Comparison of the effect of LASIK parameters on the percent tissue altered (1-dimensional metric) versus percent volume altered (3-dimensional metric)

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Purpose: To determine the theoretical volumes of flap and tissue ablation altered during laser in situ keratomileusis (LASIK) correction of myopic refractive errors.

Setting: Rothschild Foundation, Paris, France.

Design: Experimental study.

Methods: The theoretical volumes of the flap and ablated corneal lenticules for spherical myopic corrections were calculated by mathematical approximations based on a simplified geometric model. These results were then compared for various zone diameters, dioptric corrections, and the percentage of the volumes altered (PVA) with the percentage of tissue altered (PTA).

Results: The volume of the flap varied linearly with flap thickness and with the square of the flap diameter. The volume of ablated corneal tissue was estimated to be proportional to the magnitude of myopia treatment and to the 4th power of the treatment diameter. For the same depth of ablation, the volume of tissue ablated can vary significantly, depending on the magnitude of the correction and the optical zone diameter. As a result, the PTA calculation is not predictive of the actual PVA.

Conclusions: The flap diameters and the laser correction were the most important determinants of the PVA altered during LASIK surgery. New models estimating the volume of the flap and corneal tissue might be necessary to determine their influence on corneal biomechanical stability and each procedure's outcome.

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For lamellar refractive surgery, it has been assumed that the residual stromal bed (RSB) thickness might be the critical factor in the cornea's postoperative biomechanics and stability. This concept was developed from empirical data and previous observations and promulgated without formal investigations. The concept of the percentage of tissue altered (PTA) was introduced by Santhiago et al.[1–3] and Santhiago[4] as a screening metric for refractive surgery candidates. The PVA is an estimation of the percentage of central corneal tissue modified during the creation of the laser in situ keratomileusis (LASIK) flap and subsequent stromal photoablation. It considers the relationship between preoperative corneal thickness, the tissue altered through excimer laser ablation and flap creation, and the ultimate RSB thickness.

In their study introducing the PTA, Santhiago et al.[1] investigated the association between the PTA and the occurrence of ectasia after LASIK in eyes with normal corneal topography. Their study included 30 eyes of 16 patients with bilateral normal preoperative Placido-based corneal topography that developed ectasia after LASIK and 174 normal eyes of 88 consecutive patients that had uneventful LASIK and at least 3 years of postoperative follow-up. In the ectasia group, a PTA of 40% or greater was the most prevalent risk factor (97%). This value was selected from receiver operating characteristic curves, which showed that a cutoff of 40% led to a specificity of 91% and a sensitivity of 87%. In a recent study comprising 593 eyes,[5] we assessed the specificity value of this PTA metric to 78.7%. In their paper, Santiago et al.[1] reported that all cases with a PTA value above 47% developed this complication. In our study,[5] 19 eyes (3.2%) that had a PTA above 47% did not develop ectasia after 2 years (mean 31 months) of follow-up.

The term *tissue* for the *T* in the acronym PTA suggests that a volume, not a simple thickness of the elements, is used in the calculation. However, the cornea is a

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3-dimensional (3-D) structure and its volume can be computed and expressed in volume units (mm^3). The quantity of tissue cut, as in automated lamellar keratoplasty, and the quantity of tissue photoablated, as in photorefractive keratectomy (PRK) or LASIK, can also be expressed as a volume instead of a distance. However, the metrics involved in PTA calculation correspond to axial (1-dimensional [1-D]) measurements and are expressed as a distance measured along the axis of symmetry of the system and in general given in microns. The measurements have been estimated using expected flap thicknesses or measured by ultrasonic pachymetry, optical coherence tomography, or Scheimpflug technology.

The goal of our current study was to establish the importance of the volume of tissue altered in LASIK surgery for myopia and evaluate how the PTA estimated from axial measurements predicts the percentage of volume altered (PVA), a new metric computed from the estimation of implicated modified tissue volumes. Can purely axial metrics predict with reasonable accuracy the ratios of tissue volumes implied in LASIK surgery? To our knowledge, the ratios between the volume of the cornea and that of the tissues involved in LASIK surgery have never been computed. This might allow clinicians to better appreciate the respective importance of the combined volume of the LASIK flap incised plus the removed (photoablated) corrective lenticule on the corneal tissue.

MATERIALS AND METHODS

Preliminary Considerations for Theoretical Volume Calculations

Figure 1 shows the formulas using the various parameters that enable the computations for the tissue volumes required for this study. When the corneal surface is modeled as a spherical cap, its cross-section profile is an arc of circle. The sagittal height, denoted s, is the distance of the highest point of the arc from the midpoint of the chord. This parameter is necessary for volume calculations. Using the Pythagorean theorem, the sagittal height can be computed from the radius of curvature (r) of the considered spherical cap and its base radius (half of the chord), denoted d.

$$s = r - \sqrt{r^2 - d^2} \tag{1}$$

The anterior and posterior corneal surfaces are modeled as spherical caps of respective radii or curvature R_a and R_p. Each cap would correspond to the region of a given sphere, both of which lie above the same plane; here, we assume the plane is that of the limbus.

The volume of a cap (V_{cap}) is equal to

$$V_{cap} = \frac{1}{6}\pi s(3d^2 + s^2) \tag{2}$$

and its surface (S_{cap}) is given by

$$S_{cap} = \pi(d^2 + s^2) \tag{3}$$

The formula producing the volume of a cylinder of radius d and height h is

$$V_{cyl} = \pi h d^2 \tag{4}$$

These formulas allow one to calculate the volume of the cornea contained within a concentric cylinder and the volume of a LASIK flap of constant thickness within a specified diameter zone.

Volume Calculations

Corneal Volume The corneal flap volume was approximated as the volume contained between 2 spherical surfaces of different radii of curvature (anterior surface radius R_a; posterior surface radius R_p) whose apical distance is the central corneal thickness t_c. Figure 2 shows the parameters used for this calculation, which was restricted to the corneal volume contained within a cylindrical section C1 of radius d_p (semi chord of the posterior corneal surface) and height equal to ($s_p + t_c$) where s_p is the sagittal height of the posterior surface and t_c the central corneal thickness. The volume of C1 is equal to

$$V_{c1} = \pi\left(s_p + t_c\right)d_p \tag{5}$$

The corneal volume can be computed as the difference between the total volume of the cylinder C1 and 2 hollow volumes delineated by the cylinder base and the posterior corneal surface as boundaries for the first empty volume and by the cylinder top and the anterior corneal surface as boundaries for the second empty volume

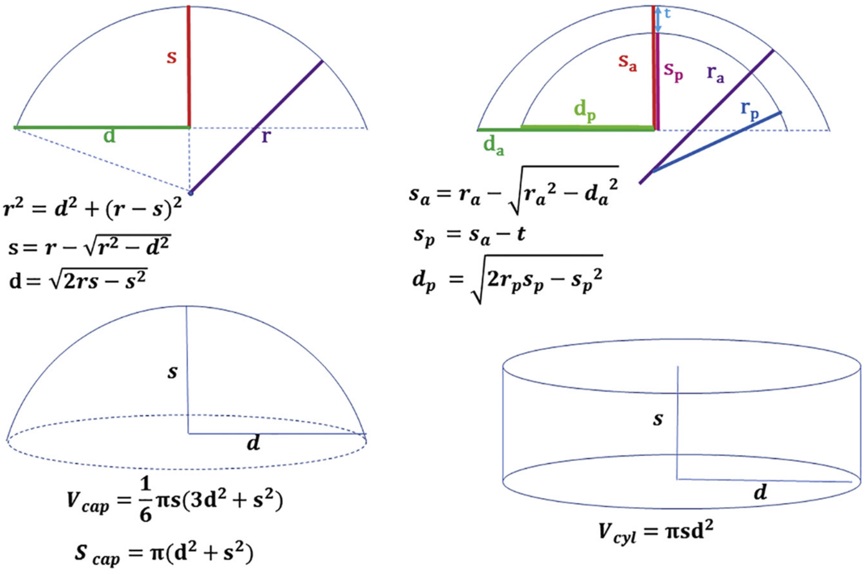

Figure 1. Basic geometric elements and primitives used in volume calculations. The corneal profile can be modeled as an arc of a circle of radius r and hemi chord d, from which the sagittal height s can be computed (*top left*). These calculations can be applied to both the anterior corneal profile (radius r_a, sagittal height s_a, and hemi chord d_a) and posterior corneal profile (radius r_p, sagittal height s_p, hemi chord d_p) (*top right*). A corneal surface can be modeled as a spherical cap, the region of a sphere that lies above the limbal plane. Its volume can be computed from the sagittal height s and base radius d (*bottom left*). The volume of a cylinder can be computed from the values of its height s and base radius d (*bottom right*). (See text for full description of the formulas.)

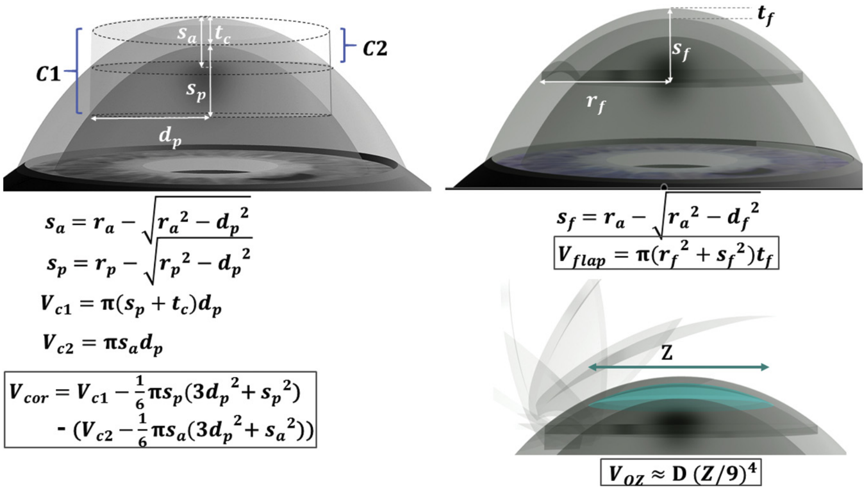

Figure 2. *Left*: Representation of the sagittal heights (s_a *and* s_p) and the zone-related, and depth-related variables used for calculating the respective volumes of the cornea (V_{cor}) of central thickness t_c and anterior and posterior radii of curvature r_a and r_p, respectively. The sagittal height variables s_a and s_p can be computed from equations in Figure 1. To compute the volume of a corneal lenticule of base radius d_p, 2 concentric cylinders (*C1* and *C2*) of base radius d_p are considered (*top left*). The V_{cor} can be computed by subtracting to the volume of *C1* the following 2. The first volume is contained between the base of *C1* and the posterior surface of the cornea, and the second volume is computed as the difference of the total volume of *C2* and the volume contained between the anterior surface of the cornea and the top of *C2*. *Top right*: The volume of the LASIK flap (V_{flap}) is a function of the flap radius (d_f), the flap thickness (*df*), and the corresponding sagittal height of the anterior flap surface s_f. *Bottom right*: The volume of stromal tissue etched for a spherical myopic correction can be computed from the dioptric magnitude of the correction (D) and OZ diameter (Z) (LASIK = laser in situ keratomileusis; OZ = optical zone). (See text for full description of the formulas.)

(Figure 2). This second hollow volume, V_h, located below the posterior corneal surface, can be easily computed and is equal to

$$V_h = \frac{1}{6}\pi s\left(3d_p^2 + s_p^2\right) \qquad (6)$$

The calculation of the hollow volume located above the anterior corneal surface can be performed by considering within C1 a second cylinder C2 of hemi chord d_p and height s_a with

$$S_a = r_a - \sqrt{r_a^2 - d_p^2}$$

Its volume is equal to $V_{c2} = \pi s_a d_p$. This hollow volume is equal to the difference between V_{C2} and the volume contained between the anterior corneal surface and the base of C2. Finally, the analytical expression of the corneal volume V_{cor} contained within the cylinder C1 is obtained. This represents the total volume of the cornea contained in a diameter, defined as d_p.

$$V_{cor} = V_{c1} - \frac{1}{6}\pi s\left(3d_p^2 + s_p^2\right) - \left[V_{c2} - \frac{1}{6}\pi s\left(3d_p^2 + s_a^2\right)\right] \qquad (7)$$

Laser In Situ Keratomileusis Flap The volume of a flap of parallel surfaces (constant thickness) and circular perimeter is given by

$$V_{flap} = \pi\left(r_f^2 + s_f^2\right)t_f \qquad (8)$$

where r_f is half the flap diameter, t_f the central thickness of the flap, and s_f the sagittal height at the flap center (Figure 2). For the sake of simplicity, the volume of the flap hinge was neglected because, for example, an 8.0 mm flap of 100 µm thickness with a 70-degree hinge volume would be 0.23 mm^3, which would result in an overestimation of less than 4.5% of the flap volume.

Photoablated Tissue A previous study[6] established a simplified formula for estimating the volume (in mm^3) etched by the excimer laser for a Munnerlyn-based correction of diopters of myopia (D) within the optical zone (OZ) of diameter Z (in mm):

$$V_{OZ} \approx D(Z/9)^4 \qquad (9)$$

Percentage of Tissue Volumes Altered

The PVA was computed as the ratio between the sum of the volumes of the flap and photoablated tissue against the volume of the corneal tissue lenticule having the same diameter of the flap ($d_p = d_f$) (Figure 3). The PVA is expressed by the following ratio:

$$PVA = \frac{V_{flap} + V_{OZ}}{V_{COR}} \qquad (10)$$

The Munnerlyn formula relates the theoretical maximum depth of ablation P_{oz} (in µm) attained with a correction of magnitude (D) and the diameter (Z) (in mm):

$$P_{OZ} \approx \frac{1}{3}D \times Z^2 \qquad (11)$$

This equation can be rearranged to obtain the value of the diameter of the OZ to be programmed so that for a given correction (D), one obtains a maximum depth of ablation equal to P_{oz}.

$$Z \approx \sqrt{(3xP_{OZ}/D)} \qquad (12)$$

Using formula 12, several laser myopic corrections that share the same ablation depth can be generated. However, these

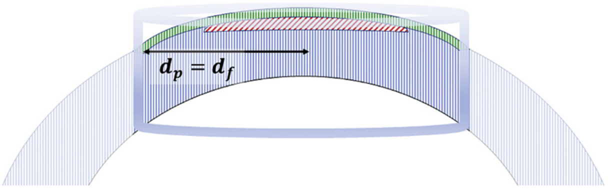

Figure 3. Volumes used for the PVA calculation. The green represents the volume of the LASIK flap, and the red represents volume of the excised lenticule for the correction of myopia. The corresponding volume of the corneal button used for calculation is shown enclosed in a cylinder (also comprising the LASIK flap) and is outlined in blue (d_f = flap radius; d_p = base radius; LASIK = laser in situ keratomileusis; PVA = percentage of volume altered).

corrections would differ by the magnitudes of correction and the OZ diameters. Hence, each of these corrections would generate the same maximum depth of ablation, but a different volume of tissue ablation. This formula shows that the same maximum depth of ablation can result from various combinations of magnitude of corrections with various OZ diameters.

For the same central flap thickness, and/or maximum central depth of ablation (resulting in similar PTA values), different volumes of tissue can be altered when the respective diameter of the flap and OZ are varied. This would result in variations in the PVA. In this examination of the value of the PVA metric, we computed the percentage of volume altered (PVA) and compared it with the PTA value for various theoretical situations including different magnitudes of myopic correction and flap thickness. For the same depth of ablation, it is possible to compute various pairs of numerical values of D and *Z* that would result in the same maximum depth of ablation, which is the metric currently used in the PTA calculation. The volume of the cornea at various concentric diameters and with different anterior and posterior radii of curvature was computed. Different tissue volumes were computed for a cornea having anterior and posterior radii of curvature of 7.8 mm and 6.6 mm, respectively.

RESULTS

Volume of the Cornea

Table 1 shows an estimation of the volumes of the cornea having various concentric diameters and anterior versus posterior radii of curvature. The volume of the corneal tissue tended to increase slightly with the curvature of its anterior surface and posterior surface. Figure 4 shows the predicted impact of corneal thickness on the volume of the corneal tissue contained within a concentric 8.0 mm zone. Variation of the central corneal thickness (CCT) resulted in an apparent linear variation in corneal volume. An increase in the CCT from 500 μm to 600 μm (+120%) resulted in a corneal volume increase from 30.70 mm^3 to 35.75 mm^3 (+116%).

Volume of the Flap

Figure 5 shows the predicted effect of flap thickness and flap diameter on flap volume. The volume of an 8.5 mm diameter flap of a uniform thickness equal to 100 μm approximated 6.0 mm^3. As predicted from the analytical expression of the predicted flap volume (see formula 9), an increase in the flap thickness resulted in a linear increase in flap volume whereas an increase in flap diameter created a quadratic increase in flap volume. An increase in the diameter of a 100 μm central thickness flap of parallel faces from 8.0 mm to 9.5 mm resulted in an increase of 150% of the flap volume.

Volume of Photoablated Tissue for Myopic Corrections

Figure 6 shows the impact of the maximum depth of ablation and the volume of photoablated tissue on the increase in the OZ diameter. Based on formula 9, the volume required to correct 1.00 D of myopia ablated using a 6.0 mm OZ was equal to 0.2 mm^3. The volume of photoablated tissue increased linearly with the magnitude of correction but exponentially with the diameter of the OZ. Although enlargement of an OZ from 5.0 mm to 7.0 mm resulted in an area increase of 150%, an increase in treatment diameter caused the ablated volume to increase by 350%.

Percentage of Volume Altered

The PVA was computed and compared with the PTA value for various theoretical LASIK parameters (Tables 2A and 2B). In all the tested scenarios, the value of the PTA tended to overestimate the actual percentage of volumes resulting from the LASIK procedure. By failing to reflect the variation of actual tissue volume, the calculated PTA values might overestimate the theoretical biomechanical structure of altered tissue.

Figure 7 shows the simultaneous variations in the PTA and PVA metrics using various theoretical LASIK surgeries. All these theoretical procedures were performed with the same flap thickness and diameter, keeping the volume of the flap constant. Using formula 12, different surgeries combining various attempted corrections and OZ diameters would each induce the same maximum depth of ablation (92 μm) but create different volumes of excimer laser photoablated (altered) tissue (Figure 7, *A*). In this example, although the PTA value is kept constant at 39%, the PVA varies from 22.2% to 26.5% (Figure 7, *B*). In these scenarios, the calculated PTA value overestimated the volume of altered tissue. This PTA metric was insensitive to the variations in the actual tissue volume removed from the corneal stroma if their maximum depth of ablation was invariant.

DISCUSSION

Few studies have examined the question of the impact of the volume of corneal tissue altered or removed on corneal biomechanics. Using a dynamic bidirectional applanation

Table 1. Estimation of the corneal lenticule volume (mm^3) for various diameters and anterior and posterior surface radii of curvature. The CCT is 540 μm for all simulations.

	Corneal Lenticule Diameter (mm)						
R_a/R_p (mm)	6.0	7.0	8.0	9.0	10.0	11.0	12.0
8.0/6.8	16.80	23.73	32.39	43.23	56.87	74.33	97.46
7.9/6.7	16.85	23.82	32.57	43.54	57.42	75.33	99.32
7.8/6.6	16.90	23.92	32.75	43.88	58.02	76.40	101.37
7.7/6.5	16.95	24.02	32.95	44.23	58.66	77.57	103.66
7.6/6.4	17.00	24.13	33.16	44.61	59.35	78.84	106.26
7.5/6.3	17.06	24.25	33.37	45.01	60.08	80.24	109.23
7.4/6.2	17.12	24.37	33.61	45.45	60.88	81.77	112.70

CCT = central corneal thickness; R_a = anterior surface radius of curvature; R_p = posterior surface radius of curvature.

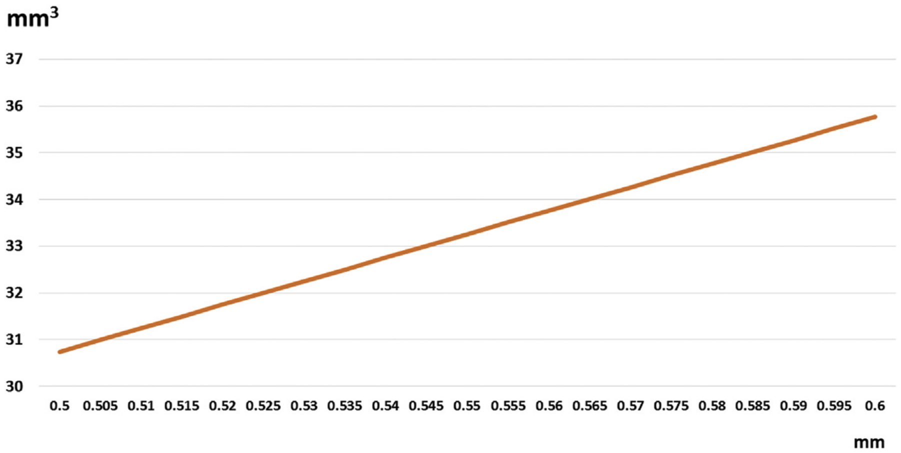

Figure 4. Effect of increasing the central corneal thickness (mm) on corneal volume (mm^3) (anterior corneal radius of curvature r_a = 7.8 mm; posterior radius of curvature r_p = 6.6 mm; flap diameter = 8 mm).

device (Ocular Response Analyzer, Reichert Technologies), Sedaghat et al.[7] found a correlation between corneal hysteresis, the corneal resistance factor, and the corneal volume obtained from Scheimpflug tomography in normal participants. In their study, the mean corneal volume value in the 3.0 mm, 5.0 mm, 7.0 mm, and 10.0 mm zones in all eyes was 3.8 mm^3 ± 0.2 (SD) (range 2.9 to 4.6 mm^3), 11.2 ± 0.6 mm^3 (range 9.2 to 13.4 mm^3), 24.3 ± 1.4 mm^3 (range 20.9 to 29.1 mm^3), and 60.1 ± 3.5 mm^3 (range 51.2 to 71.2 mm^3), respectively. These values align closely to what we computed with our simplified corneal model. Other studies have shown that the corneal volumes were significantly different in normal eyes versus eyes with subclinical keratoconus and in normal eyes versus eyes with keratoconus.[8–10]

In the current study, we have shown that the current PTA metric is not predictive of the ratio of the volumes of tissue altered in LASIK (flap volume and etched tissue volume versus corneal volume). Although the flap thickness and magnitude of correction had a linear effect on the flap and photoablated (altered) tissue volumes, respectively, the diameter of the flap and treatment zone had a more significant effect on the altered tissue volumes. Hence, for an eye with a given flap thickness and a fixed amount of intended myopia correction, the respective diameters of the flap and of the planned laser OZ might be the most important variables influencing the volume of tissue altered by the LASIK procedure. The depth of ablation is proportional to the squared value of the treatment diameter, whereas the volume of laser ablation is proportional to the 4th power of the treatment diameter. Thus, in patients who have large pupils and/or a low planned myopic correction, a large OZ could create a greater ratio of tissue altered than a higher myopic correction delivered in a smaller OZ. This is of particular importance because experimental studies[11–13] have shown that the cornea shows a regional in-plane variation in strain and deformation and that corneal elastic strength is a function of depth, with decreasing strength from the anterior to the posterior stroma. The relative smaller impact of the volume of the flap (1 order of magnitude) over the photoablated volume might account for the relatively low incidence of ectasia after PRK, in which no flap is cut and the refractive tissue volume is etched from the apical part of the stroma.

The volume of the epithelial layer was not taken into account in our volumetric flap calculations. The isolation of the specific stromal volume within the flap might better correspond to the part of the cornea that is responsible for its biomechanical strength. This would alter both the PTA estimation and PVA estimation. We modeled flaps with uniform thicknesses, whereas studies[14–16] found that with mechanical microkeratomes,

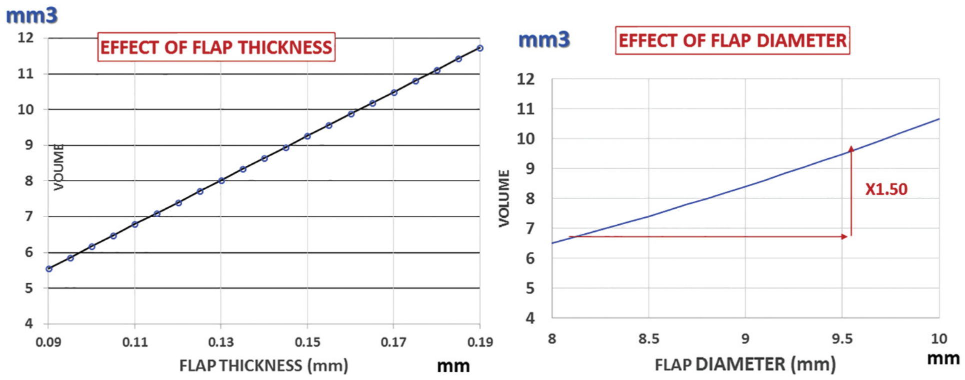

Figure 5. Effect of flap thickness on the flap volume and flap diameter on flap volume.

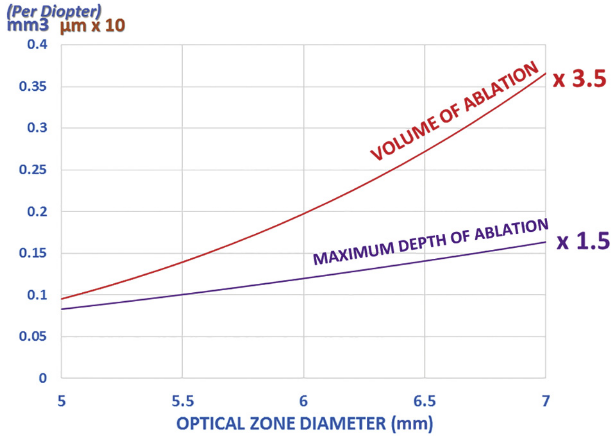

Figure 6. Comparison of the effect of the diameter of the planned laser optical zone on the photoablated volume and maximum depth of ablation for a 1.00 D myopic correction.

the peripheral flap thickness was greater than the central flap thickness (meniscus flap). Our calculations (data not reported) showed that for a gradual increase in the flap thickness toward the periphery attaining 10 μm at the flap edge, the increase in the flap volume would be approximate 10% of a flap of uniform thickness.

The impact of these variations might be mitigated by the increase in the corneal stromal thickness toward the periphery. However, it must be kept in mind that a meniscus flap shape begins and ends deeper in the cornea than the achieved central thickness, thereby cutting more lamellae and creating more biomechanical instability than a flap of parallel faces with the same measured CCT.

The impact of corneal refractive surgery on corneal biomechanics has been studied in animal, clinical, and theoretical models.[11,12,17–19] In our study, we focused on the comparison of the volumes implied by the 2 main steps of the LASIK procedure, ie, the flap creation and stromal tissue photoablation. For the same volume subtracted for either the flap or laser ablation, its depth into the stroma and its distance to the center of the cornea might significantly affect the biomechanical impact.

The PVA concept could provide insight to account for cases in which the PTA seems not to be predictive of ectasia.[4] However, a metric that accounts for the volume of tissue altered is likely to be a more sensitive approach than the current PTA estimation but remains to be shown. In addition, the proper calculation of the volumes implied would require the assistance of a computer and a dedicated program, which could also be implemented in the software of full-thickness corneal tomography instruments or excimer lasers to specifically calculate a PVA for a specific combination of flap creation device (microkeratome or femtosecond laser) and specific excimer laser algorithm. In tomographic systems enabling epithelial mapping, these calculations could be refined by excluding the volume corresponding to the epithelial layer.

In a recent study,[5] we queried a LASIK database created by 1 surgeon (P.S.B.) for LASIK cases that had a minimum follow-up of 24 months (mean 30 months). Completeness of the preoperative data and intraoperative data permitted the calculation of PTA values greater than 40%, which is assumed to be the criterion value for being at higher risk for developing ectasia.[6] From that group, we calculated the PTA and flap thickness data. In our series of 593 eyes, 21% of cases had a measured PTA above 40%. None of the eyes developed iatrogenic ectasia after more than 24 months of follow-up (mean 30 months), which represents a specificity of 78.7% for the PTA as a predictive tool in this series. Nineteen cases (3.2%) had a PTA above 47% and did not develop ectasia. This relative lack of specificity might partly derive from the discrepancies between the PTA estimate based on a 1-D metric (PTA) versus a 3-D metric (PVA). Santhiago et al.[2] found that for patients with a high PTA (>40%) and a flap thickness that represented 50% or more of that PTA, the ectasia risk increased beyond what it would be from the PTA value alone. This could reflect the importance of the LASIK flap tissue volume over the photoablated tissue volume. Given the discrepancies between the intended versus the achieved flap diameters, it is not possible to calculate the PVA values

Table 2A. Increments in the magnitude of the correction: PTA versus PVA.*

Center Flap Thickness (μm)	Flap Volume (mm^3)	Correction (D)	Maximum Ablation Depth (μm)	Laser Volume (mm^3)	PTA	PVA
110.00	5.95	1.00	12.00	0.20	0.23	0.19
110.00	5.95	2.00	24.00	0.40	0.25	0.20
110.00	5.95	3.00	36.00	0.59	0.28	0.20
110.00	5.95	4.00	48.00	0.79	0.30	0.21
110.00	5.95	5.00	60.00	0.99	0.32	0.22
110.00	5.95	6.00	72.00	1.19	0.34	0.22
110.00	5.95	7.00	84.00	1.38	0.37	0.23
110.00	5.95	8.00	96.00	1.58	0.39	0.23
110.00	5.95	9.00	108.00	1.78	0.41	0.24
110.00	5.95	10.00	120.00	1.98	0.43	0.25

PTA = percentage of tissue altered; PVA = percentage of volume altered

*Parameters used for the calculations: anterior surface radius of curvature = 7.8 mm; central corneal thickness = 530 μm; corneal lenticule diameter = 8.0 mm; flap diameter = 8.0 mm; optical zone = 6.0 mm; posterior surface radius of curvature = 6.6 mm

Table 2B. Increments in flap uniform thickness: PTA versus PVA.*

Center Flap Thickness (μm)	Flap Volume (mm^3)	Correction (D)	Maximum Ablation Depth (μm)	Laser Volume (mm^3)	PTA	PVA
90.00	4.87	1.00	12.00	0.20	0.19	0.16
100.00	5.41	1.00	12.00	0.20	0.21	0.17
110.00	5.95	1.00	12.00	0.20	0.23	0.19
120.00	6.49	1.00	12.00	0.20	0.25	0.21
130.00	7.03	1.00	12.00	0.20	0.27	0.22
140.00	7.57	1.00	12.00	0.20	0.29	0.24
150.00	8.11	1.00	12.00	0.20	0.31	0.26
160.00	8.65	1.00	12.00	0.20	0.32	0.27
170.00	9.20	1.00	12.00	0.20	0.34	0.29
180.00	9.74	1.00	12.00	0.20	0.36	0.31
190.00	10.28	1.00	12.00	0.20	0.38	0.32

PTA = percentage of tissue altered; PVA = percentage of volume altered

*Parameters used for the calculations: anterior surface radius of curvature = 7.8 mm; central corneal thickness = 530 μm; corneal lenticule diameter = 8.0 mm; flap diameter = 8.0 mm; optical zone = 6.0 mm; posterior surface radius of curvature = 6.6 mm

retrospectively in eyes in which a mechanical microkeratome was used for LASIK flap creation.

Our approximation of the photoablated volume was limited to the correction of the myopia using Munnerlyn-based calculations. It might underestimate the actual volume removed from current custom aspheric corrections, which can increase the maximum depth of ablation of the case of increased preoperative corneal topographic prolateness.[20] For the same OZ diameter and maximum depth of ablation, the photoablated volume removed during compound myopic astigmatism corrections would also be underestimated using our calculation. Using Boolean operations with a 3-D modeling software (Bryce 3D, Metacreation Corp.), we modeled the 3-D characteristics of astigmatic corrections.[21] Based on this modeling, the volume removed for the correction of 1.00 D of simple myopic astigmatism (eg, −1.00 × 180 degrees) would be approximately 150% that of a 1.00 D myopic correction with the same OZ diameter. A multidimensional nomogram could be computed based on these results of compound myopic astigmatism corrections.

Despite some limitations, the PVA metric as a 3-D-based metric could provide a more robust estimation of the risk for ectasia than the PTA, which is by definition an axially based (1-dimensional) metric. Because of the complexity of the corneal biomechanics at play during LASIK, we postulate that the PVA could become an adjunct 3-D–based metric combined with other clinical-, biomechanical-, and topography-based data rather than as a standalone index. Further study is necessary to confirm the predictability of the PVA metric and define appropriate thresholds for accurate evaluation of the risk for ectasia.

WHAT WAS KNOWN

- The PTA, a 1-D metric, calculated at the time of LASIK has been proposed as an indicator of the ectasia risk in eyes with normal preoperative topography.

WHAT THIS PAPER ADDS

- Three-dimensional corneal modeling of the cornea, flap, and photoablated tissues showed that the PTA does not account for PVA altered during LASIK.

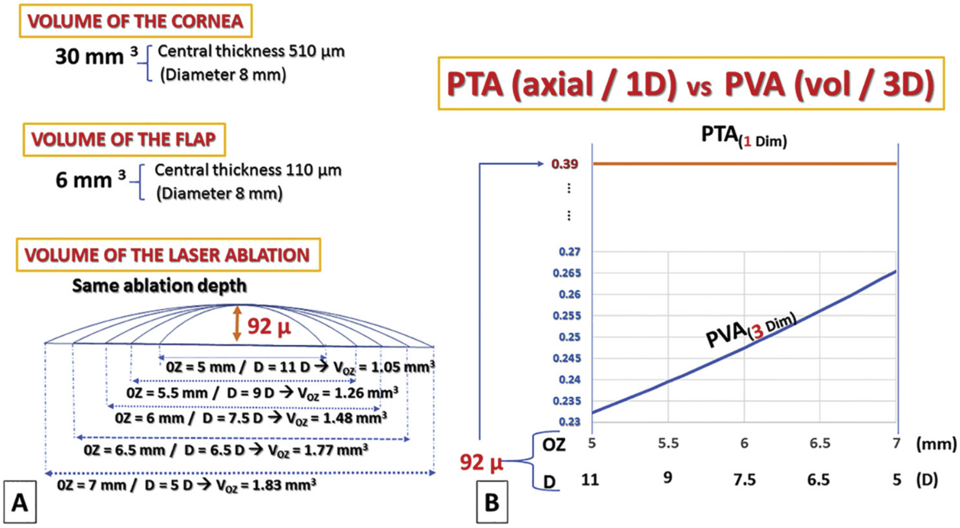

Figure 7. *A*: Comparison between the PTA and PVA values for theoretical LASIK procedures with the same flap thickness and diameter and various combinations of optical zone and magnitude of correction, all resulting in the same maximum depth of ablation (92 μm). *B*: Although the PTA metric is unchanged, the PVA metric increases proportionally to the increase in the volume of stromal laser ablation (D = diopters of myopic correction; Dim = dimensional; LASIK = laser in situ keratomileusis; OZ = optical zone; PTA = percentage of tissue altered; PVA = percentage of volume altered; V$_{OZ}$ = volume of the laser ablation).

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