Research Progress on Morphological Changes and Surgery-Related Parameters of Corneal Cap in Small-Incision Lenticule Extraction

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Keywords

Small-incision lenticule extraction · Corneal cap · Re-treatment · Surgical parameters · Complication

Abstract

Small-incision lenticule extraction (SMILE) is an “all-in-one” surgical method for refractive correction. An advantage of the SMILE over traditional surgery is that it depends on the corneal cap’s design. This review discusses the morphological evaluation of the corneal cap, selection of the corneal cap with different thicknesses and diameters, influence of the corneal cap design on re-treatment, and management of corneal cap-related complications. The following points should be recognized to define the correct morphology and design of the operation-related parameters of the corneal cap during SMILE: (1) the thickness and diameter of the corneal cap are predictable and influence postoperative visual quality, (2) the change in the anterior surface curvature of the corneal cap should be considered in the design of the nomogram value, (3) for patients with moderate myopic correction, early visual quality is better with a 6.9-mm than with a 7.5-mm-diameter corneal cap, (4) there is no significant difference in visual quality or biomechanics among corneal caps with different thicknesses, (5) the primary corneal cap thickness plays an important role in the SMILE re-treatment, (6) a 7.78-mm diameter corneal cap has a greater risk of suction loss than a 7.60-mm diameter corneal cap, (7) if suction

loss occurs when lenticular scanning exceeds 10%, then SMILE can be continued by changing the corneal cap thickness, (8) preventive collagen cross-linking with SMILE caps are 90–120 µm thick and 7–7.8 mm in diameter, and (9) properly treating SMILE-related complications ensures better postoperative results. The data presented herein shall deepen the understanding of the importance of the corneal cap during SMILE and provide diversified analysis for personalized operational design of corneal cap parameters.

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Introduction

Small-incision lenticule extraction (SMILE) is an “all-in-one” corneal refractive surgery that was first introduced in 2011. This procedure corrects myopia or myopic astigmatism and has been widely accepted by doctors and patients, owing to its excellent safety, effectiveness, stability, and predictability [1]. The procedure involves scanning the corneal stroma at different depths using a femtosecond laser, cutting the lenticule and creating a corneal cap and extracting the lenticule through a 2.0–4.0-mm incision on the side of the corneal cap. Compared with the traditional “flap” operation, SMILE reduces wound-

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Fig. 1. Changes in the central thickness of different corneal caps over time. Several studies have shown that the postoperative central corneal cap thickness is significantly greater than that expected and stabilizes over time.

healing responses, owing to the small incision design [2]. The biomechanical strength of the cornea after SMILE is reportedly greater than that observed, following photorefractive keratectomy and laser-assisted in situ keratomileusis (LASIK) [3, 4]. Furthermore, SMILE causes less damage to the corneal nerve fibers, and the risk of dry eyes following surgery is significantly lower with SMILE than with femtosecond lenticule extraction (LE) [5].

One of the advantages of SMILE is the creation of the corneal cap. Unlike the lenticule, the corneal cap does not function in vision correction. However, the cap is important to ensure surgical success and reduce postoperative complications. The surgical design around the cap thickness is an important problem faced by surgeons. Different thicknesses of the corneal cap may affect the postoperative visual quality and corneal biomechanics of patients and may affect whether the remaining stromal thickness is within the safe range of surgery. In addition, if refractive regression occurs after surgery, the corneal cap thickness could play a role in the re-treatment. Finally, especially for less-experienced surgeons, the management of corneal cap-related complications should be considered.

Morphological Changes in the Corneal Cap

One of the characteristics of SMILE is that it is a flapless procedure, and designing a regular corneal cap is one of the key steps to ensure the accurate creation of a lenticule. Therefore, a deep understanding of the morpho-

logical changes in corneal caps is necessary. At present, most studies have focused on changes in the corneal cap thickness and diameter. It is believed that with the continuous improvement of technology, the study of the corneal cap area or volume will receive more attention.

Predictability of the Corneal Cap Thickness

It is reported that although the corneal cap becomes thicker than the preoperative intended value, the predictability of the cap thickness remains good and is consistent with the low error rate of femtosecond laser ablation [6]. The predictability of the corneal cap thickness is evaluated by the difference between the preoperative and postoperative thickness of the corneal cap.

Several studies have shown that the postoperative central corneal cap thickness is significantly greater than expected (shown in Fig. 1) and stabilizes over time [6–9]. These results are consistent with the accuracy range of -11 to $+14$ μm for the cap thickness as described by Reinsteint et al. [10]. Conversely, the flap thickness of LASIK tends to become thinner from the first day to the first week following operation and then gradually increases 1 month following the operation [11].

Olsen et al. [9] conducted a 6-month follow-up study of SMILE by using a cap thickness of 130 μm , designed before the operation. The authors found that the thicknesses of the central corneal cap (average corneal cap thickness, 0.5 and 1.0 mm from the apex) and peripheral central corneal cap (average corneal cap thickness, 1.5, 2.0, and 2.5 mm from the apex) were greater than those

before surgery. They also reported that the corneal cap thickness in patients with low myopia was less than that in patients with moderate and high myopia at 1 and 6 months following surgery. The change in the corneal cap thickness may be related to stromal edema, epithelial remodeling, and wound-healing responses [12].

Uniformity of the Corneal Cap

Maintaining good uniformity of the corneal cap may contribute to the safety of surgery by preserving the remaining stromal bed thickness and reducing the occurrence of spherical aberration of the cornea. The uniformity of the corneal cap is characterized by the fact that its thickness gradually increases from the center to the periphery [7].

The reasons for this shape may be related to the following factors: (1) differences in the femtosecond-laser scanning sequence on the front and rear surfaces of the lenticule, which may lead to a delay effect [13] of peripheral fibers and cavitation overworked of fibers and (2) damages in the central cornea caused by the laser despite that the corneal matrix in the periphery may retain strong tensile strength.

Regularity of the Corneal Cap

In SMILE, the regularity of the corneal cap indirectly reflects the morphological changes in the lenticule, such as the emergence of a tissue bridge [14]. The symmetrical distribution of the corneal thickness at the same distance from the corneal apex is described as the regularity of the corneal cap [7].

Similar regularity is related to the visual quality in LASIK surgery [15]. In addition, Fu et al. [7] found that differences in the thickness (the thickest point minus the thinnest point) were related to the objective scattering index. Compared with the preset corneal cap diameter of 7.5 mm before surgery, the mean horizontal and vertical radial cap diameters were 7.61 ± 0.07 mm and 7.57 ± 0.06 mm, respectively, 1 month following the operation, which showed good repeatability. On the contrary, Holzer et al. [16] demonstrated that the flap diameter for an intended size between 8.0 and 9.5 mm was within a range of ± 0.4 mm, while the median at the maximum was 0.3 mm off. Binder et al. [17] also reported a similar situation, stating that the maximum diameter of the flap measured after the operation was 0.6 mm, when compared with the expected diameter.

Anterior Surface Curvature of the Corneal Cap

The features of the large central curvature and small periphery of the corneal cap after SMILE are consistent

with the shape of maintaining corneal asphericity [18]. Moreover, the decrease in curvature remains stable long after the operation.

Qin et al. [19] studied the curvature stability of the corneal cap in the early stage after SMILE-corrected high myopia and found that a curvature of 4 mm in the central area of the corneal cap decreases significantly after the operation, whereas there is no difference between 1 day and 6 months after the operation. Xia et al. [20] observed long-term changes in the curvature of the central 4-mm zone of the corneal cap after the correction of high myopia. The study showed that the curvature value of this area decreases significantly 5 years after the operation but increases slightly and remains stable 5–7 years after the operation compared with the value in the previous follow-up. Yang et al. [21] measured a curvature change of 3 mm in the center of the cap after SMILE-corrected high myopia and observed that the curvature decreases by -0.43 ± 0.54 D from 1 to 5 months after the operation, which is related to the slight refractive regression of -0.24 D and an increase of 0.20 μ m in spherical aberration after the operation.

An in vitro study [22] showed that for a myopic correction of -8 D, the curvature of the anterior surface of the corneal cap in the 110- μ m cap thickness group is lesser than that in the 160- μ m thickness group. Wu et al. [23] also found small changes in the curvature of the 4-mm area in the anterior surface of the corneal cap after the operation in the 140- μ m group compared with that in the 110- μ m group.

The arrangement of collagen fibers is responsible for stability of the curvature of the anterior surface of the corneal cap [24]. The curvature of the thinner cap varies greatly because the lenticule includes more anterior stroma. Therefore, it is necessary that eyes with thicker corneal caps compensate for possible under-correction caused by less flat surfaces, by increasing the nomogram value.

Parameters Related to the Surgical Design of the Corneal Cap

Selection of the Thickness and Diameter of the Corneal Cap

Since morphological changes in the corneal cap are relatively stable, it is important to design the corneal cap before the operation. The thickness of the corneal cap can be designed to be 100–160 μ m [1, 25]. The range of the corneal cap diameter recommended by the equipment manu-

facturer is 5.00–8.00 mm. In 2018, Chinese experts recommended that the thickness of the corneal cap should be 110–120 μm . Clinicians choose different cap thicknesses based on the central corneal thickness and correction of diopter (D) that would be attempted. There are 2 main postoperative outcomes: corneal biomechanics and visual quality. An improper thickness selection may damage the tensile strength of the cornea, thus increasing the difficulty of lenticule removal and risk of iatrogenic ectasia [26]. Furthermore, different cap thicknesses may affect the asphericity of the cornea, which is closely associated with changes in wavefront aberration and effective optical zone [27].

Influence of the Corneal Cap Thickness on Corneal Biomechanics

The anterior one-thirds of the corneal stroma has stronger biomechanics than the posterior two-thirds [28]. As the depth increases, the collagen lamellae in the anterior corneal stroma are arranged in parallel, and the distance between them is gradually increased [29], which makes the extraction of the lenticule easier [30, 31]. However, most studies have not found significant differences in corneal biomechanics among corneal caps with different thicknesses [30, 32].

Liu et al. [33] compared the biomechanics between corneal caps that were 110 μm or 150 μm thick. The authors found that there were no differences in the first and second applanation time, peak distance, or deformation amplitude between the 2 groups at 3 months following surgery. However, they did observe that the corrected intraocular pressure changed less in eyes with a 150- μm thick cap. To compare the biomechanical strength of corneal caps of 110 and 160 μm in thickness, Damgaard et al. [22] performed SMILE surgery on donor corneas with the epithelium removed. As the pressure in the chamber increased, the change in the curvature of the front surface of the 110- μm cap was greater than that of the 160- μm cap for -8 D SMILE. In addition, in a contralateral eye study, a 100- μm thick cap showed less corneal hysteresis and corneal resistance factor than a 160- μm thick cap [34]. However, whether these 2 parameters represent the overall characteristics of the biomechanics should be viewed with caution [35].

The elevation of the posterior surface of the cornea is an early sign of corneal ectasia [36]. Animal and clinical studies have shown that the posterior corneal elevation does not move forward following SMILE surgery with different cap thicknesses but tends to move backward [30, 32]. However, when the residual bed thickness is <250 μm , the posterior corneal elevation of a 150- μm thick cap is steeper than that of a 110- μm thick cap [22].

Influence of the Corneal Cap Thickness on Visual Quality

Previous studies have reported that in the stable postoperative period (3 months), there is no difference in the postoperative visual quality as measured by the spherical equivalent, visual acuity, and high-order aberrations [24, 30, 31, 33, 34]. These results reflect the safety and effectiveness of SMILE [25, 31].

Liu et al. [33] compared corneal cap thicknesses of 110 μm and 150 μm and found that the uncorrected visual acuity, objective visual quality parameters (Strehl ratio, objective scattering index, and modulation transfer function), and contrast sensitivity at the medium spatial frequency were greater in eyes with a cap thickness of 110 μm in the early postoperative stage (1 day) than in those with a cap thickness of 150 μm . However, the incidence of an opaque bubble layer (OBL) in 110- μm corneal caps was also higher. Wu et al. [37] quantitatively analyzed the area and density of the OBL in 110- μm and 140- μm caps following SMILE and concluded that the thinner the cap, the greater the probability of the OBL and that the presence of a moderate or severe OBL may affect vision.

Research by Damgaard et al. [22] on donor corneas revealed the same trend in both -4 D and -8 D correction surgery. The anterior and posterior surfaces of the cornea were steeper following the 160- μm cap operation, and the difference was more obvious in the -8 D correction. These results may suggest that for patients with high myopia, there is a risk of under-correction when choosing a thicker corneal cap.

Liu et al. [31] examined the smoothness of the lenticule surface by scanning electron microscopy and found that the front surface of the lenticule produced by a cap depth of 120 μm was rougher than that produced by a 140- μm cap. This result was contrary to that reported by Weng et al. [25], who concluded that the lenticules produced by 120- μm and 130- μm caps were smoother than that produced by 140- μm and 150- μm caps following qualitative and quantitative analysis of the tissue bridge on the lenticule surface. Since lenticule smoothness is associated with postoperative visual quality, further investigations on this topic are warranted.

Dry eye is an inevitable problem following corneal refractive surgery and affects patient's subjective visual experience. Yang et al. [38] evaluated corneal nerve destruction following SMILE in patients who had corneal cap thicknesses of 100 μm and 120 μm . There were no differences in the density and number of nerve fibers under the basement membrane between these groups at 1 week following surgery.

Table 1. Comparisons of SMILE enhancement surgeries

Surgical methods	Primary corneal cap thickness, μm	Safety and efficacy	Flap or flapless	Enhance hyperopia or myopia	Advantage	Disadvantage
Excimer laser ablation	Any	Good	Flapless	Both	The simplest surgical method Little biomechanical change	Slow healing reaction The risk of haze The use of mitomycin C
Thin-flap LASIK	≥ 120	Good	Flap	Both	Little biomechanical change	Must consider a safe distance between the corneal epithelium and the initial operation interface The risk of flap-related complications
CIRCLE	≤ 120	Good	Flap	Both	VisuMax owns the program, convenient Rapid recovery	Increased changes in biomechanics
ReSMILE*	≥ 140	Good	Flapless	Myopia	The most rapid healing Little biomechanical change	Difficult surgical method
Sub-cap LE**	≤ 130	–	Flapless	Myopia	–	–

LASIK, laser-assisted in situ keratomileusis; SMILE, small-incision lenticule extraction; Sub-cap LE, sub-cap lenticule extraction; reSMILE, secondary small-incision lenticule extraction. * The secondary LE plane is in front of the primary plane. ** A case report: the safety, efficacy, advantages, and disadvantages of this method need further study.

Influence of the Corneal Cap Diameter on Visual Quality

Since SMILE does not have an iris-tracking device to the center, postoperative eccentricity would induce high-order aberrations. Moreover, the diameter of the corneal cap is related to intraoperative centration.

In a study by Torun Acar et al. [39], the diameter of the optical zone designed before the operation was 6.5 mm, and subsequently, the visual quality of the corneal caps with diameters of 6.9 mm and 7.5 mm was compared. The authors found that uncorrected distance visual acuity of 6.9 mm was greater in the early postoperative period. Furthermore, fewer instances of total high-order aberrations, horizontal and vertical coma, and spherical aberrations were noted at 6 months following surgery in patients with cap diameters of 6.9 mm.

Influence of the Corneal Cap Design on Re-Treatment Options

Although SMILE surgery has been favored by many doctors and patients, the re-treatment rate is still low (2.3–4.4%) [40–42]. According to a study by Liu et al. [42] on enhanced surgery following SMILE, the average spherical equivalent of 524 eyes that underwent enhancement was -0.50 ± 0.86 D, which was a low myopic correction. The methods for enhancement surgery can be summarized as follows: excimer laser ablation [40], thin-flap LASIK [41], CIRCLE [43], and secondary SMILE.

Excimer Laser Ablation

Excimer laser ablation is the simplest enhancement surgery because it can be performed without considering the thickness of the initial cap [44]. However, patients need to accept certain disadvantages resulting from excimer laser ablation (such as slow recovery).

Thin-Flap LASIK

For thin-flap LASIK, a thin flap on the patient's initial corneal cap is made, and subsequently, conventional LASIK is performed. Reinstein et al. [45] suggested that the prerequisite for successful secondary LASIK with a thin flap is the presence of at least 40 μm of space between the maximum epithelial thickness and the minimum cap thickness. Considering some postoperative reactions, such as epithelial thickening following the first SMILE operation [46], the initial cap thickness is designed to be ≥ 120 μm [47].

CIRCLE

CIRCLE is achieved by changing the initial corneal cap into a corneal flap with femtosecond laser and then performing femtosecond-laser-assisted LASIK. When the initial cap thickness is < 120 μm [48], the VisuMax CIRCLE program (Carl Zeiss Meditec AG, Jena, Germany) [43, 45] can be considered. However, if the CIRCLE program is performed in a thick cap, such as caps of 150–160 μm thickness, it will inevitably cause damage to the corneal biomechanics [49].

Secondary SMILE

SMILE is still selected for enhancement, which could be performed by 2 methods: (1) secondary LE, where the plane is in front of the primary plane [48] and (2) sub-cap LE, where the plane is behind the primary plane [50]. When the initial corneal cap thickness is $\geq 140 \mu\text{m}$ and the secondary correction D is $\geq -1.00 \text{ D}$, the secondary SMILE procedure could be performed to maintain the flapless characteristic and minimize the wound-healing response [48]. If the initial cap thickness is $110\text{--}130 \mu\text{m}$, the depth limit makes it impossible to extract the lenticule in front of the original interface. In this case, the initial operation interface can be used as the front surface of the new lenticule. This method is known as sub-cap LE [50]. However, considering the safety range of the remaining stromal-bed thickness, Riau et al. [48] recommended that the primary cap thickness should be designed to be $\leq 130 \mu\text{m}$. The selection of the cap thickness corresponding to each method and other factors to be considered are presented in Table 1.

Application of the Corneal Cap Thickness and Diameter in Collagen Cross-Linking with SMILE

Compared with “flap” surgery, SMILE has greatly improved the biomechanics due to its unique cap design to protect the anterior stroma. However, corneal ectasia is still reported after SMILE surgery [51–53]. Corneal collagen cross-linking (CXL) can prevent or delay the progression of corneal ectasia by improving the biomechanics of the corneal stroma [54, 55]. Collagen cross-linking with SMILE (SMILE Xtra) is undoubtedly a choice to prevent postoperative corneal ectasia in young patients, with a high refractive power and thin cornea, as determined by preoperative screening. At present, the parameters of caps with different thicknesses or diameters are not unified. Irradiation energy and the selected cap diameter and thickness affect the extent of cross-linking.

Ng et al. [56] studied the early clinical effect of SMILE Xtra on myopia. They used a corneal cap thickness of $110\text{--}120 \mu\text{m}$ and a cap diameter of $7.0\text{--}7.5 \text{ mm}$. After 6 months, SMILE Xtra had good predictability. In addition, 1 year after SMILE Xtra, CXL under a cap with a thickness of $120 \mu\text{m}$ and a diameter of 7.6 mm also achieved good safety, effectiveness, predictability, and stability [57].

Ganesh et al. [58] performed myopia correction by SMILE Xtra under a cap thickness of $100 \mu\text{m}$ and cap diameter of $7\text{--}7.5 \text{ mm}$. All 40 eyes studied maintained stable visual quality and corneal morphology at 1 year after the operation. Konstantopoulos et al. [59] compared the

corneal stability with SMILE Xtra and CXL with LASIK. They cross-linked SMILE under a cap with a depth of $120 \mu\text{m}$ and a diameter of 7.5 mm and found no difference in the changes in the posterior corneal elevation and corneal thickness between SMILE Xtra and CXL with LASIK after the operation. Osman et al. [60] performed SMILE Xtra on patients with corneas thinner than $520 \mu\text{m}$. The thickness of the corneal cap was $90 \mu\text{m}$, and the diameter was 7.5 mm . One year after the operation, 94% of the eyes obtained an uncorrected distance visual acuity of 20/30 or above, and the biomechanics was significantly higher than that with traditional SMILE. Zhou et al. [61] observed corneal morphological changes after SMILE Xtra by optical coherence tomography and in vivo confocal microscopy. In their study, the ultraviolet radiation of riboflavin was carried out under a cap with a thickness of $110\text{--}120 \mu\text{m}$ and a diameter of $7\text{--}7.8 \text{ mm}$. Six months after the surgery, the researchers observed hyper-reflectivity in the corneal tissue with a cap thickness of $60 \mu\text{m}$ to a stromal bed of $388 \mu\text{m}$, an indirect sign of corneal cross-linking, illustrating the extent of corneal cross-linking.

Because the anterior stroma with high collagen-fiber density is the main site of cross-linking, a thicker cap is expected to reduce the concentration gradient of riboflavin permeation to the cap and stromal bed [62–64]. The selection of different cap diameters is also related to the volume of the stromal pocket.

Management of Corneal Cap-Related Complications

SMILE has helped achieve encouraging results in correcting myopia and myopic astigmatism. However, it is undeniable that the long learning curve of surgery could lead to certain complications. Corneal cap-related complications include suction loss, cap perforation, cap lenticular adhesion, and cap striae. Therefore, it is necessary to consolidate the doctors' understanding and management of corneal cap-related complications.

Suction Loss

The morphological characteristics of corneal caps are related to the adsorption stability between the cone and eyes. In addition, corneal caps with different thicknesses also play an important role in the treatment of suction loss.

Suction loss is an intraoperative complication and results in the detachment of the suction cone from the patient's cornea. The development of software combined with experienced operators has reduced the rate of suc-

tion loss to 0.17–0.93% [65–70]. Suction loss could result in the decline of postoperative visual quality, and the possibility of this complication should be recognized by the ophthalmologist [71].

In addition to the eye movement, the liquid present at the corneal contact interface may interfere with suction [67]. Osman et al. [67] found that the diameter of the cap, rather than the thickness, was also a potential factor in suction loss, which could be related to poor matching between the cone and the cornea. These data were confirmed by Ma et al. [72], who found that patients in the control group had a mean cap diameter of 7.60 mm, while the cap diameter in the suction-loss group was 0.18 mm larger.

The conventional method for managing suction loss is to adopt excimer laser ablation or femtosecond-laser-assisted LASIK when the laser scanning of the lenticule exceeds 10%, while SMILE can be continued after suction loss in other stages [73]. However, Reinstein et al. [74] pointed out that when the thickness of the corneal cap is $\geq 135\text{ }\mu\text{m}$, even in the first case, SMILE may be restarted by reducing the thickness of the cap. In addition, Qin et al. [70] adopted an innovative method for increasing the thickness of the corneal cap following suction loss during SMILE, when $>10\%$ of the back surface of the lenticule had been subjected to scanning, and they achieved good postoperative results. Therefore, changing the corneal cap thickness following suction loss during SMILE surgery could be a plausible alternative for shortening the recovery time or reducing corneal flap complications caused by conventional eye surgeries.

Cap Perforation and Cap Lenticular Adhesion

Severe cap perforation and cap lenticular adhesion affect the visual outcome. At present, with the emergence of many new technologies, these complications can be well prevented. However, low myopic correction and OBL may increase the difficulty of LE [75]. Therefore, for patients with low myopic correction, the incidence of OBL can be reduced by increasing the thickness of the corneal cap, thus reducing the incidence of cap lenticular adhesion.

Perforation of the corneal cap has been reported during the separation of the front surface of the lenticule [75] and was shown to be related mainly to the clinicians' inexperience. The incidence of cap perforation is 0.25–4.38% [73]. Ivarsen et al. [71] treated patients with cap perforation by having them wear contact lenses, and only a small scar remained on the corneal surface 3 months following the surgery, which did not affect their vision.

The main reason for cap lenticular adhesion is that OBL interferes with the surgeon's operating visual field and causes disordered anatomy of the lenticule (the normal order is the front surface and the back surface) [76]. At present, various markings have been described to avoid inaccurate positioning of the cutting plane, such as the white ring sign [77], shimmer sign [78], meniscus sign [79], and stop sign [80]. Furthermore, some new technologies have been developed to reduce adhesions, such as Chung's swing technology, which uses a fan shovel to separate the posterior surface of the lenticule [81]; double-crescentic edge separation technology, which uses a Sinskey hook to separate the lenticule [82]; hydroexpression technology, which places an irrigation cannula under the lenticule [83]; and intraoperative optical coherence tomography [84]. These newer technologies are particularly beneficial to less-experienced physicians. For the complete removal of lenticular fragments or residues, which is difficult to separate, a second surgery can also be adopted [76, 85].

Cap Striae

Although cap striae rarely occur, the principles of prevention and treatment are still worthy of attention. A case report described the treatment of patients with moderate and high myopia with cap striae following operation [86]. In the operation of the left eye, owing to the dislocation of the anatomical sequence, the operator performed repeated LE to prevent lenticular adhesion; thus, the tear of the cap incision and cap striae of the cumulative visual axis appeared on the first day following the operation. The patient complained of glare. Doctors flushed the interface with a balanced salt solution, used a scraper to remove the corneal epithelium corresponding to the cap striae, washed the exposed stroma layer with distilled water, stretched the cap striae with a sponge, and finally covered the striae with a bandage contact lens. The cap striae disappeared completely, and the uncorrected distance vision was 20/20 at 9 months after the operation.

Therefore, cap striae caused by excessive operation should be avoided during extraction. Furthermore, it is necessary to flush the surgical interface, which can reduce the risk of epithelial implantation.

Conclusion

The following points should be considered for the morphological changes and surgery-related parameters of the corneal cap: (1) the corneal cap shows good pre-

dictability and repeatability both laterally (diameter) and longitudinally (thickness); (2) the anterior surface curvature of the corneal cap is significantly smaller than that before the operation, and this flattening change should be considered in the design of nomogram values, especially when the corneal cap is thick; (3) the corneal cap thickness and morphology influence the postoperative visual quality, and the influence of different cap thicknesses is mainly limited to the first day post-surgery; (4) for patients with moderate myopic correction, the visual quality is greater with a 6.9-mm-diameter corneal cap than with a 7.5-mm-diameter cap; (5) there is no significant difference in visual quality and biomechanics between different corneal cap thicknesses during the stable period. These results suggest that for patients with high myopic correction, the thickness of the corneal cap should be reduced to retain a greater depth of the remaining stromal bed. Furthermore, creating a thick cap may cause under-correction for high myopic patients (-8 D); (6) the thickness of the first corneal cap plays an important role in SMILE re-treatment (Table 1); (7) a corneal cap with a 7.78-mm diameter has a greater risk of suction loss than a cap with a 7.60-mm diameter; (8) when lenticular scanning exceeds 10%, SMILE surgery can be continued by changing the thickness of the corneal cap; (9) preventive SMILE Xtra caps are 90–120 μm thick and 7–7.8 mm in diameter. For patients with high myopic correction and a thin cornea, it is a favorable choice to design the stromal pocket according to the shape (thickness and diameter) of the corneal cap for SMILE Xtra; and (10) by properly treating cap-related complications, such as cap perforation, cap lenticular adhesion, and cap striae, the majority of patients shall obtain better postoperative results.

In the future, the long-term biomechanical changes due to different cap thicknesses, the smoothness of lenses, and the significance represented by Bowman's membrane microfold should be further studied. In addition, further research on the optical density of the corneal cap [8] and the application of LE for presbyopia [87] is need-

ed. As ophthalmologists gain a deeper understanding of corneal caps, the depth and diameter of the caps may be personalized according to the patient's condition, which would benefit more patients with thin corneas and high myopia and may reduce the incidence of complications.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

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Author Contributions

Chen Liang and Yan Zhang share the first authorship and contributed to the conception and design, data collection, analysis and interpretation of data, and writing the manuscript. Yuxi He contributed to critical revision of the manuscript. Shurong Wang is the corresponding author.

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