Topographic changes in corneal asphericity and effective optical zone after laser in situ keratomileusis

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Purpose: To determine the relationship between the spherical refractive change after myopic excimer laser surgery and the effective optical zone (EOZ) and corneal asphericity determined by corneal topography.

Setting: Baylor College of Medicine, Houston, Texas, USA.

Methods: Preoperative and postoperative topographies along with refractions were evaluated in all patients who had had laser in situ keratomileusis since January 1999 and had at least 6 months of follow-up. The VISX Smoothscan S2 excimer laser and the Hansatome® microkeratome (Bausch & Lomb) were used in all cases. Because optical zones are oval with astigmatic treatments with the VISX laser, only patients with spherical refractions and treatments were included. Thirty-nine cases met the criteria; their treatments ranged from −1.50 to −18.00 diopters (D). The preoperative and postoperative corneal asphericities (Q-values) were taken directly from the Holladay Diagnostic Summary Report on the EyeSys 2000, version 4.0. The mean diameter of the optical zone was measured on the local radius of curvature map using the outer edge of the yellow zone, which corresponds to 2 color changes or approximately 0.50 D steepening from the mean central radius (green).

Results: The EOZ decreased as the amount of treatment increased. The decrease was slightly nonlinear, decreasing slightly more rapidly at higher treatments. For an "intended" 6.0 mm optical zone, the nominal EOZs from the least-squares second-order polynomial regression were 6.0 mm for −1.5 D, 5.4 mm for −5.0 D, 4.6 mm for −10.0 D, 3.8 mm for −15.0 D, and 3.2 mm for −18.0 D. The least-squares second-order polynomial regression yielded a standard error of the estimate (SEE) of ± 0.22 mm (R^2 = 0.90). The asphericity increased nonlinearly in a positive direction (oblate) with the amount of treatment, indicating greater amounts of correction produced progressively more oblate corneal surfaces. The least-squares second-order polynomial regression yielded an SEE of ± 0.42 (R^2 = 0.55).

Conclusions: The EOZ decreased and the Q-value increased with the amount of myopic excimer laser treatment. The optical zone was approximately 4.3 mm with a spherical treatment of −12.0 D. These findings may explain the clinical studies that indicate high myopic treatments (above −12.0 D) are associated with poor visual outcomes.

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Functional vision following laser in situ keratomileusis (LASIK) is reduced in scotopic conditions. The reduction is primarily due to the change in the corneal shape from prolate to oblate.[1–4] It has also been shown that with treatment of higher myopia (above −12.0 diopters [D]), the quality of vision is significantly reduced, so most clinicians will not treat higher refractive errors because of the poor results and patient dissatisfaction.[5] The major complaints from patients with higher treatments are halos,

glare, and lack of sharpness, especially in dark conditions.[6–9]

Studies show that the shape of the cornea often becomes oblate after myopic excimer laser treatment.[1,10] This shape results in a progressively smaller effective optical zone (EOZ) than the normal prolate shape.[1,3,4] We obtained the asphericity and EOZ from corneal topography to show the relationship between these 2 variables and the amount of spherical refractive change after myopic excimer laser surgery.

Patients and Methods

Preoperative and postoperative topographies in all patients who were at least 6 months post-LASIK were evaluated. Because optical zones are often oval with astigmatic treatments, only patients with spherical treatments were included (no cylinder component in the refraction or laser treatment). Thirty-nine patients had LASIK spherical ablations ranging from −1.50 to −18.00 D.

All patients received 6.0 mm optical zones as designated by VISX. Although the manufacturer considers the optical zone to be 6.0 mm as specified, there is actually a multizone treatment for higher treatments. At the corneal plane, for treatments of −6.0 D or less, there is a single zone of 6.0 mm. For treatments from −6.0 D to −10.0 D, there are 2 zones: the first 6.0 D is at 6.0 mm, and the remainder up to −10.0 D is at 5.5 mm. For treatments above −10.0 D, there are 3 zones: the first 6.0 D is at 6.0 mm, the next 4.0 D is at 5.5 mm, and those above −10.0 D are at 5.0 mm.

The VISX Smoothscan S2 excimer laser and the Hansatome® microkeratome (Bausch & Lomb) were used in all cases. Topography was performed with the EyeSys 2000 topographer, version 4.0, with the Holladay Diagnostic Summary Report preoperatively and postoperatively in all patients.[11] The most recent postoperative topography within 18 months was used; no postoperative topography less than 6 months was included.

The preoperative and postoperative corneal asphericities (Q-values) were taken directly from the quantitative values on the Holladay Diagnostic Summary. The change in the Q-value (delta Q) was taken as the difference between

the postoperative and the preoperative values. The EOZ was measured from the local radius of curvature (ROC) map and then confirmed on the profile difference map.

The mean diameter of the optical zone was measured on the local ROC map using the outer edge of the yellow zone, which corresponds to 2 color changes or approximately 0.5 D steepening from the mean central radius (green). The optical zone was then confirmed on the profile difference map to the perimeter of the light green or 1.0 D stronger than the mean central power (green). The local ROC was easier and repeatable because the color change is so abrupt. There were no maps in which the optical zone diameter varied by more than 0.5 mm on the profile difference and local ROC maps.

Figures 1 and 2 illustrate the size of the EOZ of 2 different treatments. Both patients had an intended optical zone size of 6.0 mm. In Figure 1, the patient received a −1.50 D treatment and the EOZ was 6.0 mm. In Figure 2, the patient received a −18.0 D spherical treatment and the EOZ was 2.8 mm.

Results

Figure 3 shows the relationship between the amount of spherical myopic treatment and the EOZ. The EOZ decreased as the amount of treatment increased. The decrease in the EOZ was slightly nonlinear, decreasing slightly more rapidly at higher treatments (T). For an "intended" 6.0 mm optical zone, the nominal effective optical zone sizes from the least-squares second-order polynomial regression were 6.0 mm for −1.5 D, 5.4 mm for −5 D, 4.6 mm for −10 D, 3.8 mm for −15 D, and 3.2 mm for −18 D. The least-squares second-order polynomial regression is shown in equation 1 ($R^2 = 0.90$; standard error of the estimate (SEE) $\pm$ 0.22 mm):

$$EOZ = -0.001056T^2 + 0.140156T + 6.118327 \tag{1}$$

where T is the amount of spherical treatment in diopters.

Figure 4 illustrates the relationship between the asphericity (Q-value) and the amount of treatment. The asphericity (Q-value) increases slightly nonlinearly with the amount of treatment, increasing slightly more rapidly at higher treatments. The value for Q is 0 for a sphere, −1 for a parabola, −1 < Q < 0 for a prolate ellipsoid, and Q > 0 for an oblate ellipsoid. All corneas had asphericity changes in which the Q-value became more positive (oblate). The least-squares second-order

Holladay Diagnostic Summary 2000

Refractive Map — = 42.50D, Step = 0.5D

Local ROC (Radius) Map — = 8.13mm, Step=0.10mm

Profile Difference Map — = Normal, Step = 0.5D

Distortion Map — = 20/20, Step = 1 line

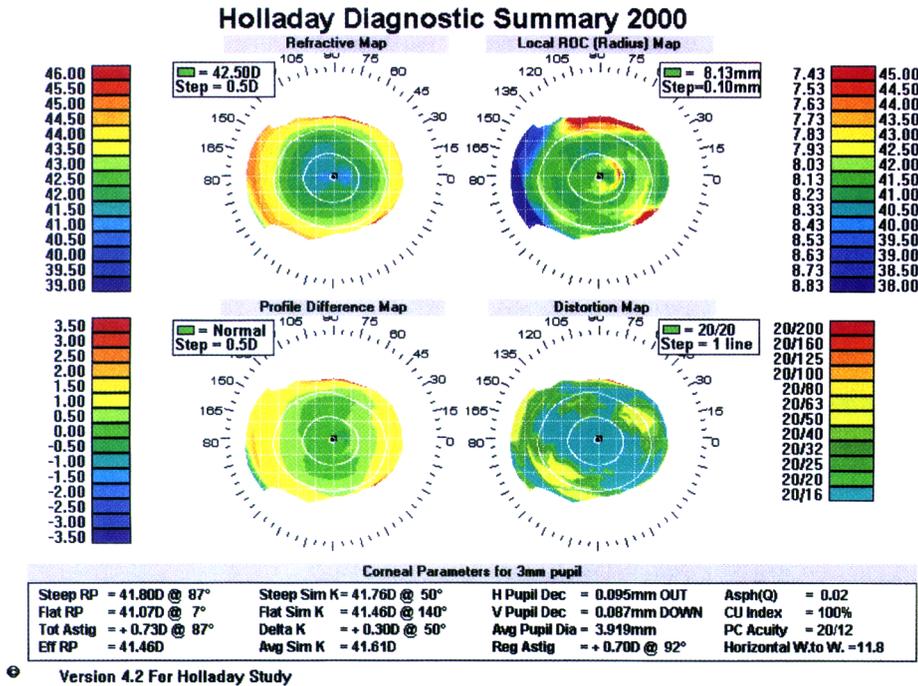|					
Steep RP	= 41.80D @ 87°	Steep Sim K = 41.76D @ 50°	H Pupil Dec = 0.095mm OUT	Asph(Q)	= 0.02
Flat RP	= 41.07D @ 7°	Flat Sim K = 41.46D @ 140°	V Pupil Dec = 0.087mm DOWN	CU Index	= 100%
Tot Astig	= +0.73D @ 87°	Delta K = +0.30D @ 50°	Avg Pupil Dia = 3.919mm	PC Acuity	= 20/12
Eff RP	= 41.46D	Avg Sim K = 41.61D	Reg Astig = +0.70D @ 92°	Horizontal W.to W. =11.8

Version 4.2 For Holladay Study

Figure 1. (Holladay) The patient received a −1.50 D treatment. The local ROC map demonstrates that the optical zone is almost exactly 6.0 mm in diameter. The red zone at 12 o'clock is on the 6.0 mm circle, and the red zone at 4 o'clock is 0.3 mm outside the circle. The profile difference map in the lower left corner shows green and light green in the entire 6.0 mm circle. The optical zone was recorded as 6.2 mm.
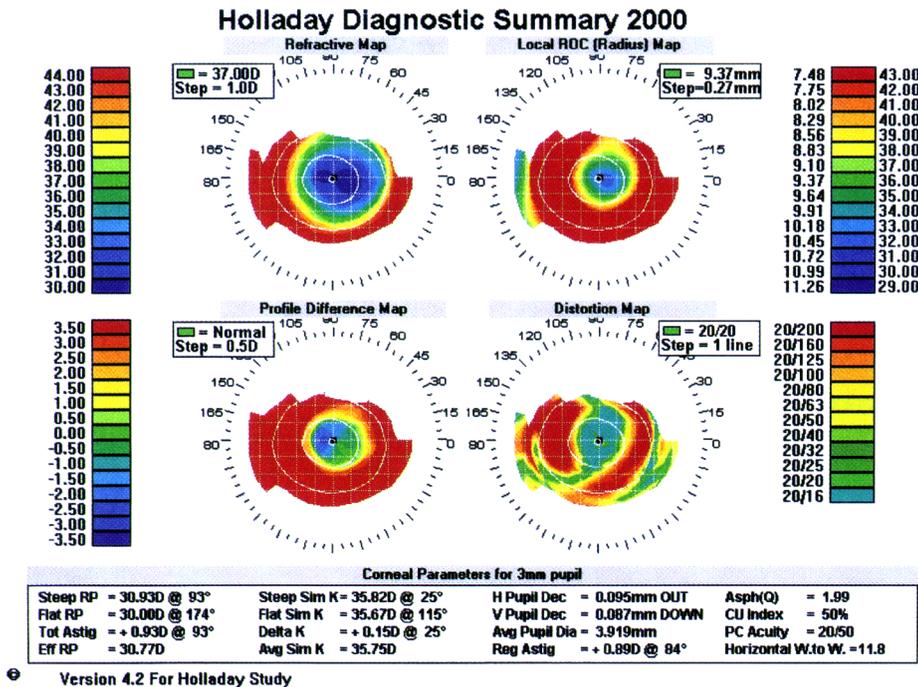
Holladay Diagnostic Summary 2000

Refractive Map — = 37.00D, Step = 1.0D

Local ROC (Radius) Map — = 9.37mm, Step=0.27mm

Profile Difference Map — = Normal, Step = 0.5D

Distortion Map — = 20/20, Step = 1 line

Steep RP	= 30.93D @ 93°	Steep Sim K = 35.82D @ 25°	H Pupil Dec = 0.095mm OUT	Asph(Q)	= 1.99
Flat RP	= 30.00D @ 174°	Flat Sim K = 35.67D @ 115°	V Pupil Dec = 0.087mm DOWN	CU Index	= 50%
Tot Astig	= +0.93D @ 93°	Delta K = +0.15D @ 25°	Avg Pupil Dia = 3.919mm	PC Acuity	= 20/50
Eff RP	= 30.77D	Avg Sim K = 35.75D	Reg Astig = +0.89D @ 84°	Horizontal W.to W. =11.8

Version 4.2 For Holladay Study

Figure 2. (Holladay) The patient received a −18.00 D treatment. The local ROC map demonstrates that the optical zone is almost exactly 3.0 mm in diameter. The profile difference map in the lower left corner shows a red zone that is approximately the size of the 3.0 mm circle. The optical zone was recorded as 3.0 mm.

polynomial regression is shown in equation 2 ($R^2 = 0.55$; SEE ± 0.42).

$$Q = +0.000994\ T^2 - 0.094209\ T + 0.127011 \qquad (2)$$

where T is the amount of spherical treatment in diopters and Q is the asphericity.

Discussion

Figure 5 shows the ray trace of a prolate (Q-value < 0) cornea and Figure 6, the ray trace of an oblate (Q-value > 0) cornea. The excessive refraction of rays in the periphery by a spherical surface is termed *spherical aberration*. Since an oblate surface has more power in the
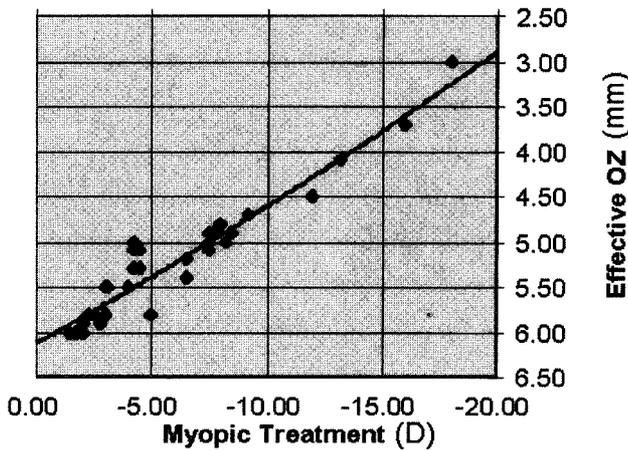
Figure 3. (Holladay) The relationship between EOZ and the spherical myopic treatment. The EOZ decreased as the amount of treatment increased ($\blacklozenge$ = EOZ; —— polynomial fit; $y = -0.001056x^2 + 0.140156x + 6.118327$; $R^2 = 0.899110$; SEE = ± 0.22).
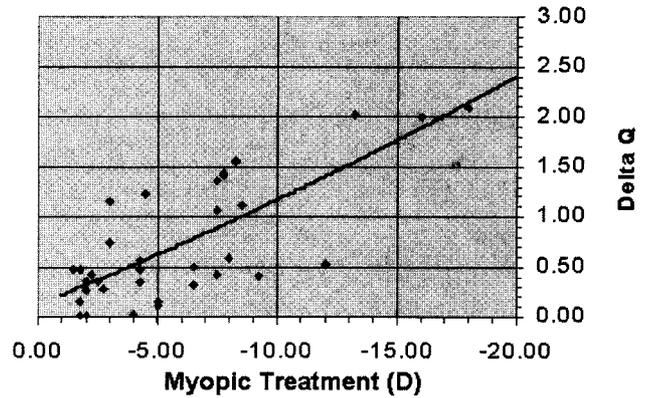

Figure 4. (Holladay) The relationship between asphericity and spherical myopic treatment. The asphericity increased nonlinearly in a positive direction (oblate) with the amount of treatment, indicating greater amounts of correction produced progressively more oblate corneal surfaces ($\blacklozenge$ = delta Q; —— polynomial fit; $y = 0.000994x^2 - 0.094209x + 0.127011$; $R^2 = 0.553046$; SEE = ± 0.42).

periphery than a sphere, the spherical aberration of an oblate surface is worse than that of a sphere.

As the Q-value of an oblate surface increases positively, the spherical aberration increases and the EOZ decreases. The definition of the EOZ as a steepening of 0.50 D is conservative. The normal cornea is prolate and actually becomes flatter toward the periphery. Any steepening as we move radially is abnormal and would be beyond the point of the "true" optical zone. The true

optical zone may actually be smaller than our data but cannot be larger.

As the patient's entrance pupil becomes larger than the EOZ, the foveal image quality will decrease because of the progressive increase in the spherical aberration. However, the effect of the peripheral rays are reduced by the Stiles-Crawford effect.[12–15] Rays entering at the 6.0 mm diameter are 35% to 40% as effective as at the central peak; at the 8.0 mm diameter, the rays are 20% as
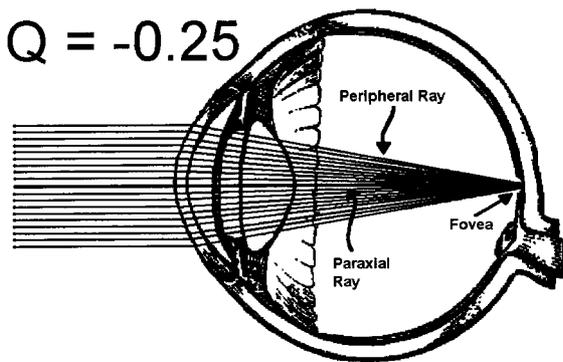

Figure 5. (Holladay) The normal human cornea is prolate with a mean Q-value of −0.25. A prolate ellipsoid is steeper at the pole and progressively flattens toward the periphery. This shape is similar to a bullet (bell or inverted tulip). A prolate shape reduces spherical aberrations by causing less bending of light rays in the periphery so all rays come to a single point of focus.
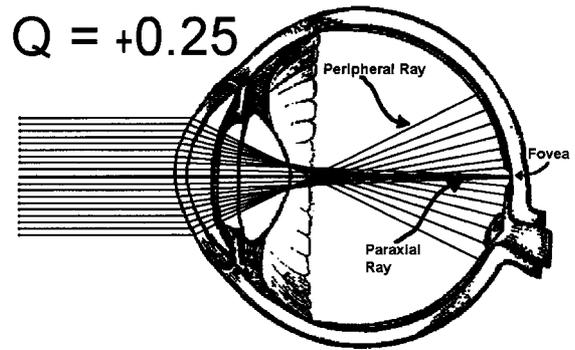

Figure 6. (Holladay) After radial keratotomy, photorefractive keratectomy, and LASIK, the cornea becomes oblate. An oblate ellipsoid is flatter at the pole and progressively steepens toward the periphery. The shape is similar to the top half of a hamburger bun. An oblate shape exaggerates spherical aberrations by causing excessive bending of the light rays in the periphery. The result is that peripheral rays are refracted too strongly and cause a halo around a point source of light.

effective. The conclusion from these studies is that aberrations peripheral to the 8.0 mm zone have a negligible effect on the foveal image quality. Between 6.0 mm and 8.0 mm, aberrations will begin to minimally affect the foveal image and below 6.0 mm, the optical quality of the image on the fovea will begin to decrease significantly. As shown,[1] the contrast sensitivity in scotopic conditions is one of the first visual functions to be affected.

All patients became oblate (Q-value positive) after laser surgery; however, the correlation with the amount of treatment was better for the EOZ than for asphericity. The explanation relates to the reliability of the Q-value calculated by the EyeSys 2000. Studies show that this is variable.[16–18] Variability in the Q-values with repetitive examinations increased with the magnitude of astigmatism and was more variable postoperatively than preoperatively. Although the least-squares second-order polynomial curve for asphericity is almost identical in shape to the EOZ curve, there is a higher degree of variability in the asphericity because of the calculation algorithm for the Q-value by the EyeSys 2000.

The refractive power maps were not used because of the EyeSys 2000 software's method of choosing the value for the center of the graph. The central value for the refractive power map is always rounded-off to the nearest 0.50 D. Choosing a rounded value for the scale can make up to a 0.49 D difference in the color change on the map. We recognized this problem and used the local ROC and profile difference maps, which are centered exactly on the mean value for the patient, not on the rounded value.

Only spherical myopic treatments were evaluated because the optical zone from VISX was stated to be 6.0 mm and circular in every case. Astigmatic treatments are oval, and the calculated size varies depending on the laser and the amount of sphere and cylinder. For example, in high myopic astigmatism with very little sphere (plano -6.00×12), the optical zone in the minor axis is usually about 4.5 mm for a 6.0 mm major axis (VISX, Summit, Automomous, Nidek, and Technolas), as shown in the topography in Figure 7. In these cases, the minor axis of the ellipse, not the major axis, is the diameter that must be used to determine the optical quality of the foveal image. Most laser manufacturers provide the major and minor diameters of the ellipse on the data printout or screen so the surgeon can determine the intended minor axis optical zone before surgery.

Our study indicates that the EOZ is approximately 4.3 mm with a spherical treatment of -12.0 D and progressively smaller with higher treatments. Small EOZs may explain the clinical studies indicating that high myopic treatments (above -12.0 D) are associated with poor visual outcomes.[5–10] Our study confirms the need
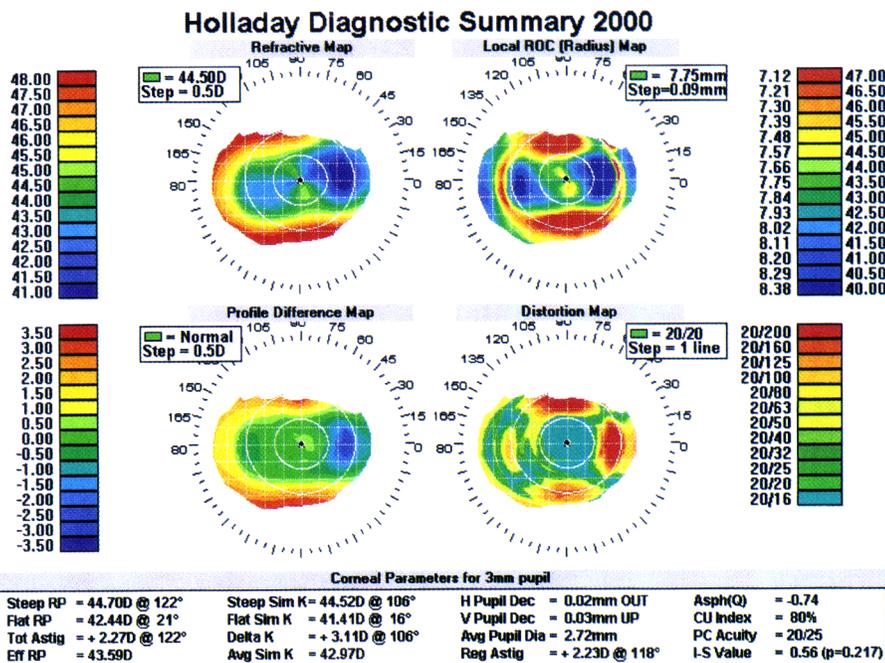

Holladay Diagnostic Summary 2000

Figure 7. (Holladay) The patient received treatment of plano -6.00×12. The local ROC map demonstrates that the optical zone is oval at 3.5 mm × 6.1 mm at 12 degrees. Vertically, the red zone is on the 3.0 mm circle superiorly and slightly outside the circle inferiorly. Horizontally, the red is just inside the 6.0 mm circle at 3 o'clock and just outside the circle at 9 o'clock. The profile difference map demonstrates similar findings. The optical zone was recorded as 3.5 mm × 6.1 mm.

Corneal Parameters for 3mm pupil					
Steep RP = 44.70D @ 122°	Steep Sim K= 44.52D @ 106°	H Pupil Dec = 0.02mm OUT	Asph(Q) = −0.74
Flat RP = 42.44D @ 21°	Flat Sim K = 41.41D @ 16°	V Pupil Dec = 0.03mm UP	CU Index = 80%
Tot Astig = +2.27D @ 122°	Delta K = +3.11D @ 106°	Avg Pupil Dia = 2.72mm	PC Acuity = 20/25
Eff RP = 43.59D	Avg Sim K = 42.97D	Reg Astig = +2.23D @ 118°	I-S Value = 0.56 (p=0.217)

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for more research to prevent reduction in the EOZ as the amount of myopic treatment increases.

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