Refractive Laser Surgery

14

Corneal refractive surgery is effective through one of two mechanisms: firstly by altering the shape of the whole thickness of the corneal stroma (Chap. 13) or secondly by affecting only the anterior corneal surface (*this chapter*).

Mechanisms

The aims of superficial procedures are the same as those of full-thickness procedures: the central cornea is flattened to correct myopia, steepened to correct hyperopia and altered in the appropriate meridian for astigmatism (Chap. 13).

In superficial procedures, tissue is either added to the anterior corneal surface (e.g. epikeratophakia [1]), removed (e.g. keratectomy and excimer or femtosecond laser procedures) or structurally altered (laser thermokeratoplasty). Of those procedures removing tissue, photorefractive keratectomy (PRK) removes tissue from the corneal surface, whereas laser in situ keratomileusis (LASIK) and femtosecond small incision lenticule extraction (SMILE) remove tissue from just below the surface, under a flap or within the anterior stroma. All these superficial techniques, unlike incisional refractive surgery or intrastromal rings, maintain the integrity of the deep corneal stroma, and the shape of the posterior corneal surface remains unaltered.

Topography for Superficial Procedures

The role of topography is similar for all forms of refractive surgery (Tables 13.1 and 13.2). The value of the topographic information obtained can be enhanced by using facilities such as the local radius of curvature, difference maps and statistical indices.

However, one limitation of topography after superficial procedures is that there is an error (about 11.4% for PRK) in the absolute corneal power reading [2]. This is

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because the shape of the anterior corneal surface is changed by the procedure, without the corresponding change occurring in the posterior surface. Topography systems use the standardised keratometry index (SKI) to convert measurements of radius of curvature of the anterior corneal surface into estimates of total corneal power (Table 1.1). This value is an estimate and makes an assumption about the power of the posterior corneal surface based on the measured anterior surface and knowledge of the normal corneal thickness, which is no longer applicable after surgery.

Photorefractive Keratectomy

All refractive procedures have, to some extent, suboptimal accuracy, predictability and stability of the refractive change and adverse effects on the quality of vision [3]. These shortcomings arise from two sources: firstly, the variations and inaccuracies inherent within the surgical techniques and, secondly, individual differences in the wound healing response. The first of these problems is a major contributor to the variability of the outcome of incisional procedures. However, this aspect has been largely overcome by the use of the excimer and, more recently, the femtosecond lasers in refractive surgery.

Mechanism

Excimer Laser

The excimer laser was introduced into ophthalmology in the early 1980s, when it was realised that it had characteristics ideally suited to performing refractive surgery [4, 5]. This laser could remove tissue with submicron precision, leaving a smooth surface with minimal damage to adjacent structures [6, 7]. When the beam was configured as a narrow slit, it could be used as an efficient scalpel blade to incise corneal tissue [8, 9]. However, the ability of the laser to generate a broad beam provided the additional benefit of being able to remove tissue from relatively large areas [5]. Using this technique, it became possible to change the power of the cornea by the differential ablation of superficial tissue to change its anterior curvature (photorefractive keratectomy, PRK). This avoided the weakening of the globe associated with other popular refractive procedures of the time, such as radial keratotomy.

The term “excimer” is a contraction of the words “excited dimer”. Excited dimers are two atoms of an inert gas bound in a highly excited state with atoms of halogen. The excimer lasers used for refractive surgery contain argon fluoride. The decay one of these unstable molecules is accompanied by the emission of a highly energetic photon of light in the far ultraviolet portion of the spectrum (UVC, 193 nm). Each individual photon has sufficient energy to break a covalent bond, by the process termed photoablation. When this occurs in biological tissues, the cleaved macromolecule rapidly expands and is ejected from the surface at high speed [5].

Ultraviolet C radiation has a penetration depth of less than 1 μm. Each photon emitted is absorbed by a single molecule, and therefore adjacent areas beyond 60–200 nm show no conductive effect. Each pulse removes a well-defined layer of corneal stroma 0.25 μm thick, leaving the underlying tissue undisturbed. The ablated surface is smooth and is immediately sealed by a pseudomembrane [6]. This is a layer 20–100 nm thick formed by the random recombination of double bonds uncoupled during the ablation process.

Wound Healing

In photorefractive keratectomy (PRK), the corneal epithelium is first removed, and then the excimer laser is used to ablate the underlying stroma. During the subsequent healing period, the wound is resurfaced by epithelium in a few days, and then new subepithelial tissue is produced and remodelled in a process taking many months [10–12]. The corresponding refractive changes comprise an initial overcorrection, followed by a gradual reduction in refractive error until a plateau is reached near emmetropia (or the intended refraction).

The variability of the refractive outcome after PRK arises from individual differences in the wound healing response. All patients can be considered to lie on a spectrum of wound healing [13]. The majority are near the centre, with normal healing resulting in approximately emmetropia. At one end of the spectrum are those patients with a limited healing response, who remain overcorrected with a relatively large change in corneal topography. At the other end of the spectrum are those with an aggressive healing response, who regress with a return towards their original refraction. Similarly, the topography reverts towards normal, with the treatment zone becoming much less obvious.

Myopia

To correct myopia, the excimer laser flattens the central cornea by etching a negative lens into its anterior surface (Figs. 14.1, 14.2 and 14.3). This may be achieved by passing a broad beam of relatively uniform energy distribution through either an expanding aperture, a preshaped erodible mask or a rotating slit [14]. As a result, a greater number of pulses fall on the centre than the periphery of the treatment zone, and a saucer-shaped disc of tissue is removed. The computer-controlled expansion of the aperture, the shape of the mask or slit or the movement of a flying spot determines the exact profile of the ablation. The depth of ablation is greater for corrections of higher magnitudes and larger diameters. However, still only the very superficial corneal layers are removed; for example, a −6.00D 6 mm correction has a central ablation depth of 78 μm [15].

Hyperopia

The correction of hyperopia requires the optical zone to be steepened (Fig. 14.4). This is achieved by removing an annulus of tissue from the midperiphery of the cornea [16, 17]. Therefore ablation zones need to be much larger than for the correction of myopia and are typically about 9 mm in diameter.

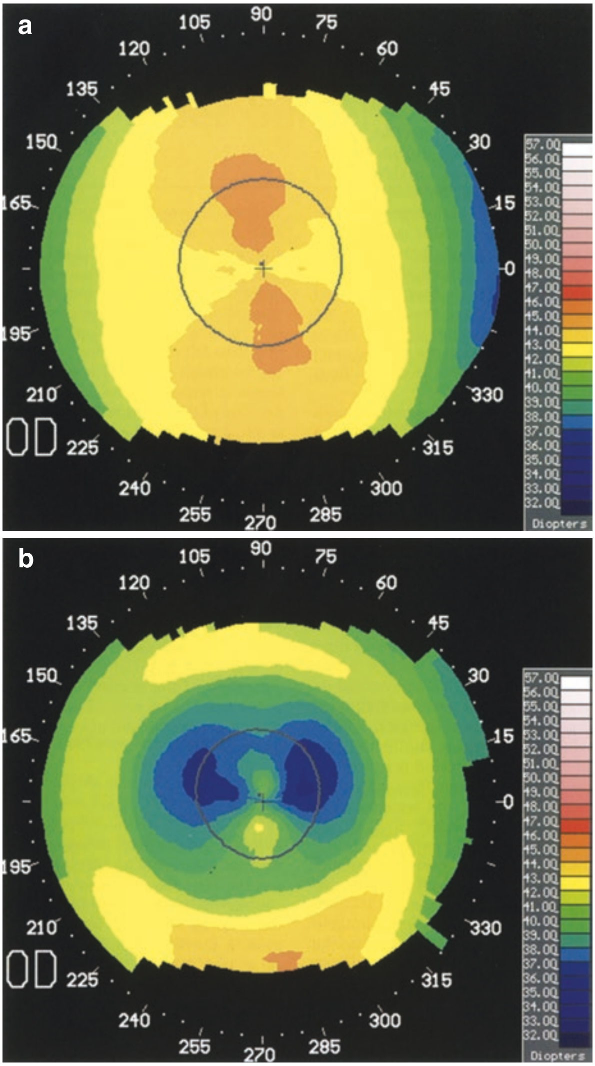


Fig. 14.1 Myopic photorefractive keratectomy. The excimer laser removes more tissue from the centre than the periphery of the treatment zone to correct myopia. This patient underwent a spherical −6.00D 6 mm PRK. (**a**) Preoperatively there was −2.00D with-the-rule astigmatism. (**b**) At 1 week postoperatively, the majority of patients are overcorrected, and in this case, the spherical equivalent was +1.50D. The contours are closest together just inside the edge of the treatment zone. There was marked flattening of the central cornea making the cornea oblate rather than prolate. Therefore the astigmatism appeared as a blue horizontal bow tie. (**c**) One month postoperatively, wound healing mechanisms have started replacing ablated tissue. This has reduced the spherical equivalent to +0.50D, and the corneal flattening is less marked. (**d**) By 1 year, the refraction has stabilised to –0.25D spherical equivalent, and the topography again appears less flat than previously

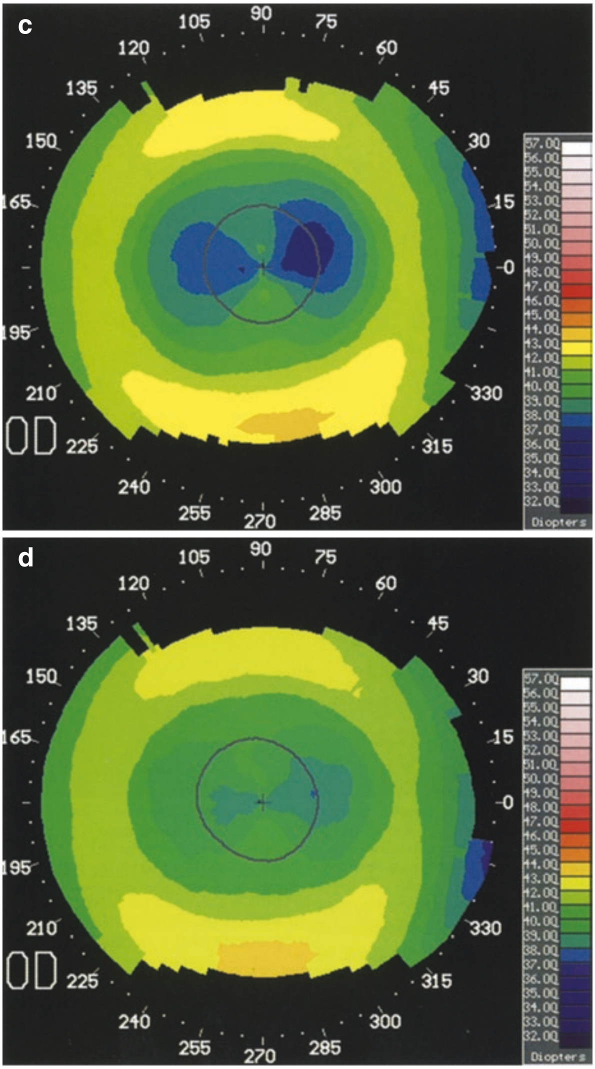


Fig. 14.1 (continued)

Regular Astigmatism

Regular astigmatism is corrected by the differential ablation of tissue in the steeper meridian, and therefore the treatment zone is usually hemicylindrical or oval (Fig. 14.5). As this involves the removal of tissue from part of the optical zone, a purely astigmatic correction is usually associated with some central corneal flattening and a corresponding hyperopic shift in the spherical equivalent [18]. The coupling seen following incisional procedures does not occur, because the middle and deep stromal lamellae are still intact. Astigmatic corrections are frequently performed in combination with spherical procedures [19].

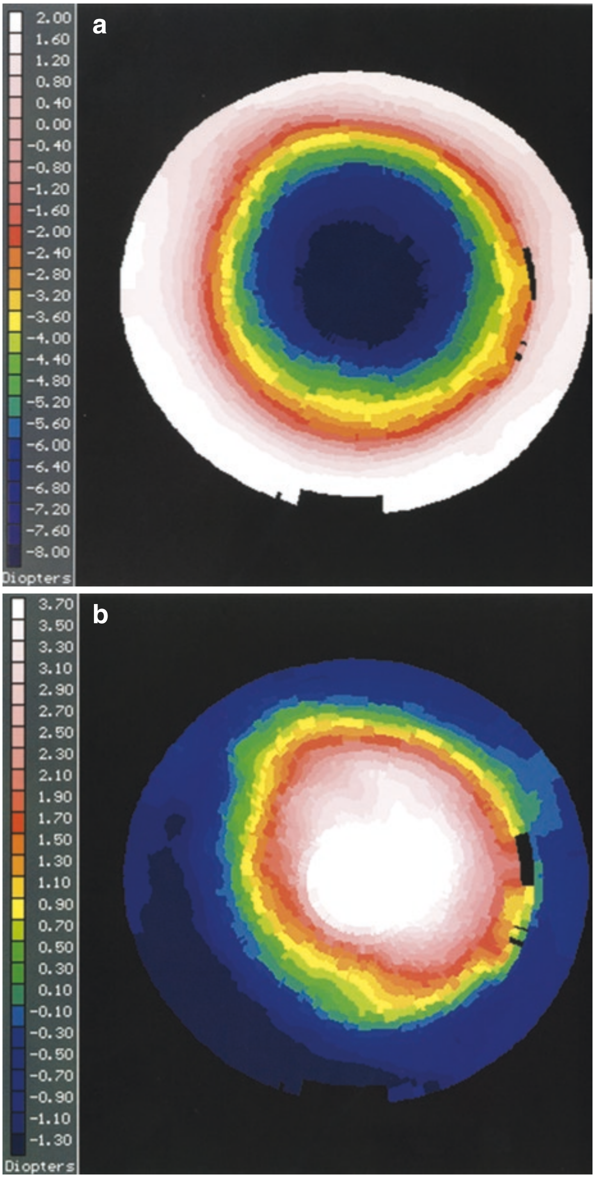


Fig. 14.2 Photorefractive keratectomy (PRK) difference maps. The most effective way of displaying the change occurring is on a difference map. (**a**) The change induced by the surgery is obtained by subtracting the preoperative map (Fig. 14.1a) from the immediate postoperative map (Fig. 14.1b). The treatment zone appears blue because tissue was removed by the treatment. If the two maps are similarly aligned, there should be no change in the region outside the treatment zone. This is useful for medicolegally documenting the surgery which has been performed. (**b**) The change occurring postoperatively as a result of wound healing is obtained by subtracting a late map (Fig. 14.1d) from an immediate postoperative map (Fig. 14.1b). The treatment zone appears red because since the ablation, new tissue has been laid down and the cornea has become less flat

Irregular Astigmatism

Topography can be used to guide the excimer laser treatment of irregular astigmatism arising postoperatively or as a result of corneal disease. Originally in phototherapeutic keratectomy (PTK), fluid masking agents were used to protect depressions from the laser energy, whilst protuberances above the fluid level were ablated. This technique was useful for smoothing rough surfaces but lacked the precision required for a refractive procedure.

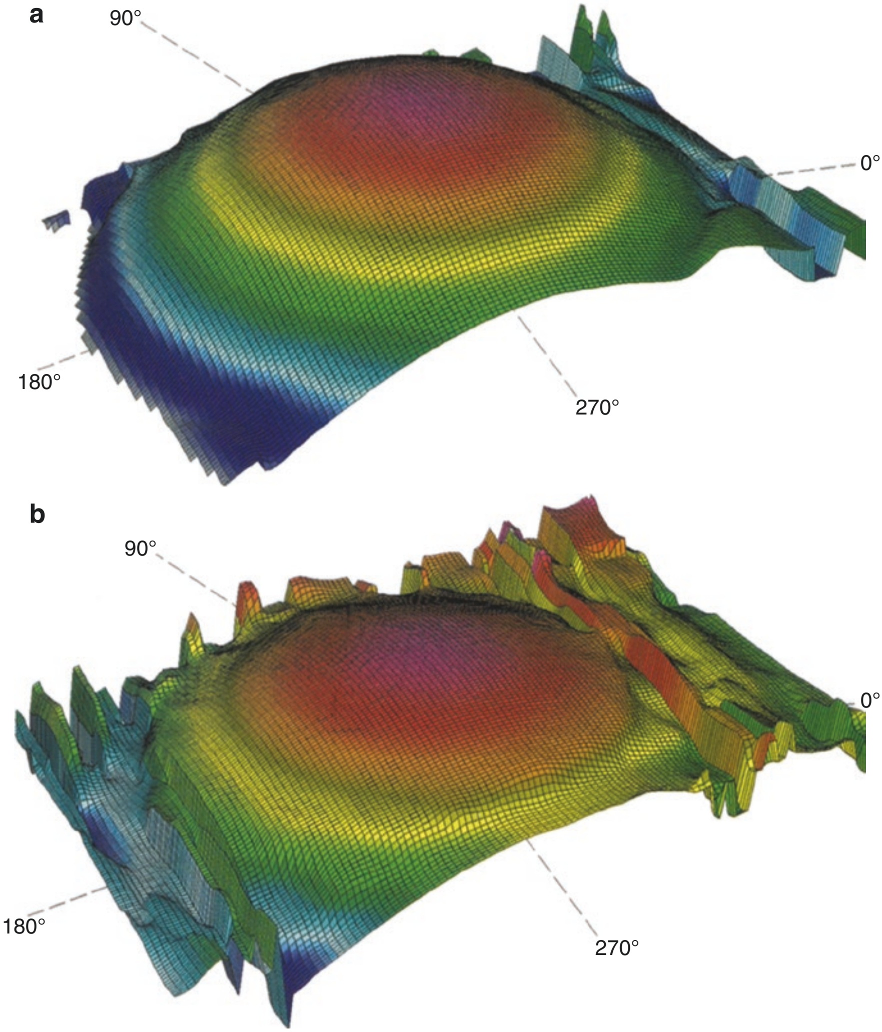


Fig. 14.3 Photorefractive keratectomy (PRK) height maps. This patient underwent −6.00D 6 mm PRK. (**a**) Three-dimensional representation of the preoperative corneal height. (**b**) Projection-based systems are able to accurately record the corneal topography immediately postoperatively. The central cornea has been flattened by the removal of the epithelium and ablation of the underlying stroma. The slightly heaped edge of the margin of the debrided epithelium can be seen just peripheral to the ablation zone. (**c**) The difference map shows the total depth of tissue removed by the procedure. For a myopic correction, more stroma is ablated from the centre of the treatment zone than from its periphery. (**d**) The cross section of the difference map shows the saucer-shaped ablation profile

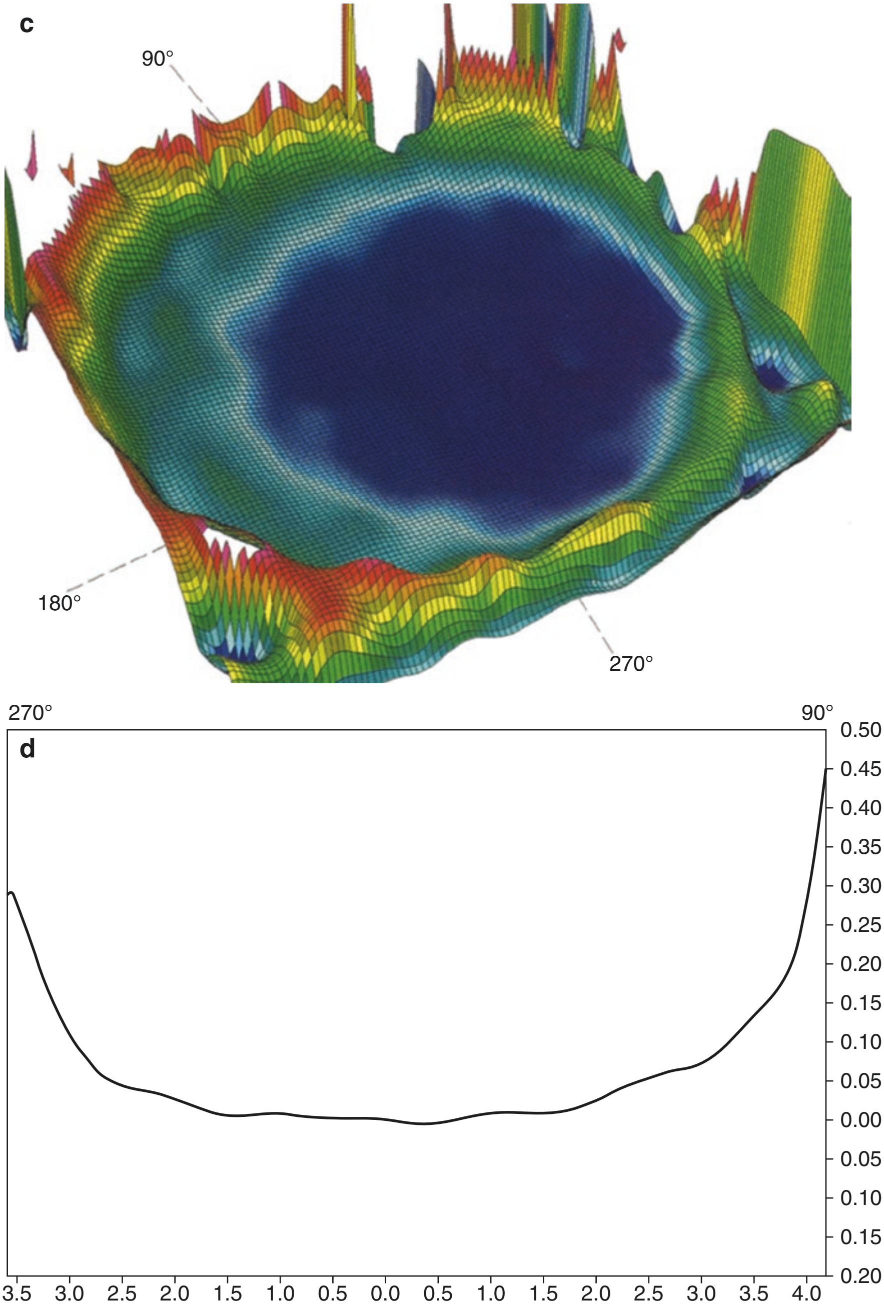


Fig. 14.3 (continued)

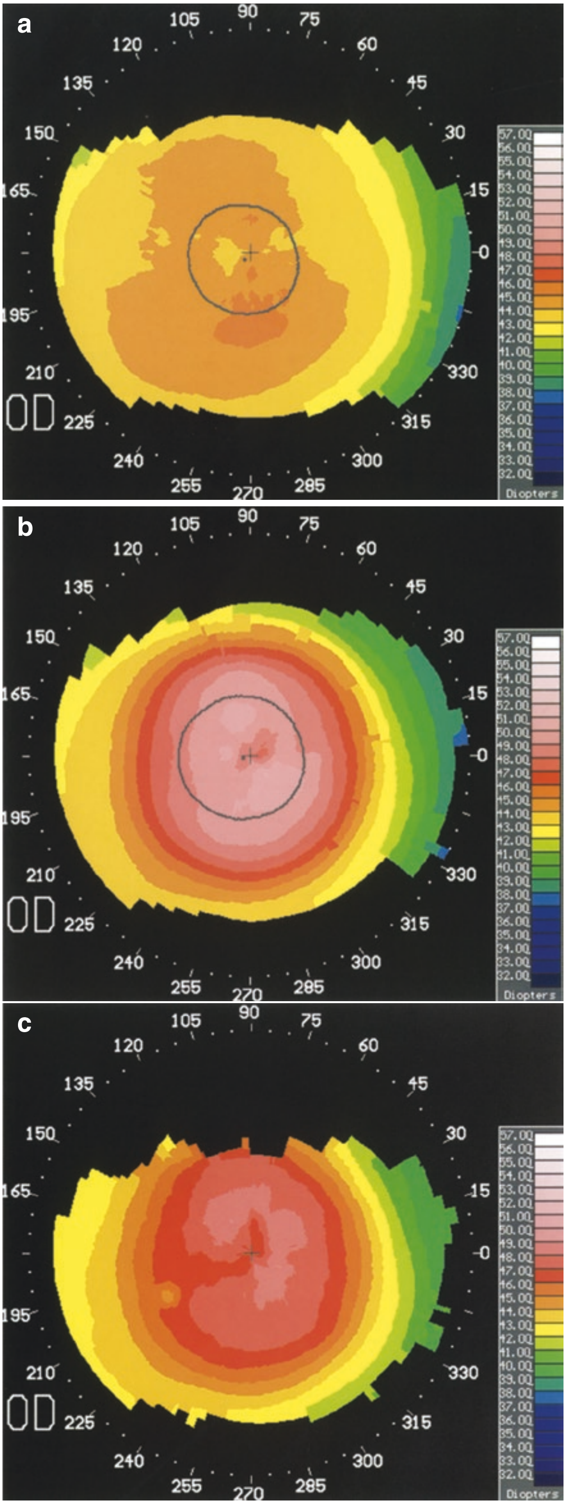


Fig. 14.4 Hyperopic photorefractive keratectomy (PRK). To correct hyperopia, the excimer laser removes an annulus of tissue from the midperiphery to steepen the central cornea. (**a**) Preoperatively, the cornea had a normal oval pattern. (**b**) One week after a +3.50D PRK, the refraction was −0.50D, and there was steepening of the central cornea. In the midperipheral cornea, the contours are closer together than normal, representing the rapid change from central steepening to flattening over the treated area. (**c**) By 1 year new wound healing tissue has been laid down where the ablation was deepest. This slightly reduced the effect of the correction, and the refraction stabilised at +0.25D

A few surgeons tried applying freehand small (e.g. 1 mm) treatment zones to patches of the cornea corresponding to the steep areas on videokeratoscopy maps. However, this commonly exacerbated visual problems by creating a multifocal cornea. Others have used Fourier techniques to better identify areas of irregularity by removing the spherical and cylindrical components of the corneal shape [20].

If topography is to be used to guide the correction of irregular astigmatism, it is imperative that height maps are used so that the treatment can be applied to the peaks, rather than the steep sides, of any elevated area. Ideally, the site and distribution of the ablation should be computer controlled, because any malposition of the

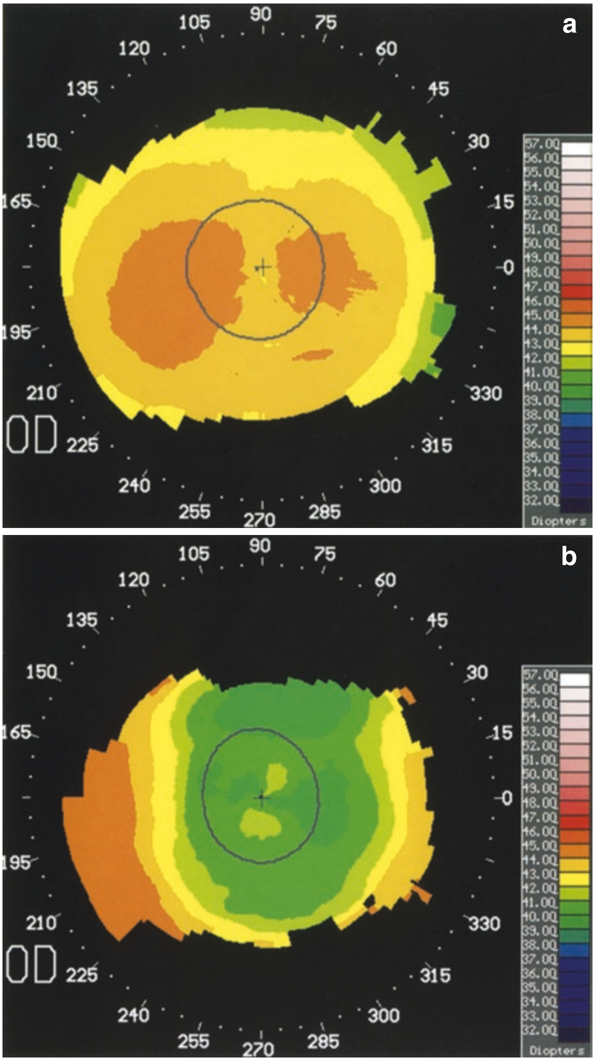


Fig. 14.5 Astigmatic photorefractive keratectomy (PRK). To correct astigmatism, the excimer laser removes more tissue in the steep axis than the flat axis. (**a**) Preoperatively the refraction was −3.00/−2.00 × 180°. The against-the-rule astigmatism appears as a horizontal bow tie. (**b**) One week postoperatively, the corneal surface is slightly irregular due to the healing epithelium. The overall pattern is almost spherical, although there is a very slight early overcorrection of the stigmatism centrally. (**c**) The difference map demonstrates that the power has been changed by approximately 2D in the vertical meridian and 5D in the horizontal meridian. (**d**) The height difference map shows that more tissue has been removed from the horizontal axis than the vertical axis and ablation appears oval

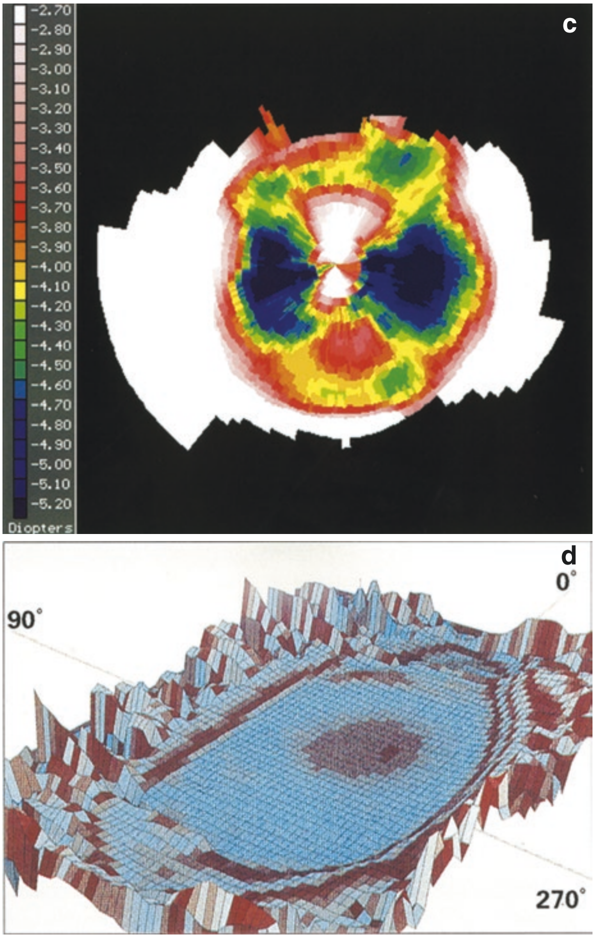


Fig. 14.5 (continued)

treatment can result in removal of tissue from the troughs rather than the peaks leading to increased irregularity.

There are two potential mechanisms by which the application of laser energy could be controlled. Firstly, the topographic map could be used to lathe an individualised erodible mask complementary to the corneal shape, which was then correctly positioned in the path of the laser beam. Secondly, the topographic information could directly drive the ablation pattern of a "flying spot" laser, in which a computer-guided 1 mm beam is used to "paint" the corneal surface. Any of these techniques require that the subsequent wound healing is symmetrical. Even if they were able to smooth the surface of the cornea accurately [21], the refractive outcome would be difficult to predict, and the effect on visual function is currently unknown [22, 23].

Topography After PRK

As with any refractive procedure, the first postoperative map shows most accurately the topographic change achieved by the procedure itself. The treatment zone is usually easily delineated by the close proximity of adjacent contours at its edge. Its diameter can be measured using the grid or cursor facilities (Fig. 5.10). The position of the edge of the treatment zone is accentuated by the use of a difference map [24] (Figs. 14.2, 14.4c and 14.5c).

Myopic corrections result in flattening of the whole treatment zone (Figs. 14.1, 14.2 and 14.3). Following hyperopic corrections, there is steepening of the central cornea, which increases the corneal asphericity. This is surrounded by a ring of relative flattening at the edge of the treatment zone where most corneal tissue has been removed (Fig. 14.4). Sometimes this is not evident on the colour-coded contour map if a scale with a large step interval is used; but on the Placido image, the rings are more widely spaced in this region [16, 25].

For corneas that have round or oval topographic patterns preoperatively, the contours tend to remain concentric following spherical procedures. The appearance of a preoperative bow tie is changed little by a hyperopic procedure. However, following a myopic correction, the red bow tie is replaced by a blue bow tie in the perpendicular axis (Fig. 14.1). This arises from the way in which the corneal slope is measured by videokeratoscopes, and does not reflect a change in astigmatism.

In astigmatic procedures the treatment zone is oval. During the period of overcorrection, the preoperative red bow tie is replaced by a blue bow tie in the same axis (Fig. 14.5).

Following any PRK treatment, the induced flattening or steepening is most pronounced initially during the period of overcorrection and then becomes less marked with time as new wound healing tissue is produced (Fig. 14.1). This process and the subsequent remodelling may produce changes in the topographic pattern as described below.

In the early days of myopic PRK, small diameter ablations were used with the aim of minimising the volume of tissue removed. This resulted in wide individual variations in the refractive outcome. Some patients with a limited healing response were left hyperopic with persistent corneal flattening (Fig. 14.6). In contrast, those with an aggressive healing response underwent regression, with reduction of the corneal flattening and, in the worst cases, corneal steepening (Fig. 14.7). However, with the introduction of larger diameter ablations, cases of this severity are no longer seen [26, 27].

Projection-based topography systems are useful because they can measure the topography immediately postoperatively as they do not require the anterior corneal surface to be reflective [28] (Table 3.1). Height maps are particularly valuable for PRK because the refractive outcome achieved is directly related to the precise depth of tissue removed from the anterior corneal surface [15]. The difference between the preoperative and immediately postoperative maps demonstrates the profile of the ablation and the spatial uniformity of the laser beam. Subtraction of the immediate

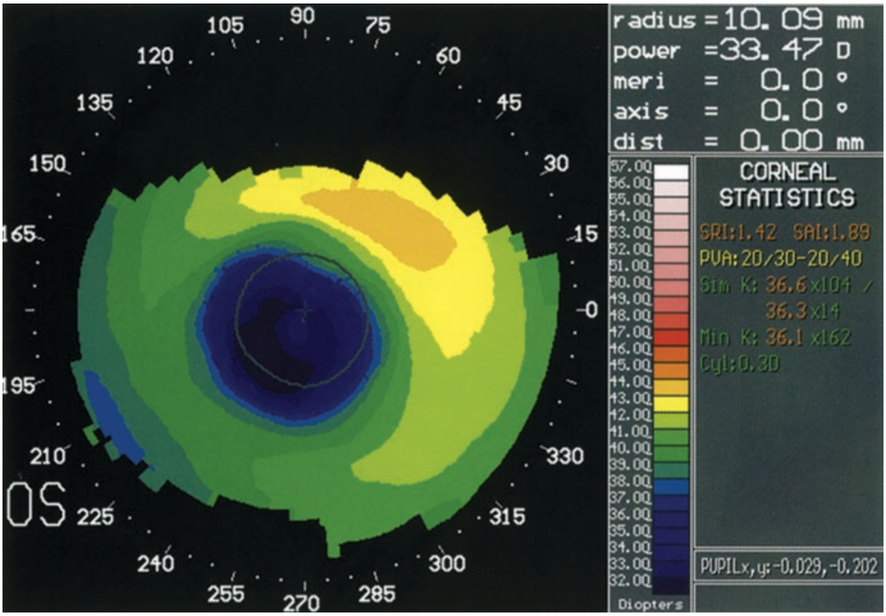


Fig. 14.6 Photorefractive keratectomy (PRK) overcorrection. Following a -6.00D 4mm PRK, the refraction in this 66-year-old man swung to +5.50D where it remained for about a year before slowly reducing to +5.00D over the subsequent year. He had extreme central corneal flattening (see cursor box) as a result of his minimal wound-healing response and never developed any haze. When wearing an optical correction, he suffered halos in moderate and dim illumination (Fig. 13.1). This was due to a combination of the small treatment diameter and the large +11.50 hyperopic shift. Fortunately such extreme cases are very rarely seen nowadays because larger diameter treatments are used

postoperative topography from subsequent maps quantifies the new tissue produced at intervals during the healing process [29].

Ablation Zone Centration

Accurate centration is best achieved by aligning the ablation on the centre of the pupil [30, 31], whilst the patient is fixating coaxially with the surgeon [32]. Alternatively, some surgeons fixate the eye by the use of a suction ring or other instruments, but this tends to be less effective [33]. Alignment is optimised by preoperative calibration of the aiming beams and the surgeon taking care to ensure that they are properly positioned on the eye before and during treatment.

Decentration most commonly occurs as a result of patient movement secondary to loss of fixation. The incidence is increased in higher-order corrections, presumably because the duration of the ablation is longer [34–37]. There is no correlation with the diameter of the ablation, but the visual effects of decentration are greater for smaller optical zones and in patients with big pupils (Fig. 14.8).

The risk of decentration can be reduced by the surgeon ensuring the careful preoperative counselling of patients to reduce anxiety, preoperative training of patients

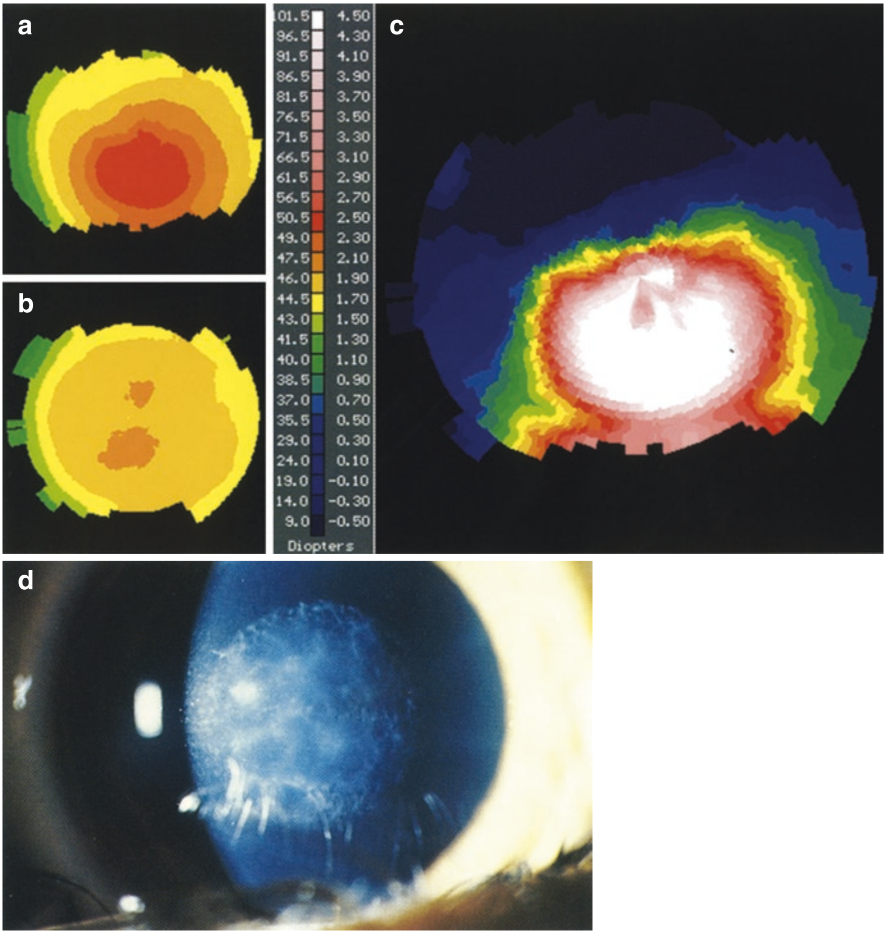


Fig. 14.7 Photorefractive keratectomy (PRK) regression and haze. Following a -6.00D 5mm PRK, there was an initial overcorrection of +2.25D, followed by a steady increase in regression until the residual spherical equivalent error was -7.00D at six months, when it stabilised. Subtraction of the one-year (**a**) from the preoperative (**b**) topography shows that the net result of the procedure has been a steepening of the cornea (**c**). This is due to an aggressive wound-healing response, which has produced excessive new tissue, causing severe corneal haze (**d**). Fortunately, cases of this severity are now very rare due to the use of larger diameter ablation zones

including fixation practice, comfort in the surgical chair, gentle support of the patient's head, vocal instructions and encouragement during the procedure [35, 38]. The surgeon should carefully monitor fixation throughout and stop ablating as soon as any movement occurs. The aiming beams can then be recentred and the procedure continued.

Differences in centration between surgeons are only partly explained by experience [39, 40]. This suggests that there may be variations not only in surgical skills but also in the ability of surgeons to make patients at ease. Technological advances

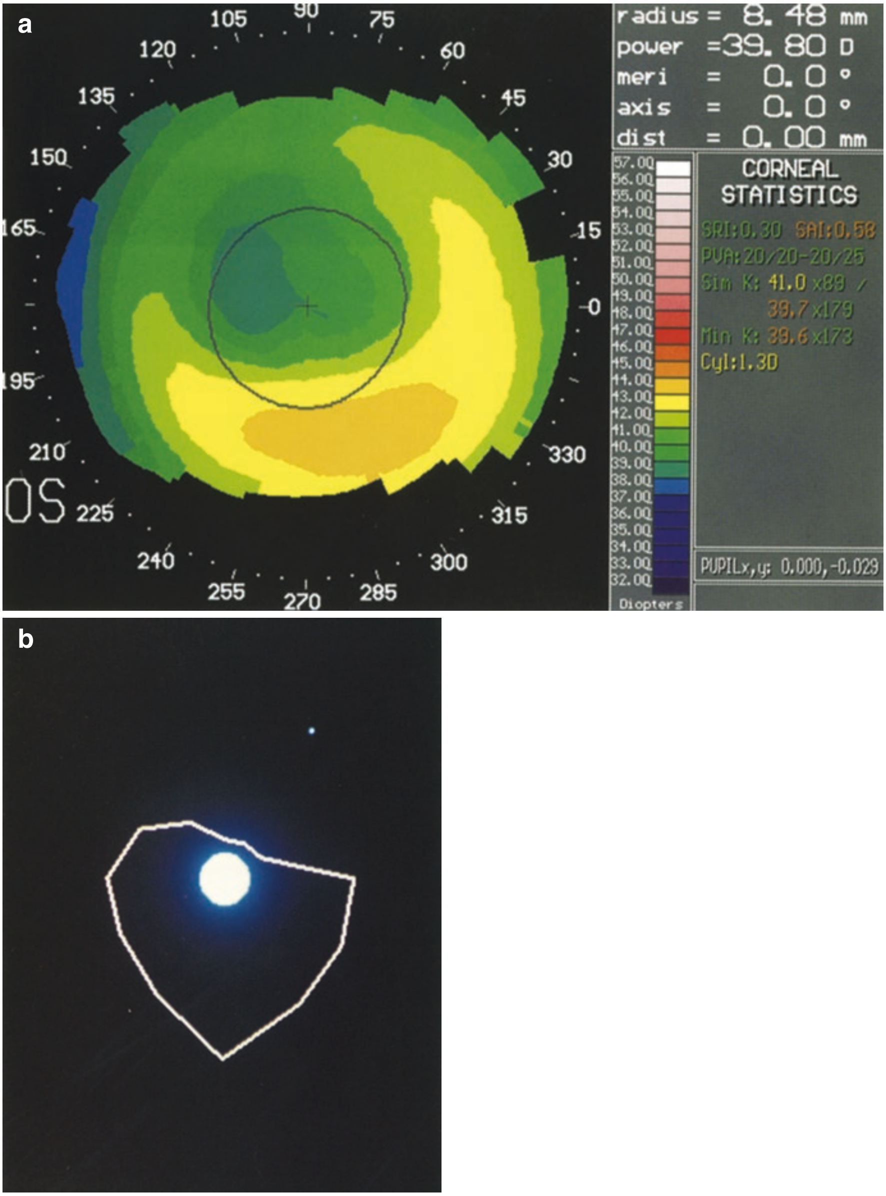


Fig. 14.8 Photorefractive keratectomy (PRK) decentration. A −5.25D 5 mm ablation zone was decentred superonasally by about 1 mm. (**a**) This resulted in marked asymmetry of the cornea (SAI = 0.58) and induced 2.00DC astigmatism. (**b**) The patient complained of halos below lights, and this was confirmed by objective testing. When viewing with his treated eye a bright central spot on a dark computer screen in a darkened room, he could trace the edge of his halo with the mouse cursor. The halo was most pronounced inferiorly because he has the equivalent of a very small diameter treatment zone in that area. The inferior cornea remains too steep, so the light passing through it defocused onto the superior retina, which is represented in the inferior visual field of the cortex (the inferior ray in Fig. 13.1)

aiming to improve centration during longer procedures include two types of eye-tracking systems [41]. The first automatically shuts off the laser when eye movement occurs. The second couples a real-time tracking device to mechanisms producing corresponding movements of the laser beam.

Decentration may be assessed postoperatively by using the software of the topographer to measure the distance from the centre of the flattened zone to the centre of the pupil (Fig. 5.10). In studies performed prior to the development of pupil detection software, measurements were made to the corneal reflex which located the corneal apex [30, 32, 42].

Measurements of decentration are best taken early after surgery, as soon as the epithelial irregularities have resolved, so the position of the ablation is not masked by asymmetric healing [43]. Ideally measurements should be taken immediately, but this requires a topography system which (unlike videokeratoscopes) can take measurements from non-reflective surfaces [28] (Table 3.1).

The results of published studies (Table 14.1) demonstrate that the magnitude of decentration has reduced over the years as laser technology and surgical experience has improved [39, 44]. Some authors have demonstrated no systematic error in the direction of displacement [39], whilst others have shown a tendency for decentration to occur either inferiorly [41, 45], inferonasally [35], superonasally [46] or down and to the right in both eyes [42]. The centre of the pupil shifts by as much as 0.4–0.7 mm at the extremes of miosis and mydriasis, but this occurs in a superonasal direction [47], and therefore preoperative miosis is not responsible for decentration. However, some surgeons have suggested that refractive surgical procedures should be centred on the natural pupil rather than one subjected to pharmacological constriction [35].

The topographic pattern resulting from decentration may be similar to that produced by pre-existing asymmetric astigmatism or an asymmetrical healing response. For example, a superior decentration may resemble a well-centred treatment performed in an eye with early keratoconus (Fig. 14.9). This highlights the importance of recording the topography preoperatively and as soon as possible postoperatively. These maps, and the difference map derived from them, may be the only way of determining the cause of subsequent irregular topography and whether the surgeon was responsible.

Table 14.1 Decentration of the ablation zone after PRK. A summary of tshe results of published work

Decentration	Mean (mm)	% ≤0.25 mm	% ≤0.50 mm	% ≤1.00 mm
Klyce and Smolek (1993) [145] phase IIA and B	0.79 ± 0.11	10	13	52
	0.47 ± 0.06	52	95	100
Cavanaugh et al. (1993) [168]	0.52		57	93
Cantera et al. (1993) [394]			75	95
Lin et al. (1993 and 1994) [462, 298]	0.34 ± 0.23	37	85	98
	0.29 ± 0.15			
Schwartz-Goldstein et al. (1995) [715]	0.46	22	65	97
Deitz et al. (1996) [845]	0.62 ± 0.34		41	91

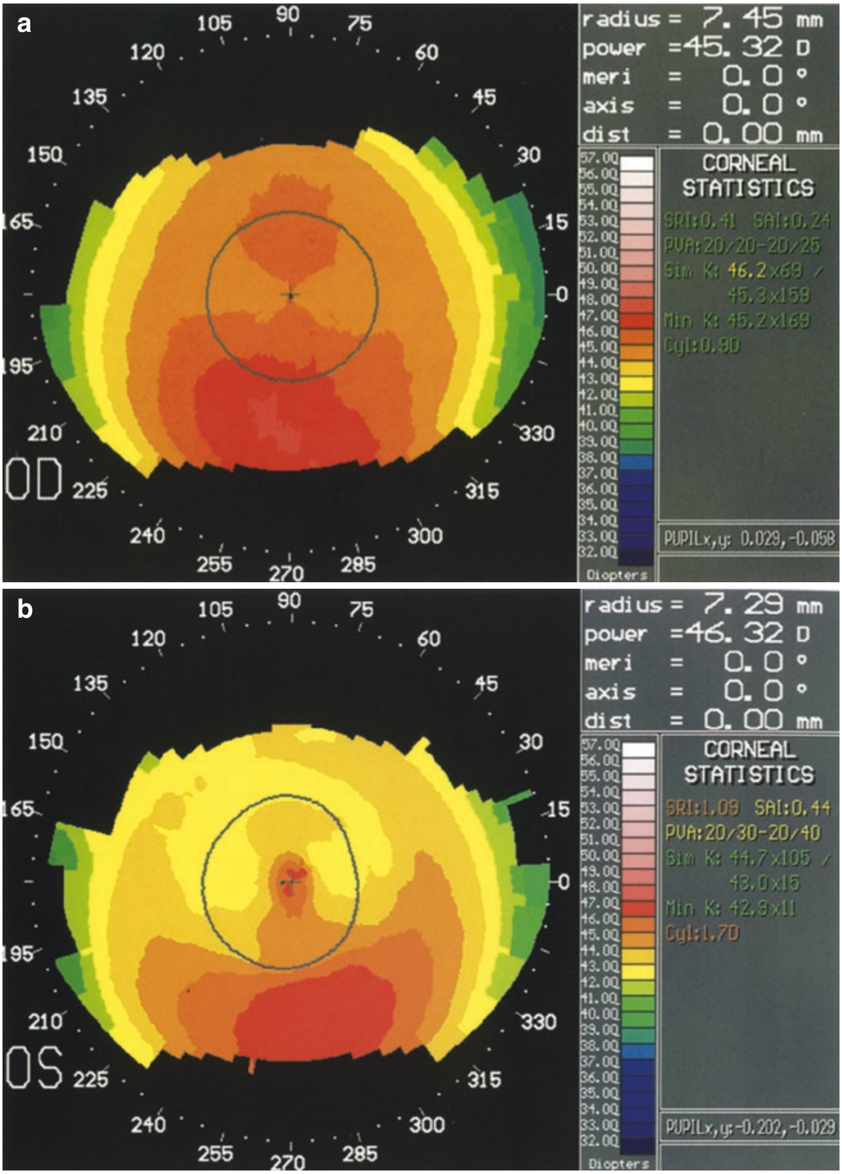


Fig. 14.9 Photorefractive keratectomy (PRK) in a keratoconus suspect. A patient with a refraction of −7.75/−0.75 × 180° underwent a left 5 mm PRK without corneal topography being performed preoperatively. After a large initial hyperopic shift (refraction about +4D at 1 week), he slowly regressed to approximately his original refraction (−8.00/−1.00×180°) with the development of grade 4 reticular haze. When topography was performed 15 months postoperatively, the left had the appearance of a superiorly decentred treatment zone. However, topography on the untreated right eye (**a**) revealed inferior corneal steepening which was compatible with a diagnosis or either a normal asymmetric bow tie or keratoconus suspect. The inferior steepening may have been more severe in the left eye (**b**) as this was the eye to be treated first. It is likely that the treatment zone was properly centred but that it was the pre-existing inferior steepening which made the topography appear decentred and gave rise to visual problems. An aggressive wound healing response with marked haze and regression is a recognised complication following the treatment of the eyes with keratoconus

The visual effects of decentration are determined by the diameter of the ablation zone and the size of the pupil. Early studies using small optical zones suggested that decentrations of 0.2–0.5 mm were clinically significant [30], whereas more recent studies using larger diameter treatments suggested that patients can tolerate up to 1 mm decentration [42]. The resultant irregular astigmatism can reduce visual acuity and contrast sensitivity. Patients may complain of polyopia and halos displaced in the opposite direction from the decentration (because the halo is largest where the radius of the treatment zone is smallest) (Fig. 14.8b).

Patterns of Healing

After PRK, new wound healing tissue is laid down over the surface of the ablation. The distribution of this new tissue determines the shape of the postoperative corneal surface. After surgery there is usually an increase in astigmatism and surface irregularity, which tends to improve with time [48, 49].

Eight corneal topographic patterns occurring after PRK have been identified (Table 14.2) [39, 44, 50, 51]. Patients with a homogeneous pattern have least astigmatism; and those with regular patterns (homogeneous or toric) have a better refractive predictability, visual acuity and level of satisfaction than those with irregular patterns [50]. The irregular patterns include semicircular (Fig. 14.10), keyhole (Fig. 14.11), central islands (Fig. 14.12), focal irregularities and irregularly irregular.

The incidence of different patterns varies between studies (Table 14.3). This may partly relate to the huge variation in healing patterns seen in different patients. In addition, it may also partly depend upon the characteristics of the laser, surgical technique and the topography system used. Surface irregularities are more likely to be detected by a device with a smaller central ring diameter and less smoothing in the algorithms, as in the TMS rather than the EyeSys.

Table 14.2 Topographic patterns after PRK [462, 298, 716]

Pattern	Description
Regular	
Homogeneous	Uniform flattening and smooth change of power, progressively decreasing power change towards periphery
Toric with axis	Smooth toric bow tie with greater induced flattening in the steep preoperative axis leading to a reduction in astigmatism
Toric against axis	Smooth toric bow tie with greater induced flattening in the flat preoperative axis, leading to an increase in astigmatism
Irregular	
Semicircular	General foreshortening of the ablation zone in one meridian
Keyhole	Area of relatively less flattening extending in from the periphery
Central island	Central area of relatively less flattening >1 mm in size and >1.00D in power
Focal variants	Generally homogeneous pattern with irregularities <1.0 mm in size or <1.00D in power
Irregularly irregular	Generalised irregularities over the treatment zone, not conforming to the specific criteria on any other pattern: more than one area >0.5 mm in size and >0.50D in power or one area >1.0 mm in size and >1.00D in power

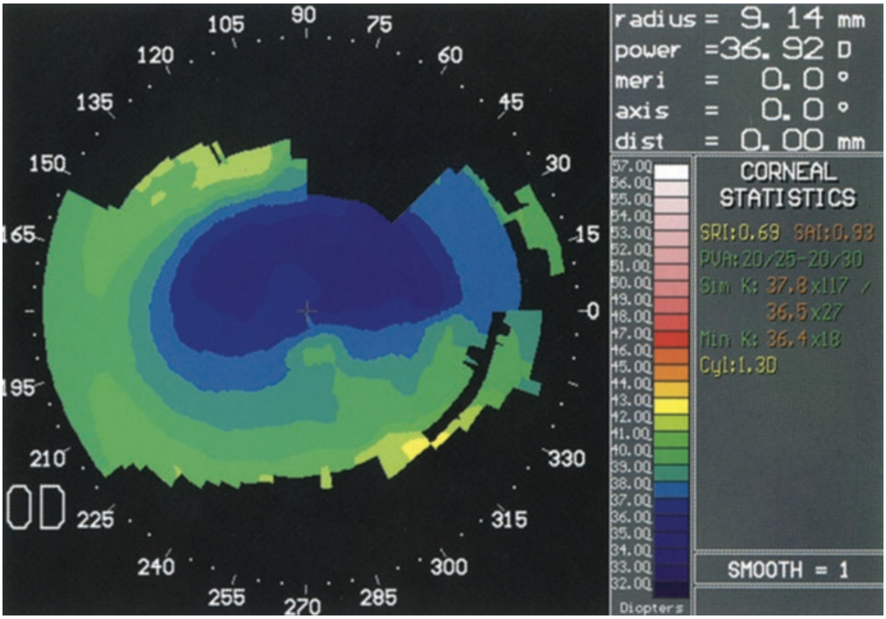


Fig. 14.10 Semicircular pattern (myopic PRK). One month following a −6.00D PRK, a greater quantity of new wound healing tissue has been generated inferiorly than superiorly, leading to asymmetry of the ablation zone. The best-corrected visual acuity is reduced to 6/9, the SAI is elevated, and the haze is denser inferiorly. The central topography became more regular during the following months

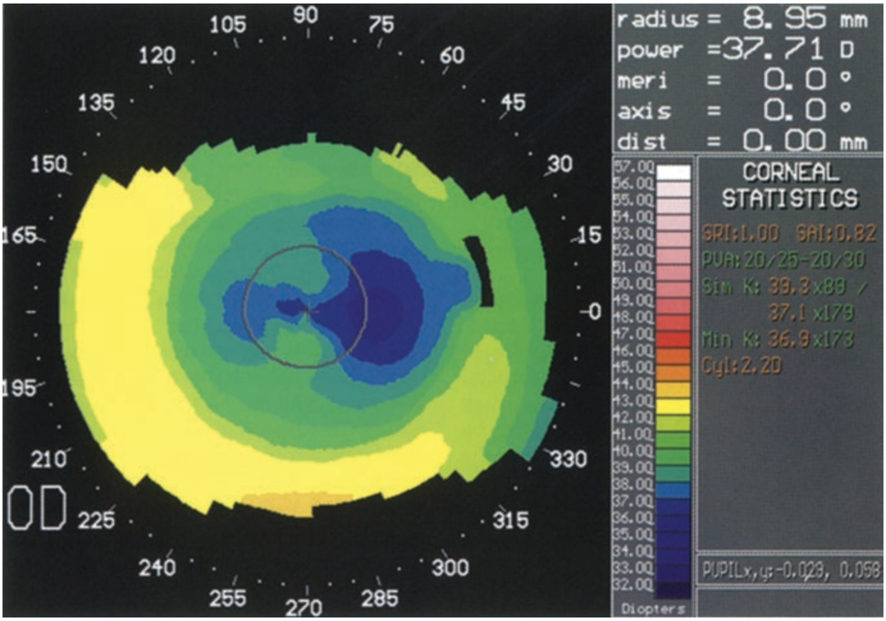


Fig. 14.11 Keyhole pattern (myopic PRK). One month after a −6.00D PRK, irregularity of the wound healing response has given rise to a keyhole topographic appearance

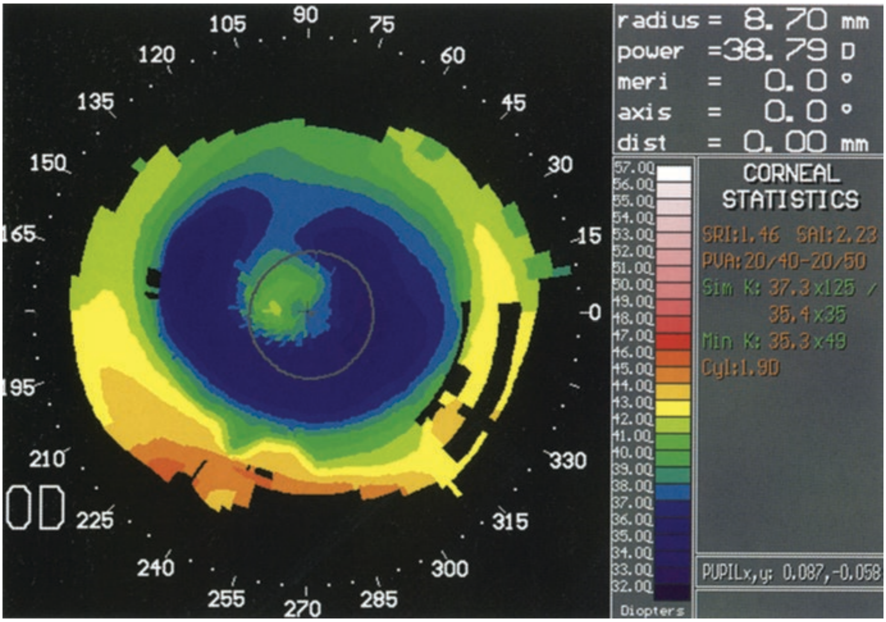


Fig. 14.12 Central island (myopic PRK). One week after a −3.00/−2.00 × 90° PRK, there is a central area of high power surrounded by an annulus of lesser power. Over the following months, the central island became less obvious, and the statistical indices reverted towards normal

Table 14.3 Incidence of topographic patterns after PRK [462, 298, 716, 982]

Lin et al. (1993 and 1994)			Hersh et al. (1995 and 1997)		
VISX laser			Summit laser, 4.5–5 and 6 mm		
TMS videokeratoscope			EyeSys videokeratoscope		
1 month postoperatively			1 year postoperatively		
Central uniform flat zone	45%	44%	*Homogeneous*	59%	21%
			Toric-with-axis-configuration	18%	28%
			Toric-against-axis configuration	3%	10%
Semicircular ablations	33%	18%	*Semicircular/keyhole pattern*	3%	25%
Keyhole patterns	12%	12%			
Central islands	10%	26%	*Central islands*	0%	0%
			Focal irregularities	4%	9%
			Irregularly irregular	13%	7%

Following astigmatic procedures, healing may be associated with a change in axis, the development of a homogeneous pattern if the astigmatism is corrected or reversion to the original axis. Irregular patterns may develop, similar to those seen following spherical procedures.

Central Islands

Central islands are a topographic complication of PRK that are relatively rarely seen since the early days of PRK [52]. However, they may still be evident in patients treated with early generation laser systems.

Table 14.4 Classification and incidence of central islands in patients treated with a VISX laser [52]. Central islands were seen in 67% of patients 3 months after surgery

Grade	Power	Diameter	Incidence
A	<3.00D		40%
B	>3.00D	<3 mm	14%
C	>3.00D	>3 mm	13%

Central islands are defined as any part of the treatment zone surrounded by areas of lesser curvature on more than 50% of its boundary (Fig. 14.12). They are classified according to the power and diameter of the central steep area (Table 14.4). No correlation was found with attempted correction [53]. The incidence and size of central islands are maximal soon after surgery and then reduce over time as corneal irregularities become smoother. In early studies, an incidence of 26% at 1 month was reported to reduce to 18% at 3 months, 8% at 6 months and 2% at 1 year [44, 54, 55].

Several mechanisms have been proposed to explain the occurrence of central islands [50–58]. Some of these mechanisms may also have a role in the determination of other postoperative corneal shape patterns. Each exerts its effects through one of the three common pathways: reduced central ablation due to characteristics of the laser, reduced central ablation due to properties of the cornea or irregularities of healing.

The difference in incidence of central islands between commercial makes of laser suggests that features of the individual lasers may be responsible. For example, ablations by Summit Excimer lasers are followed by fewer central islands than ablations by VISX excimer lasers. This may be because the Gaussian profile of the Summit beam removes relatively more central tissue than the VISX beam, which has a flat energy profile [57]. The variable incidence between different studies has led some authors to suggest that damage to the optical system of a laser can attenuate the beam, leading to "cold spots" where less energy reaches the cornea. It has also been suggested that the plume of effluent rising from the ablated surface could mask the beam [57, 58].

However, irregularities of ablation attributable to the laser should be detectable on preoperative laser beam analysis [59]. If this is not the case, differential ablation may occur as a result of mechanisms occurring in the cornea. It is known that the effective depth of ablation is determined by the hydration of the cornea: the greater the hydration of the cornea, the less corneal tissue is removed with each pulse. In theory, central islands could occur as a result of greater hydration of the central or deeper portions of the cornea [44], but there is little evidence to support this. An alternative theory suggests that, as opposed to differential hydration occurring naturally, "shock waves" produced by a flat beam profile "push" fluid centrally. However, experimental evidence of this occurring is lacking.

The great variation between individuals in the shape of the postoperative surface is more characteristic of a biological explanation. A slight irregularity and heaping of the epithelium is commonly seen at the site of closure of healing epithelial defects, including those following PRK. Normally this becomes smooth fairly rapidly, but persistence could account for some central islands. When epithelial heaping over a small stromal defect occurs, it may be incorporated into the epithelial thickening that is frequently seen. However, when the stromal defect is larger, the heaping may be surrounded by an area of relatively normal epithelium, and therefore it may become identifiable as an isolated island. This may account for the greater incidence of central islands in larger diameter ablations.

Central islands are more likely to be epithelial than subepithelial, because they are seldom associated with a localised increase in corneal haze. However, subepithelial changes may be responsible for the asymmetric or semicircular appearance of some ablations, where a wedge of increased haze is associated with relative corneal steepening and foreshortening of the ablation zone.

In any group of patients with irregularity of the postoperative corneal surface, there are probably several different mechanisms acting, either alone or in combination in different patients. The prevention of irregularities therefore requires a combined approach. Some surgeons have applied more pulses to the central 2–3 mm of the cornea, either by manually performing a shallow PTK beforehand, or by using laser algorithms with an automatic correction [57], or as a second procedure [60]. In addition, it should also be possible to modify the ablation profile to favour regular wound healing.

Long-Term Follow-Up

It has been shown that the anterior corneal topography continues to change up to 14 years post-treatment [61]. Studies have reported a mean regression of −0.5 dioptres over the first 1–2 years with a slow continued myopic regression over the following 12–14 years. However, most studies have assessed stability based on refraction and mean K readings which do not take into account various parameters including the posterior corneal surface and normal age-related changes in the cornea, lens and vitreous [61].

Laser In Situ Keratomileusis

The use of the excimer laser in refractive surgery has overcome the variability of surgical technique characteristic of incisional procedures. However, suboptimal accuracy, predictability and stability of the refractive change still persist following PRK due to variability of the wound healing response. In recent years, laser in situ keratomileusis (LASIK) has been introduced with the aim of controlling wound healing.

Mechanisms

LASIK was preceded by first manual, and then automated, keratomileusis or lamellar keratoplasty [62]. In these procedures the anterior corneal surface was reshaped by cutting the superficial tissues. LASIK is more refined and involves creating a corneal flap with a microkeratome or femtosecond laser, ablating the stromal bed with an excimer laser to produce the refractive correction and then replacing the flap [63]. The flap is usually 120–190 μm thick and 7.2–8.5 mm in diameter, with a 1 mm hinge. At least 30% of the corneal thickness should remain undisturbed to avoid possible subsequent ectasia [64]. In contrast to PRK, the stromal wound can heal without the influence of the epithelium, and this results in less corneal haze.

Femtosecond Laser

Femtosecond laser is infrared with a wavelength of 1053 nm, and it produces photodisruption or photoionization of the corneal tissue in a similar manner to Nd:YAG laser. It generates a rapidly expanding cloud of electrons and ionised molecules, and the acoustic shock wave disrupts the treated tissue 2. A Nd:YAG laser has a nanosecond pulse duration (10^{-9} s), whereas femtosecond laser pulse duration is in the femtosecond range (10^{-15} s). Reducing the pulse duration reduces the amount of collateral tissue damage making it safer for corneal refractive procedures.

Topography After LASIK

The refractive and topographic changes after LASIK are similar to PRK, with an initial overcorrection being followed by a gradual return towards emmetropia [65, 66]. However, because the surface epithelium remains intact, videokeratoscopy can be performed successfully at an earlier stage, and the corneal surface is regular within days [67]. Some authors suggest that the overcorrection is not as large and that stability is reached at an earlier stage [65, 67].

Significant decentration (>0.5 mm) occurs in 16–50% of patients undergoing LASIK [45, 64, 66]. Its frequency and severity is up to twice that of PRK [45]. This may partly arise because the stromal bed is more difficult to mark than the epithelium. In addition, the higher-order corrections typically treated by LASIK are associated with, firstly, longer treatment times during which drift may occur and, secondly, difficulty seeing the fixation target due to worse unaided vision and the greater ablation depth.

Despite the ablation being covered by a flap of corneal tissue, surface irregularities may occur [62, 65]. Central islands are similar to those seen after PRK [64–66]. In the past, suturing of the flap could contribute to irregularities, but now most surgeons float the flap on fluid until it reaches its natural resting place as determined by the hinge and then rely upon drying to hold the flap in place without sutures [66]. Irregularities may be caused by the particulate debris in the interface which can be seen on biomicroscopic examination [64]. This is possibly derived from defective cellulose sponges, the microkeratome blade, the keratotomy incision or epithelial cells from the conjunctiva or lid margins swept onto interface by excessive irrigation or patient tearing. The feint punctate grey spots seen in the stromal bed of some patients are thought to be deposits of extracellular matrix material produced during wound healing [65].

About 4–10% of patients develop surface irregularity as a result of epithelial ingrowth at the periphery of the flap-stromal interface. In the majority this is a

1–2 mm band confined to less than 120° of the circumference of the flap [66]. The most common sites are inferiorly and temporally. However, in some patients the epithelial front actively progresses across the cornea under the flap [64]. This causes increasing irregular astigmatism which reduces best-corrected visual acuity. Relifting of the flap and removal of the cells immediately restore the corneal topography and visual acuity (Fig. 14.13). Epithelial ingrowth is a risk factor for melting or necrosis of the corneal flap, so when severe, debridement should be performed early [66].

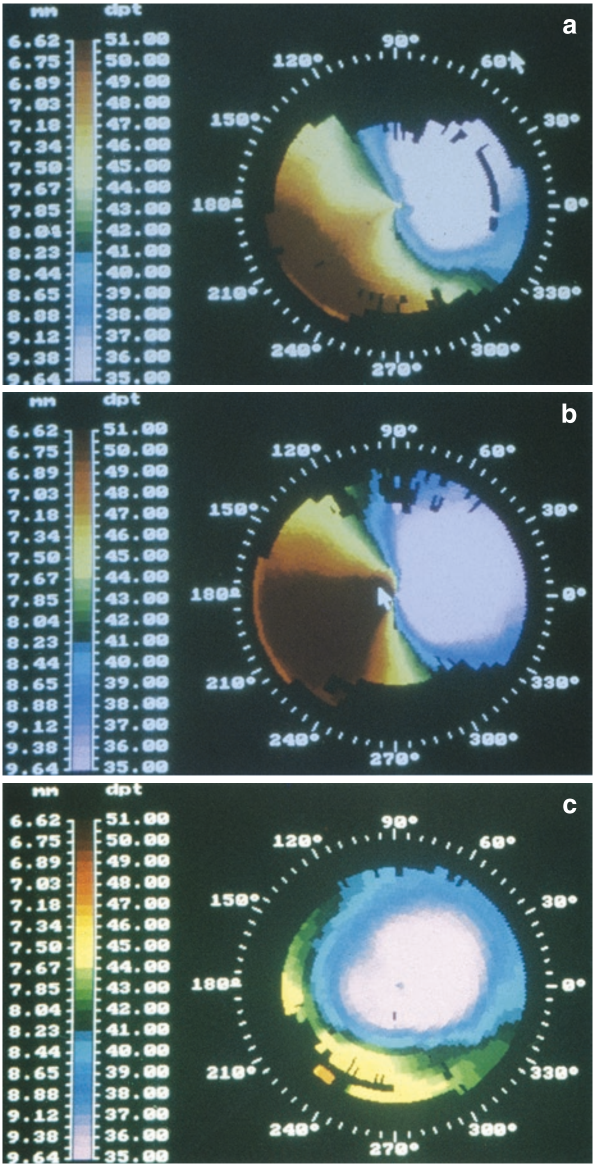


Fig. 14.13 LASIK epithelial ingrowth. A patient underwent a right −8.00D (79 μ) LASIK ablation under a 160 micron flap. (**a**) At 1 month the vision was only 6/24. On biomicroscopy there was a focal cystic lesion originating from the extreme periphery of the flap-stromal bed interface. Topography showed generalised flattening of the treatment zone, with localised steepening relating to the abnormality of the interface. (**b**) By 3 months it had enlarged and progressed across the cornea sufficiently to cause 4.00DC irregular astigmatism and reduce the best-corrected visual acuity to 6/18. (**c**) Four months after the original procedure, the flap was relifted, and the ingrowing epithelial cells were removed. This immediately improved the best-corrected acuity and restored the flattening across the whole ablation zone (Courtesy of Mr. Patrick Condon FRCS FRCOphth)

Small Incision Lenticule Extraction (SMILE)

Small incision lenticule extraction (SMILE) involves the cutting of a small intrastromal lenticule using a femtosecond laser and its manual removal. It evolved from femtosecond lenticule extraction (FLEx), which allowed the removal of a stromal lenticule without the creation of a flap [67]. It is used to treat myopia, hyperopia, presbyopia and astigmatism and has been shown to have similar outcomes to LASIK [68].

As the anterior corneal stroma is preserved, it is thought that the corneal biomechanics are less disrupted compared to post-LASIK treatment: it promises similar clinical outcomes to LASIK with potential maintenance of biomechanical integrity [69–72].

Topography After SMILE

Topography patterns following SMILE are similar to those following LASIK as similar patterns of tissue are removed in both myopic and hyperopic treatments [73–74].

Complications

Complications following SMILE are rare and include epithelial abrasions, perforated caps, stromal keratitis and postsurgical ectasia. There have been numerous studies on SMILE outcomes, but most have included small patient numbers and short follow-up [67, 74–76].

Surface or Interface Complications

Between 4 and 10% of patients may get stromal microstriae, but these have not been shown to have any clinical significance [67, 76, 77].

Other problems include corneal haze, sterile inflammation, minor islands of interface epithelial cells and interface debris [78].

Ectasia Post-SMILE

Postoperative ectasia remains the most feared postoperative complication for any refractive surgeon. Whilst rare, it does still occur [79–83], but its occurrence should be minimised by a thorough preoperative assessment similar to that for LASIK.

Laser Thermal Keratoplasty

Laser thermokeratoplasty is a surface technique which acts by structurally altering the tissues of the superficial cornea to change its anterior curvature [66, 84, 85].

Mechanisms

When collagen is heated to 50–55 °C, its interpeptide hydrogen bonds break, and the triple helical structure collapses. This results in contraction of collagen fibres to about one-third of their original length [85]. For over a century, this has been achieved using heated wires, thermal probes and radio-frequency or microwave probes. Recently the technique has been refined by the use of the infrared holmium:YAG laser (wavelength 2.1 µm) [66].

Topography After LTK

Each laser spot (diameter 300–600 µm) induces a cone of shrunken tissue, with its base on the corneal surface, and apex at a depth which increases with the total laser energy applied [10, 85]. This creates a flattened zone centred on the spot itself and a steepened zone surrounding it (Fig. 14.14b). The refractive effect achieved is dependent upon the location of the spots and their proximity to their neighbours [84].

The holmium:YAG laser utilises a polyprismatic lens to divide its beam into eight spots organised in a ring, which is centred on the pupil [66] (Fig. 14.14a). If the ring has a diameter of 3 mm or less, opposite spots are sufficiently close together that their central flattened zones overlap. This results in flattening of the optical zone of the cornea, which could theoretically be used for the treatment of myopia (Fig. 14.14c). In practice, the proximity of the altered corneal stroma to the visual axis limits its use in these cases.

At a ring diameter of 4 mm, the refractive effect is small and unpredictable because the flattened zones and steepened zones of opposite spots overlap (Fig. 14.14d).

When the diameter of the ring is 5 mm or greater, opposite spots are sufficiently far apart that the optical zone of the cornea is only steepened (Fig. 14.14e). This technique is practised for the treatment of hyperopia, when ring diameters of 6–8 mm are commonly used. Greater refractive effect is achieved by increasing the laser energy (energy per pulse or number of pulses) or the number of spots [86–88]. New spots can be added to the same ring between existing ones by rotating the delivery system through 22.5°, or a different ring diameter can be used. Postoperatively, the topographic maps show central steepening, with flattening of the corneal periphery (Figs. 14.15 and 14.16). Regression of effect is usually seen within 1 month and tends to stabilise after 3 months [86, 87].

Both myopic and hyperopic regular astigmatisms can be treated by selecting the appropriate ring diameter and then masking the spots in two opposite quadrants. When these treatments are applied experimentally to spherical corneas, the postoperative videokeratoscopy map demonstrates a blue or a red bow tie, respectively [84]. When used to treat astigmatism, a preoperative bow tie should be eliminated.

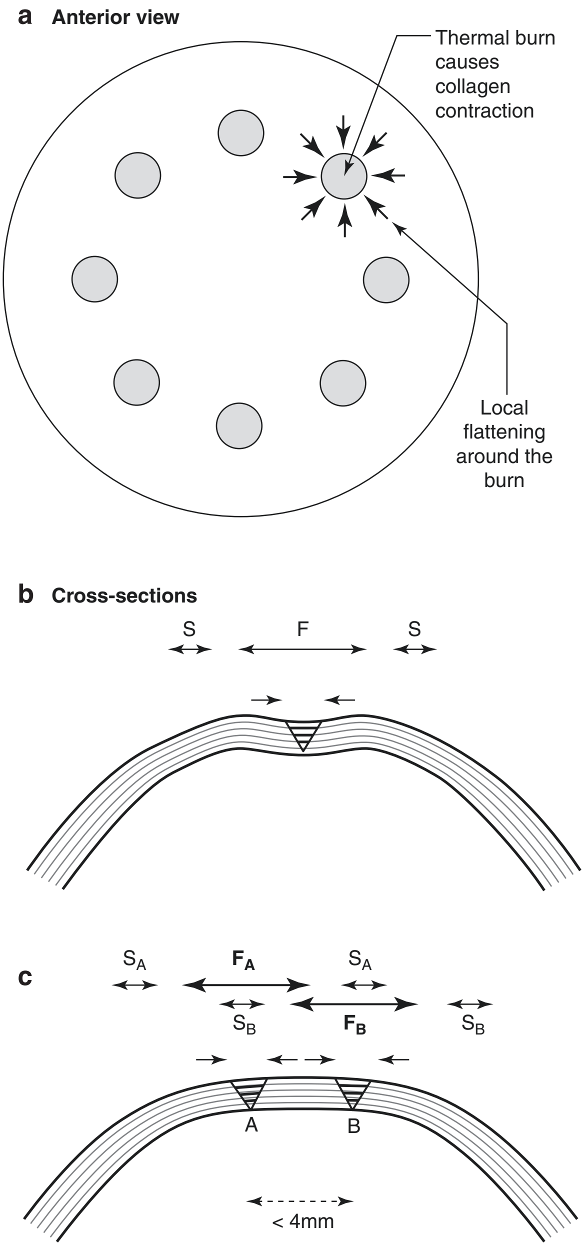
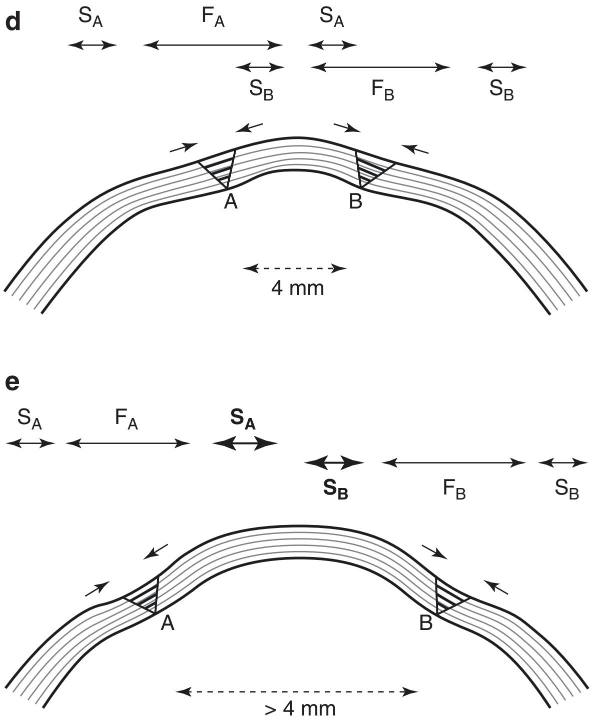


Fig. 14.14 LTK mechanism. The effect of holmium LTK on corneal topography. (**a**) Thermal spots are applied in one or two rings concentric with the pupil. (**b**) Thermal treatment has greatest effect superficially and therefore produces a cone of collagen contraction (thick black lines). This shortens the arc length of the superficial cornea (arrows) producing a flattened zone (f) centred on the spot itself. As a result the surrounding cornea is steepened (S). (**c**) When the opposite spots (**a** and **b**) are close together, the flattened zones overlap, resulting in flattening of the central cornea. (**d**) When the spots are 4 mm apart, the flattened and steepened zones overlap, producing a small unpredictable change in topography. (**e**) When opposite spots are further apart, the central cornea is steepened

Fig. 14.14 (continued)



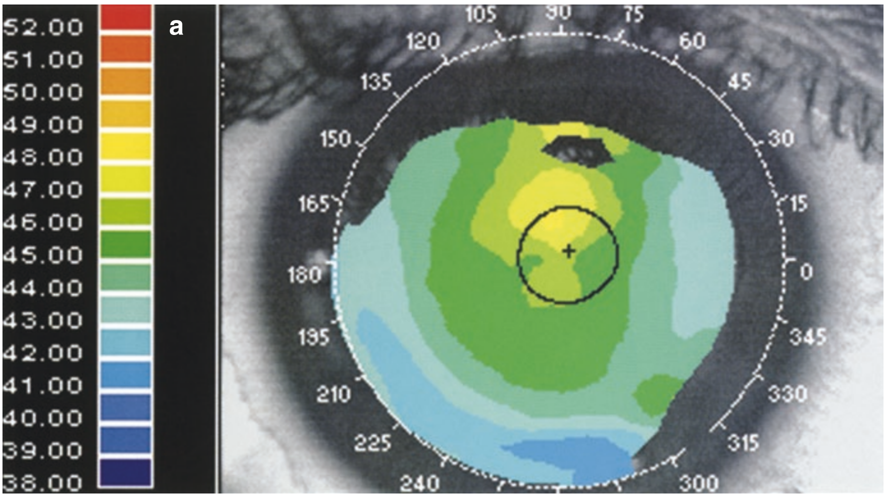


Fig. 14.15 Holmium LTK. The preoperative (**a**) and 1-week postoperative (**b**) maps of a patient who underwent a +3.00D laser thermokeratoplasty. The procedure induced steepening of the central cornea, flattening of the periphery and a rapid change in contour of intermediate zone

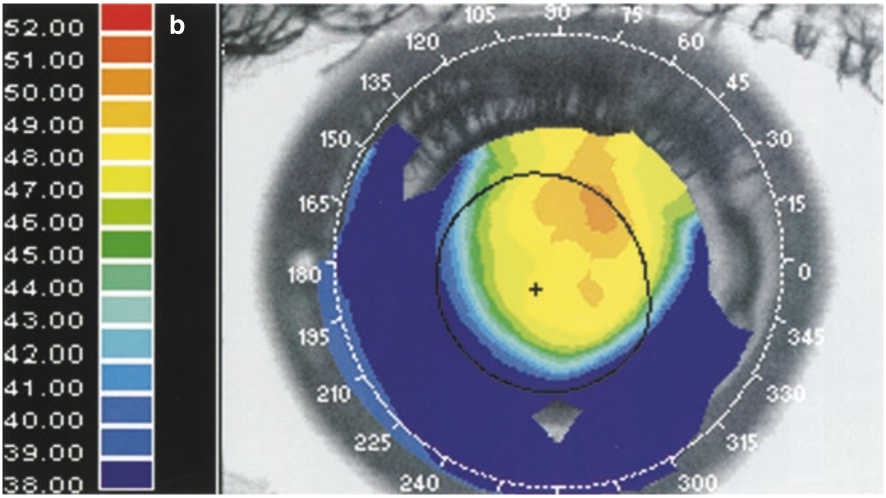


Fig. 14.15 (continued)

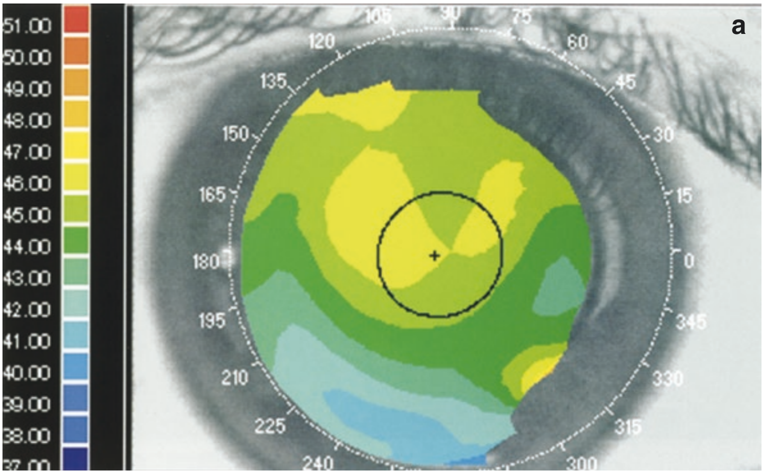


Fig. 14.16 Holmium LTK-induced change. In a patient with pre-existing against-the-rule astigmatism following cataract extraction, the difference between the preoperative (**a**) and 1-month postoperative (**b**) maps demonstrates that the +3.25D laser thermokeratoplasty induced a spherical change in the central corneal power (**c**)

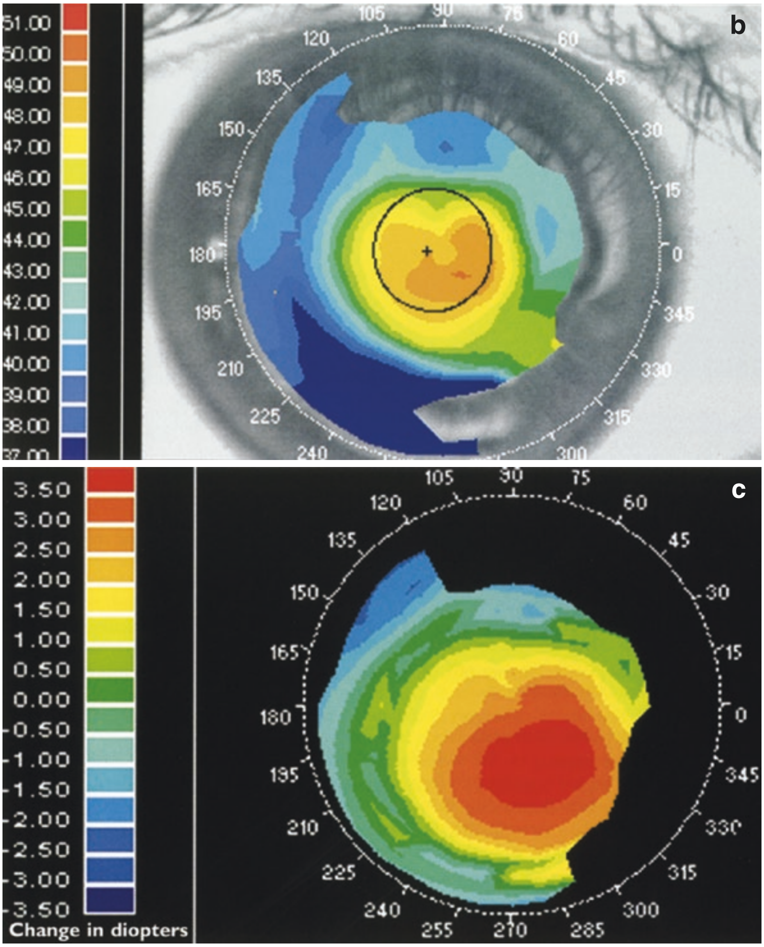


Fig. 14.16 (continued)

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