Three-dimensional representation and qualitative comparisons of the amount of tissue ablation to treat mixed and compound astigmatism

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Purpose: To compare the shape and volume of the lenticules of corneal tissue ablated for the correction of spherical, cylindrical, and spherocylindrical refractive errors using Boolean operations of theoretical 3-dimensional (3-D) surfaces.

Setting: Department of Ophthalmology, Rothschild Foundation, Paris, France.

Methods: Digital modeling software was used to perform graphic representations of ablated lenticules on 3-D virtual surfaces. Various Boolean operations were performed between different preoperative and postoperative surfaces, and the additional and subtractive properties of ablated theoretical lenticules were analyzed to determine profiles of ablated lenticules for mixed and compound myopic and hyperopic astigmatism.

Results: Negative-cylindrical treatment, used to treat simple myopic astigmatism, was equivalent to the combination of a positive-cylindrical and a negative-spherical treatment of the same magnitude. Combining a pure negative-cylindrical and a positive-spherical treatment in a sequential strategy when treating compound astigmatism resulted in redundant ablation (plano lenticule), leading to an unnecessary increase in the amount of tissue ablation.

Conclusions: Negative-cylindrical treatments result in greater tissue ablation than corresponding positive-cylindrical treatments. For any given compound astigmatic error, the strategy using the greater magnitude of positive cylinder incurs the minimal amount of tissue ablation.

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Topographical and wavefront-assisted excimer laser ablations are promising surgical approaches for the custom treatment of various refractive errors. Custom treatments are based on subtracting from preoperative profiles to change the optical power of the anterior corneal surface.[1] In contrast, noncustom laser ablations of a compound or mixed astigmatic refractive error with photorefractive keratectomy (PRK) or laser in situ keratomileusis (LASIK) usually use a combination of 4 elementary treatments: spherical myopic, spherical hyperopic, cylindrical myopic, and cylindrical hyperopic corrections.[2,3] Noncustom laser algorithms are based on paraxial models first described by Munnerlyn and coauthors.[4] Thus, to achieve emmetropia, only 1 final apical corneal curvature must be obtained by the intended tissue photoablation within the optical zone. The refraction as commonly done clinically is an arc-based mathematical expression limited to the principal major and minor axes, and any compound astigmatic refractive error can be expressed by several equivalent expressions.[4,5]

Current conventional excimer laser ablations are based on a subtraction shape model in which the profile of the ablation delivered on the corneal ablation bed allows the etching of a lenticule whose paraxial optical power corresponds to that of the spherocylindrical ametropia to be corrected. The basic characteristics of the conventional profiles of ablation to correct simple spherical refractive errors can be deducted from their sagittal 2-dimensional representation because of rotational symmetry; ascertaining their features for the treatment of compound astigmatism is more difficult for the

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clinician who is used to additive optical corrective means.

Other noncustom treatment strategies for correcting mixed and compound astigmatism consisting of a combination of spherical and cylindrical treatments have been proposed: (1) ablating the cylinder along the flattest meridian and then treating the residual spherical component (positive-cylindrical approach); (2) ablating the cylinder along the steepest meridian and then treating the residual spherical component (negative-cylindrical approach); (3) ablating the total refractive error by 2 simple cylindrical ablations of opposite signs along the principal meridians (bitoric approach); (4) ablating half the power of the cylinder along the steepest meridian and half along the flattest meridian before the residual spherical equivalent is treated (cross-cylindrical approach).

These strategies have been used to treat compound myopic, compound hyperopic, and mixed astigmatism. Azar and Primack[2] report using these strategies in cases of mixed and compound hyperopic astigmatism. They found that these strategies may result in different depths of corneal tissue ablation. Deeper ablations may increase the risk of corneal ectasia after LASIK; thus, strategies that remove less corneal tissue are preferable in the treatment of compound and mixed astigmatism, especially in LASIK retreatments and in patients with large pupils and large corrections. Azar and Primack's[2] comparison of the theoretical ablation profiles and depths of tissue removal in the treatment of compound hyperopic and mixed astigmatism shows that strategies combining hyperopic spherical and myopic cylindrical corrections incur the greatest amount of corneal tissue ablation; however, the authors do not provide an estimate of the differences in terms of the ablation amount.

In this study, we generated theoretical 3-dimensional (3-D) corneal surface simulations based on Munnerlyn and coauthors' equation for correcting mixed and compound astigmatism using Boolean operations. In contrast to abstract mathematical functions, the generated images can be interpreted easily and quickly. These representations provide a rationale that would help clinicians compare the amount of corneal tissue ablated using various conventional strategies available for the treatment of compound astigmatic corrections. The shape and amount of these elementary lenticules were analyzed qualitatively and compared. This allowed estimation of the theoretical differences in the amount of ablated corneal tissue using available treatment strategies.

Materials and Methods

Munnerlyn-Based Boolean Operations on 3-D Surfaces

Digital modeling software that allowed visualization of the results of Boolean operations on orientated 3-D surfaces (Bryce 3D, Metacreation Corp.) was used to generate a graphic representation of theoretical shapes of the lenticules ablated during LASIK treatments of similar amounts of spherical and cylindrical treatment. Boolean operations are commonly used to describe a shorthand for logical computer operations, such as those that link values (eg, *and*, *or*, *not*). In 3-D computer applications, Boolean describes the joining, intersection, or removal of 1 shape from another. For example, the Boolean intersection of 2 objects contains the intersection of the interior and boundary of each object with the interior and boundary of the other. Using these Boolean operations (subtraction, addition, or intersection of an object from another object) on geometrical primitives such as sphere, cylinder, or toroidal ellipsoid, 3-D representations of the theoretical ablations were generated. This study was restricted to comparing the amount of tissue ablated within the optical zone; the issue of the ablated amount required to sculpt the transition from the ablated optical zone to the untreated area of the cornea, although important, was beyond the scope of this paper.

For spherical corrections, the initial and final corneal surfaces were modeled as 2 spherical surfaces of different radii of curvature (the latter being flatter for myopic spherical correction and steeper for hyperopic correction). For pure cylindrical correction, the initial corneal surface was modeled as a spherocylinder with 2 major apical radii of curvature along the principal meridians, with the final surface being spherical. For myopic cylindrical correction, 1 of the principal radii of cur-

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vature of the initial surface was shorter, with the other being equal to that of the final corneal surface. For hyperopic cylindrical correction, 1 of the principal radii of curvature of the initial surface was longer, with the other being equal to that of the final corneal surface.

The difference between the radii of curvature was exaggerated compared to the clinical and surgical range to facilitate the spatial visualization of the contour features of the generated lenticules. However, when the 2 strategies were compared, the initial and final surfaces were identical and rescaled to the same ratio for comparison. Depending on the sequential strategy used, different intermediate surfaces, each corresponding to a simple treatment, were obtained. The principal radii of curvature of these intermediate surfaces were calculated based on the 1st-order approximation relating the maximum depth of ablation,[4] which equals one third of the product of the magnitude of treatment (D) and the squared optical zone diameter (S^2) (Munnerlyn: maximum depth = $1/3\ D \times S^2$, where the maximum depth is in microns, D is in diopters, and S is in millimeters).

The 3-D representation of a lenticule was obtained using 1 or 2 Boolean operations. First, the primitive amount modeling the final theoretical corneal surface was subtracted from the primitive amount modeling the initial corneal surface. Second, if needed, the resulting volume was intersected with a cylinder whose diameter corresponded to that of the predetermined optical zone. These primitives were aligned and centered on the z-axis. The ablated lenticule for the correction of spherical myopia was generated by using a single Boolean operation (subtraction) and by adjusting the distance between the apex of the surfaces so they would intersect within a predetermined circular optical zone. The lenticule depicting the treatment of the pure negative-cylindrical treatment was generated by intersecting the amount represented by the subtraction of the initial and final surfaces with a tube-like curved plane with a circular cross-section having the same diameter as the optical zone. The distance between the apex of the initial and final surfaces was adjusted so they would intersect along the initial steepest meridian on the cylinder. The same approach was used to generate the amount of the lenticule corresponding to a pure positive-cylindrical treatment; in this case, the initial and final surfaces were tangent along the initial steeper meridian (Figure 1).

By selectively coloring the points of the lenticule that were included in the sagittal plane containing the considered meridian, the theoretical profile of the ablation along any meridian could be delineated.

For the lenticules corresponding to spherical treatments, 2 arbitrarily perpendicular meridians were chosen. For the lenticules corresponding to cylindrical treatments, the profile of ablation was underlined along the principal meridians.

The shape and amount of these elementary lenticules were analyzed qualitatively and compared. This allowed an estimation of the theoretical differences in the amount of ablated cornea by the different available strategies that combine the ablation of these elementary lenticules to correct a given compound astigmatic refractive error. Qualitative analysis of the geometric properties allowed comparison of the predicted total amount of tissue ablation for the different available approaches for the sequential treatment of compound myopic, compound hyperopic, and mixed astigmatism.

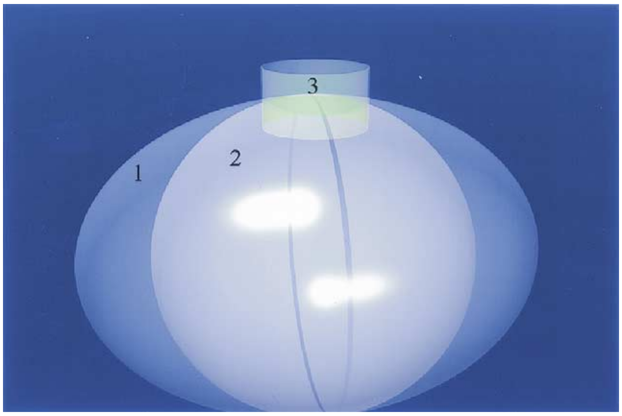


Figure 1. (Gatinel) Generation of the lenticule corresponding to the pure hyperopic astigmatism treatment (pure hyperopic astigmatism). Boolean operations are performed between a toroidal ellipsoid (1), a sphere (2), and a tube-like curved surface (cylindrical) with a circular cross-section (3). These figures are properly aligned. The sphere and the toroidal ellipsoid are tangent at their apex. The sphere is first subtracted to the toroidal ellipsoid. Then the residual amount is intersected with the tube-like surface.

Results

Shapes of Lenticules Ablated to Treat Spherical and Cylindrical Refractive Errors of Similar Magnitudes

Shape of the ablated lenticule for simple cylindrical myopia. The cylindrical myopic ablation involves ablating a lenticule of convex shape along the initial steeper meridian and of constant thickness along the initial flatter meridian to preserve its curvature. Because of this latter constraint, the amount of tissue volume removal for the pure cylinder treatment is greater in the flat meridian than when using the spherical treatment for a similar magnitude of dioptric treatment (Figure 2). The maximum thickness of the myopic cylindrical ablated lenticule occurs along the flatter meridian and is identical to that of a spherical myopic lenticule of the same magnitude of treatment.

Shape of the ablated lenticule for pure cylindrical hyperopia. The cylindrical hyperopic ablation involves ablating a lenticule of concave shape along the initial

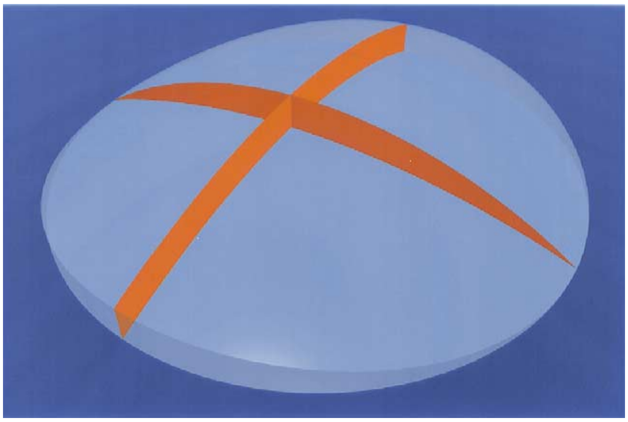


Figure 2. (Gatinel) Schematic representation of the lenticule ablated for correction of pure cylindrical myopia. The cross-section corresponding to the direction of the principal meridians is outlined in red. The lenticule thickness is maximum and constant along the direction of the initial flatter meridian.

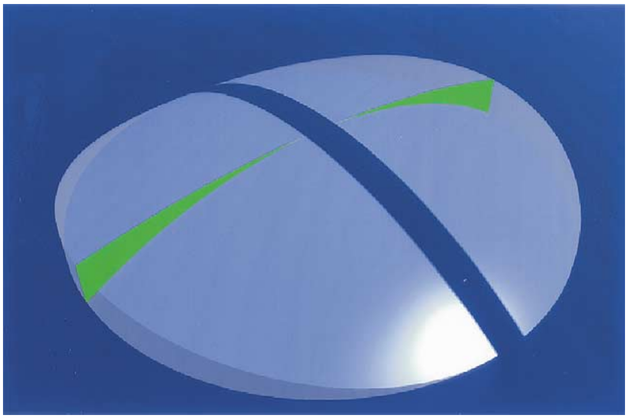


Figure 3. (Gatinel) Schematic representation of the lenticule ablated for correction of pure cylindrical hyperopia. The cross-section corresponding to the direction of the principal meridians is outlined in green. The lenticule thickness is zero along the direction of the initial steeper meridian.

flatter meridian and of null thickness along the orthogonal steeper meridian, which has the same radius of curvature as the final surface along the steeper meridian (Figure 3). The maximum thickness of the cylindrical hyperopic lenticule occurs at the outer edge of the optical zone, along the initial flatter meridian, and is identical to that of a spherical hyperopic lenticule for the same magnitude of treatment.

Additive and Subtractive Relations of the Lenticules Ablated for Spherical and Cylindrical Corrections

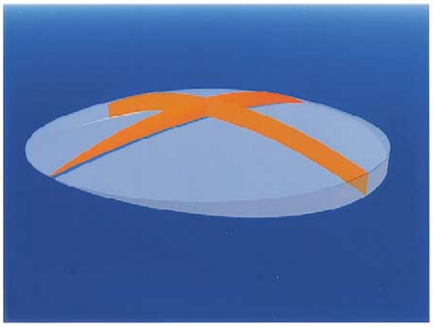
The successive ablation of a cylindrical concave and convex lenticule corresponding to the same absolute value of magnitude of treatment should result in no refractive change for the corneal surface and is also equivalent to the ablation of a plano lenticule.

By analogy to the paraxial optical properties of added corrective lenses, the result of any sequential tissue removal can be computed as the sum of the parts of the treatment. A spherical hyperopic treatment can be achieved by combining 2 successive positive-cylindrical treatments 90 degrees apart. For example, a spherical treatment of +1.00 diopter should be equivalent in terms of ablated volume to the sequential treatment of (+1.00 × 90) and (+1.00 × 180). This constraint of equivalency and symmetry implies that the volume of the lenticule removed for the treatment of cylindrical hyperopia is half the volume removed for the treatment of spherical hyperopia when the pure cylinder and the spherical power have the same magnitude.

Similarly, because the flattening of the initial steeper principal meridian cannot be performed selectively (it implies a plano ablation on the flat principal meridian), the lenticule ablated for cylindrical myopic treatment can be considered as the sequential treatment to the combination of 2 successive treatments: a positive-cylindrical treatment of equal magnitude on the initial flatter meridian (to steepen its curvature until it equals that of the opposite principal meridian) followed by a myopic spherical treatment of similar magnitude that aims to flatten both meridians to the desired radius of curvature. For example, a cylindrical treatment of plano −1.00 × 180 is equivalent in terms of the optical result and amount of ablated tissue to the sequential treatment of plano +1.00 × 90 and −1.00 sphere (Figure 4).

Comparison of Strategies to Treat Compound Myopic Astigmatism

Universal utility of combining plus cylindrical with negative sphere. The consequence of these relations is that any spherocylindrical correction can be achieved by a combination of hyperopic positive-cylindrical and negative-spherical treatments (Figure 5, *A*): (1) Steepening the flat principal meridian is achieved by the hyperopic cylindrical treatment. (2) Steepening both principal meridians is achieved by combining 2 perpendicular hyperopic cylindrical treatments on each meridian. (3) Selectively flattening 1 meridian necessitates flattening both principal meridians (negative-spherical treatment) followed by steepening of the other principal



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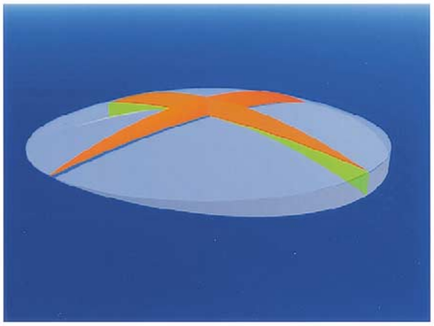

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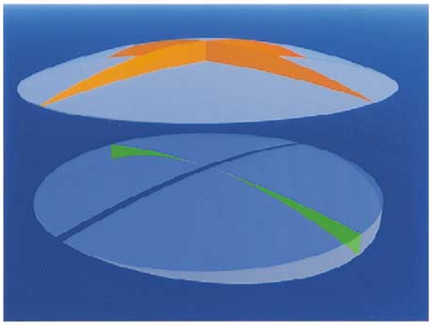

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Figure 4. (Gatinel) Decomposition of the amount of the lenticule corresponding to the treatment of pure myopic astigmatism (*A*) is 2 lenticules corresponding to a myopic spherical (*orange*) and a hyperopic pure cylindrical (*green*) component having the same magnitude (*B*). These lenticules have the same maximum thickness illustrated in the bottom figure, showing separation of the decomposed lenticules.

meridian to its initial curvature (positive-cylindrical treatment) as in Figure 4, *B*. (4) Flattening both principal meridians is achieved by the negative-spherical or compound myopic astigmatic (elliptical) treatment.

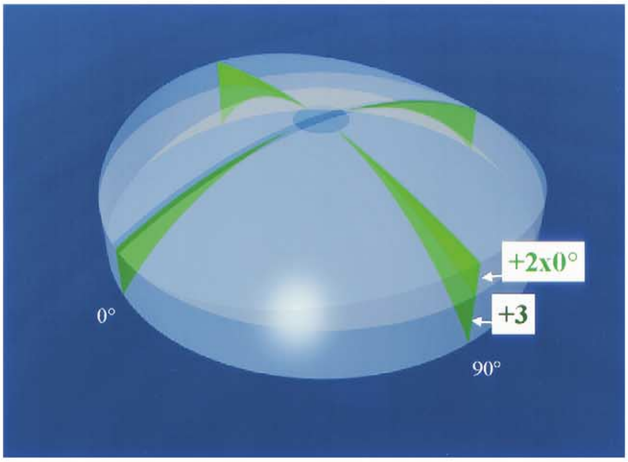
Compared to its reciprocal expression (positive-cylindrical and negative-spherical treatment) (Figure 5, *A*), a correction that stacks a negative-cylindrical treatment and a positive-spherical treatment results in the ablation of an additional amount of corneal tissue (Figure 5, *B*). This amount corresponds to a plano lenticule that results from the combination of the myopic spherical treatment in the flat meridian (which is part of the negative-cylindrical treatment) with the positive-spherical lenticule (in both meridians).

Comparison of Strategies to Treat Compound Hyperopic Astigmatism

For compound hyperopic astigmatism, the negative-cylindrical approach will add in the ablation of a plano lenticule in the flat meridian whose thickness will be equal to that of the negative cylinder. The magnitude of the negative cylinder in the flat meridian will be twice greater in the negative-cylindrical approach (Figure 5, *B*) than in the cross-cylindrical approach (Figure 5, *C*), in which the astigmatic component of the refraction is divided by 2. Therefore, the negative-cylindrical approach will result in the greatest amount of tissue ablation (Figure 5).

In the negative-cylindrical approach for the treatment of compound hyperopic astigmatism, the negative-cylindrical treatment can be split into myopic spherical and hyperopic cylindrical components. This strategy leads to treating the spherical component as a combination of 2 spherical lenticules of opposite shapes, resulting in the ablation of a plano lenticule whose thickness equals that of the initial cylindrical myopic lenticule along the initial flatter meridian (Figure 6, *brown*). In the cross-cylindrical approach for compound hyperopic astigmatism, a supplementary amount of ablation is needed that is equal to that of a plano lenticule whose thickness corresponds to the cylindrical myopic lenticule (Figure 7, *brown*).

For mixed astigmatism, the thickness of the additional plano lenticule implied by the negative-cylindrical and cross-cylindrical approaches as compared to the positive-cylindrical approach is equal to that of the negative hyperopic sphere of the considered refraction. The magnitude of the latter is greater in the negative-cylindrical approach than in the cross-cylindrical approach. For example, a refraction of −1.00 +3.00 × 90, if



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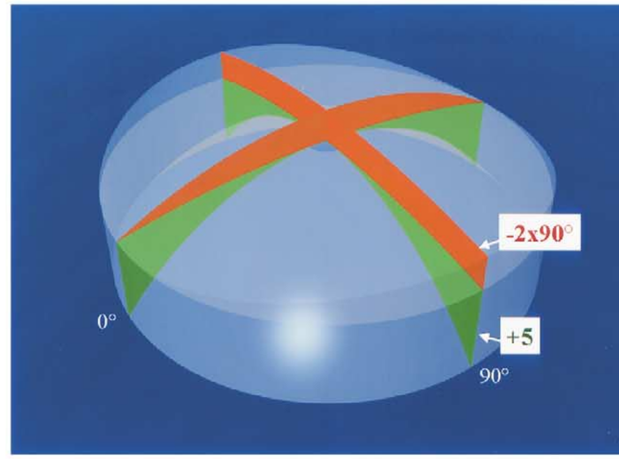

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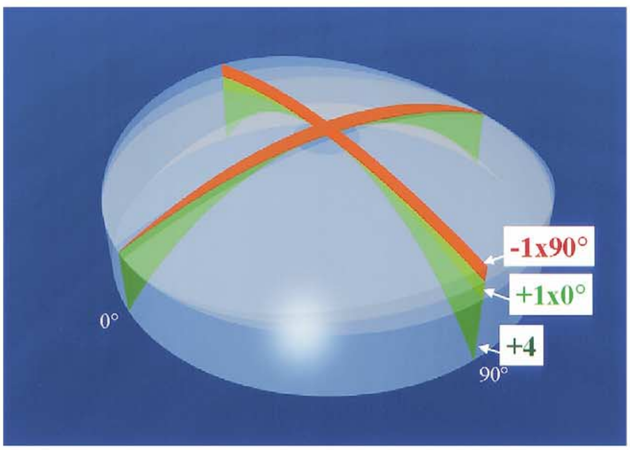

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Figure 5. (Gatinel) Treatment of compound hyperopic astigmatism. *A*: Positive cylinder approach +3(+2 × 180). Note the representation of the (plano +2 × 180) component (*light green*) over the +3 sphere (*dark green*), resulting in no tissue ablation in the center of the cornea. *B*: Negative cylinder approach +5(–2 × 90). Note the (plano −20 × 90) minus-cylinder component (*orange*) over the +5 sphere (*dark green*), resulting in the greatest volume of tissue ablation. *C*: Cross-cylindrical combining approach +4 sphere (*dark green*), (+1 × 180) cylinder (*light green*), and (−1 × 90) cylinder (*orange*).

treated with the negative-cylindrical approach +2.00 –3.00 × 180, will result in the additional ablation of a plano lenticule whose thickness will correspond to that of the positive-spherical lenticule (+2.00). If treated with the cross-cylindrical approach −1.50 × 180, +1.50 × 90, +0.50, it will result in the additional ablation of a plano lenticule whose thickness will correspond to that of the positive-spherical lenticule (+0.50).

For compound myopic astigmatism, all available strategies will lead to the same amount of tissue ablation. For example, the sequential treatments −4.00 –2.00 × 90 and −6.00 +2.00 × 180 both imply the same amount of ablated corneal tissue because −2.00 × 90 can be split in the sequence −2.00 sphere and plano +2.00 × 90.

Discussion

The first description of the use of toric ablation for the correction of astigmatism with the excimer laser was published in 1991.[6] Since then, there has been significant success in correcting astigmatism with the excimer laser.[7–11] The efficient correction of any form of astigmatism with PRK or LASIK supposes that the excimer laser energy will be delivered in an asymmetric fashion to sculpt a spherocylindrical lens on the corneal surface. Our study used 2nd-order wavefront decomposition and Boolean operations of theoretical surfaces. It confirmed that one can reduce the difference in curvature along the principal meridians by steepening the flatter meridian or flattening the steeper meridian. These procedures have the same goal but different consequences. Steepening 1 principal meridian can be done selectively because the ablation is null in the center of the optical zone and will spare the opposite principal meridian. Conversely, flattening 1 principal meridian implies that both meridians must be flattened first, before the initial flatter meridian is steepened to its original curvature.

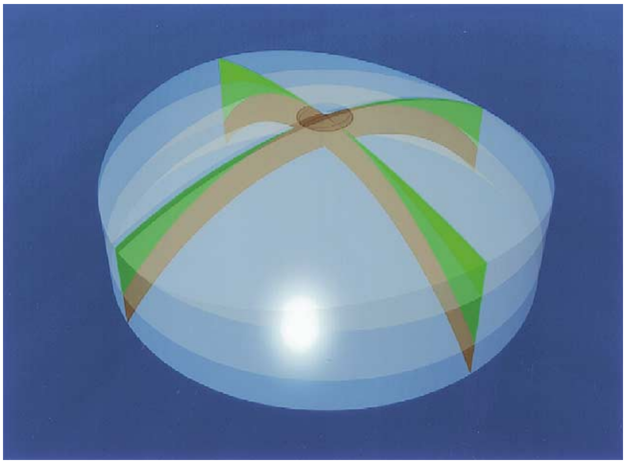

Figure 6. (Gatinel) Schematic representation of the additional amount of the lenticule by the negative-cylinder approach as compared to the positive-cylinder approach. It corresponds to a lenticule delimited by 2 parallel surfaces within the optical zone (plano lenticule), whose thickness equals that of the negative cylinder. The cross-section along the direction of the initial principal meridians is outlined in brown.

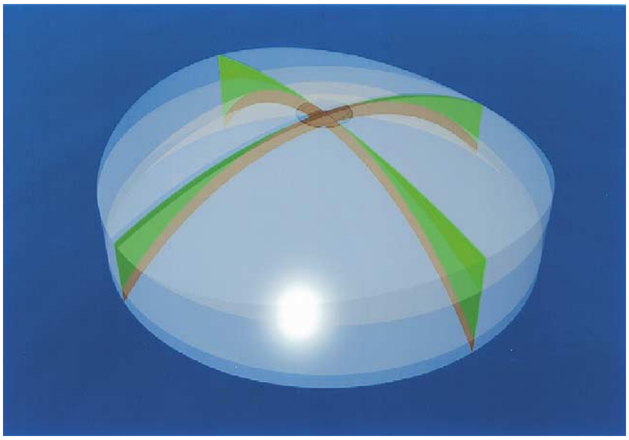

Figure 7. (Gatinel) Schematic representation of the additional amount of the lenticule by the cross-cylindrical approach as compared to the positive-cylinder approach. It corresponds to a lenticule delimited by 2 parallel surfaces within the optical zone (plano lenticule), whose thickness equals that of the negative cylinder. The cross-section along the direction of the initial principal meridians is outlined in brown.

Thus, the pure negative cylinder can be depicted as the combination of a pure hyperopic cylindrical treatment and a myopic spherical treatment, and the negative cylinder represents a sequential treatment itself.

Reports of studies in which hyperopic cylindrical ablation was used to correct mixed and hyperopic compound astigmatism were encouraging; no shift in the spherical component of the correction was observed. This is possibly due to the respect of the opposite meridian. However, regression has been shown to increase with the magnitude of the positive-cylindrical error. This might be triggered by the abrupt transition along the initial flatter meridian created by the pure cylindrical hyperopic correction. We suggest that similar phenomena might be induced by the negative-cylindrical treatment along the initial flatter meridian and would account for the hyperopic shift observed with variable intensity with different laser software after such treatment. This hyperopic shift, which might be of benefit for the correction of compound myopic astigmatism, might increase the magnitude of the hyperopic spherical treatment to achieve emmetropia in the sequential correction of mixed or compound hyperopic astigmatism based on the negative-cylindrical approach.[3] This will result in an additional increase in the total amount of ablated corneal tissue.

Although proprietary, current laser excimer ablations that aim to correct refractive errors are based on paraxial and arc-based mathematical models.[4] These models assume the initial corneal surface to be spherical (pure spherical treatments) or toroidal (pure cylindrical or spherocylindrical treatments) and the final surface to be spherical over the chosen optical zone. Furthermore, the laser systems perform as though they had to etch, from a flat surface having the same refractive index of the cornea, a lenticule whose power would correspond to the spherocylindrical error to correct. The geometric approach we used to generate the 3-D representation of the shape of the ablated lenticules follows these assumptions, in which any refractive error arises from the anterior surface of the cornea and corresponds to a particular arc-based difference model. In our theoretical model, the optical zone was circular and its diameter was identical for cylindrical and spherical corrections. Most current excimer laser software uses different optical zone diameters for pure cylindrical and spherical hyperopic or myopic treatments, and this must be taken in account when interpreting the results in light of our theoretical predictions.

The sequential method is not the only method to treat compound myopic astigmatism. The elliptical method implemented on the VISX software allows the full myopic and astigmatic correction to be sculpted into the cornea in 1 smooth ablation. This approach allows minimization of the depth and amount of tissue ablation. However, the elliptical ablation narrows the optical zone along the initially steeper meridian and thus increases the risk of induced optical aberrations. Finite calculus might be necessary to properly estimate the amount of tissue saved by using an elliptical algorithm to correct compound myopic astigmatism.

Our study focused on the amount ablated within the optical zone. The realization of a blend zone is important, especially for treatments in which most of the tissue ablation occurs at the periphery of the optical zone. In this regard, the positive-spherical ablation profile requires the greater amount of tissue ablation for the realization of the taper zone as it features a steep edge of constant depth at the edge of the optical zone. Because the positive-cylindrical approach minimizes the depth and the amount of tissue ablation for the realization of the optical zone, it is likely that the amount of corneal tissue ablation required to sculpt the transition zone may also be reduced.

Encouraging results have been reported by Vinciguerra et al.,[5] who treated compound astigmatism in LASIK procedures using cross-cylindrical ablation. As noted above, this approach does not warrant the minimal amount of tissue removal but might improve the refractive outcome by reducing the overcorrection on nonprincipal meridians and favoring the induction of a prolate asphericity.[12] However, the need for minimizing the amount of ablated tissue for the correction of compound astigmatism arises from different issues such as the preservation of corneal biomechanical stability, possibility of retreatments, and optimization of corneal shape. We suggest that refinements in the ablation profile for astigmatism will avoid an overcorrection along any meridian. Laser software for customized ablation might incorporate an improved algorithm to better achieve the cylindrical part of the treatment and to take into account corneal asphericity.

Customized ablation patterns are based on Zernike polynomial decompositions that include corrections of 2nd-order aberrations (defocus and astigmatism). Because of the splitting of the astigmatism into 2 components (cardinal and oblique), the amount of ablated corneal tissue required to correct 2nd-order aberrations might be similar to that obtained based on the cross-cylindrical approach and thus would not warrant minimum tissue ablation. In the context of wavefront or topographic customized ablation, redundant ablation might have unpredicted biomechanical and/or biological consequences that would interfere with the final refractive result and lead to difficult interpretations and refinements.

Our study reaffirms the importance of avoiding negative-cylindrical treatment for the sequential correction of compound astigmatism. Thus, to minimize the amount of ablated corneal tissue with the excimer laser, the sequential correction of any form of regular astigmatism should always be done by steepening the flatter meridian to the desired curvature before a spherical treatment is added.

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