrating CID data with non-contact biomechanical tools like Corvis ST or ORA, and utilizing machine learning algorithms to analyze multimodal datasets, could refine diagnostic and predictive models. These innovations hold the potential to significantly enhance personalized treatment planning and improve surgical outcomes by addressing the cornea's complex biomechanical behavior in a comprehensive and patient-specific manner.

Finally, measurements of corneal stiffness and tangent modulus are influenced by real IOP. However, at present, there are no instruments or methods capable of directly measuring true IOP, which remains a challenge for biomechanical studies.

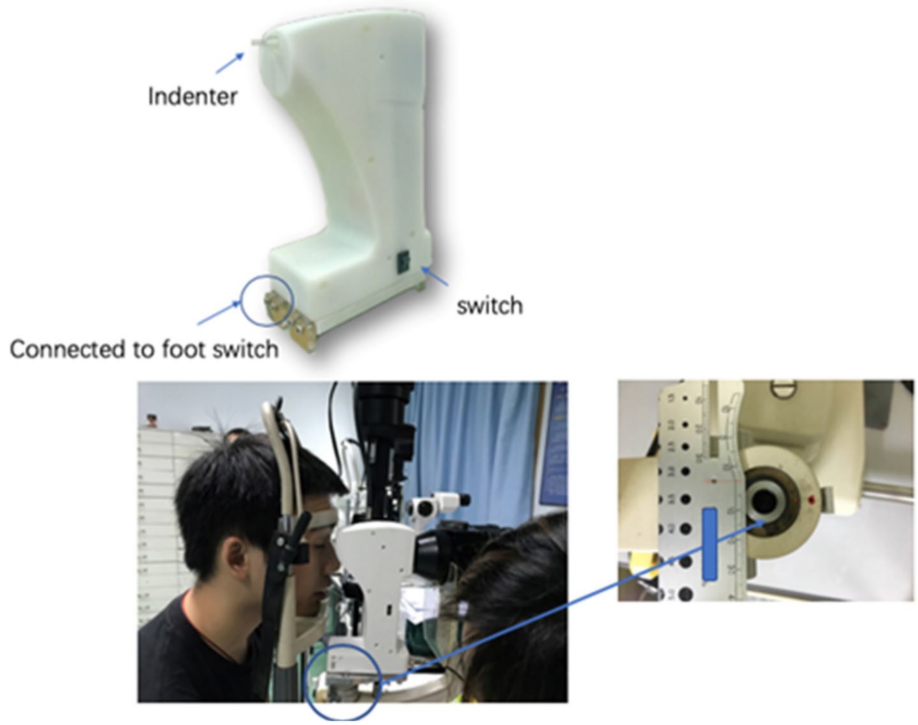

Fig. 4 Corneal Indentation Device Setup

Conclusions

This study measured corneal tangent moduli, an intrinsic biomechanical property, after FS-LASIK in vivo, providing a novel method to study biomechanical changes after surgery in a clinical study. Corneal stiffness had no significant change after FS-LASIK, while the corneal tangent modulus significantly increased by 53% postoperatively. The increase in the corneal modulus is proportional to the depth of ablation.

Methods

This study is a single-center, single-surgeon, prospective, comparative study of the medical records of healthy patients who underwent FS-LASIK at an ambulatory surgicenter. A total of 66 eyes from 66 patients were included in this study. The research protocols were approved by the Institutional Review Board at Guangdong Provincial People's Hospital (No. GDREC2017206H(R2)). The study followed the tenets of the Declaration of Helsinki, and all subjects were thoroughly informed of the procedure and provided written informed consent.

The inclusion criteria for the surgery were as follows: patients were willing to receive the surgery and had good compliance and cognitive ability, age of 18 or older, stable refraction for at least 2 years, refractive error not greater than − 8.0 diopters (D) sphere or − 4.0D of astigmatism. Exclusion criteria included any history of ocular trauma, corneal disease, corneal scarification, uveitis or retinal disease, any history of corneal laser treatment or ocular/intraocular surgery, less than 3 months of discontinued use of rigid contact lenses, less than 1 month of discontinued use of soft contact lenses, any topical corticosteroid use, pregnancy, systemic immunologic disease, long-term use of psychoactive drugs or diagnosed psychiatric disorder, and inability to cooperate with ophthalmic examinations. Eyes with possible keratoconus were excluded by using the keratoconus screening test of Pentacam HR (Oculus, Germany), with exclusion criteria including KMax > 48 D, posterior elevation (PE) > 12 μm, ART-Max < 339, and BAD-D > 1.6. Additional keratoconus indices such as ISV ≥ 37, IHA ≥ 19, IVA ≥ 0.28, and IHD ≥ 0.014 were also considered for comprehensive assessment. Bilateral comparison was performed to detect asymmetries, as early keratoconus often affects one eye first [15–19]. Central cornea thickness (CCT) was measured by ultrasonic pachymetry (Tomey Sp-3000, Japan), and corneal radius (mean R) was measured by an autorefractometer (NIDEK ARK-1 s, Japan).

CID measurements

The CID was prepared as reported elsewhere [14]. In short, the CID was put on a slit lamp unit and consisted of a 2 mm circular flat indenter, a digital screen display and a foot switch connected to it (Fig. 4).

The corneal indentation device is placed on a slit lamp unit. CID consists of a 2 mm circular flat indenter, a digital screen display, and a foot switch.

Calibration of the CID was performed daily before data collection in collaboration with team members from The Hong Kong University of Science and Technology (HKUST). Patients were seated at the slit lamp, with their foreheads and chins stabilized on the support to maintain consistent positioning. To approximate the central corneal region, patients were instructed to fixate straight ahead, using the CID indenter tip as the visual target. This alignment ensured that measurements were performed near the corneal apex, corresponding to the surgical zone in refractive procedures. After the cornea was anesthetized with one drop of 0.5% proparacaine, the indenter was moved toward the corneal surface until a low-pitch signal indicated a stable preload of 0.001 to 0.003 N. When the foot switch was pressed, the indenter moved forward and compressed the cornea to a depth of 1 mm at 12 mm/s and immediately retracted. The entire indentation process was completed in approximately 0.2 s. Effective measurement results showed a smooth and linear load–displacement curve on its screen. The CID measured corneal stiffness, which was the slope of the corneal displacement from 0.3 to 0.6 mm. Three valid results were collected for each eye, with at least 30 s between measurements to avoid potential stress effects on the cornea. Patient measurements were imported into specialized software for initial analysis, with the data subsequently evaluated by the HKUST team for consistency. Only measurements with smooth load−displacement curves and a standard deviation (SD) of less than 0.1 were retained, ensuring accuracy and reliability in the results. All measurements were conducted in a temperature-controlled room (22–24 °C) to minimize environmental variability. Since corneal biomechanics depend on IOP, Goldmann applanation tonometer (GAT) measurements were performed 15 min after CID measurements to avoid any potential massaging effect [20, 21]. Three readings (GAT-IOP) were taken, and the averaged results were used for analysis.

Determining the corneal tangent modulus (E_{IOP}) at a particular IOP involves substituting raw data, including CCT(t), mean R (r), and corneal stiffness (S_{IOP}), into a generalized Eq. [13]:

$$E_{IOP} = \frac{a(r - t/2)\sqrt{1 - \nu^2}}{t^2} \times S_{IOP}$$

ν is Poisson's ratio of the cornea, and a is a geometrical constant highly correlated with μ, where μ is determined by the equation below [22]:

$$\mu = r_0 \left[\frac{12(1 - \nu^2)}{(r - t/2)^2 t^2} \right]^{1/4}$$

The radius of the circular flat indenter that is in full contact with the cornea is denoted as r_0.

Surgical procedures

All surgeries were performed by the same experienced surgeon (J.Z.). A suction ring was applied to the anterior segment of the eye to immobilize the eyeball, after which an 8.5 mm flap of 100 μm thickness was cut with a femtosecond laser (IntraLase iFS 150, Abbott Medical Optics Inc., Santa Ana, California). The flap was separated and lifted, followed by ablation in a 6.0 mm optical zone using a wavefront-guided excimer laser (Technolas 217z100 excimer laser platform, Bausch & Lomb, Rochester, NY). After repositioning the flap, postoperative topical medications were given. The postoperative medication regimen for FS-LASIK included the use of a transparent eye shield or goggles to protect the eyes after surgery. Antibiotic eye drops were applied for 14 consecutive days, 4 times a day, with 1 drop each time. Corticosteroid eye drops were applied for 1 week, 4 times a day, with 1 drop each time, and the dosage was adjusted as needed. Artificial tears or eye surface repair agents were applied in the form of eye gel. Follow-up examinations were recommended at postoperative day 1, week 1, month 1, month 3, month 6, and year 1. The CCT, mean R, corneal stiffness and intraocular pressure (GAT-IOP) measurements were repeated 6 months after surgery. All examinations were conducted by a single experienced examiner, with the patient in a sitting position and in a single clinic visit, in the same half-day session (morning 08:30–11:30) to minimize diurnal effects.

Statistical analysis

Data analysis was performed by using SPSS for Mac software (Version 25.0; SPSS, Chicago, IL). The Kolmogorov–Smirnov test verified that the data were normally distributed. Correlation between corneal parameters and intraocular pressure changes before and after surgery was performed by paired t test; Pearson test was performed to analyse the correlation between changes in corneal tangent modulus and other biological parameters (CCT, corneal curvature, intraocular pressure, etc.). A predictive model was established to estimate the amount of change in the corneal tangent modulus. For all tests, $P < 0.05$ was statistically significant.

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Author contributions
Guarantor: JZ. YZ and JYL researched the literature and conceived the study. YZ, JYL, CY, and JQL were involved in protocol development, gaining ethical approval, patient recruitment, and data analysis. DC and JZ led the literature review. YZ and JYL finalized the draft, and other authors participated in the critical interpretation of the data. All authors reviewed and edited the manuscript and approved the final version of the manuscript.

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Availability of data and materials
No datasets were generated or analysed during the current study.

Declarations

Ethical approval and consent to participate
The research protocols were approved by the Institutional Review Board at Guangdong Provincial People's Hospital (No. GDREC2017206H(R2)). The study followed the tenets of the Declaration of Helsinki, and all subjects were thoroughly informed of the procedure and provided written informed consent.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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