Research of cornea section's shape ablated by 193-nm ArF laser spots

Zhiqiang Zhu (朱志强), Yinshan Yu (余吟山), and Guoqing Deng (邓国庆)

Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Hefei 230031

Received March 8, 2005

The ablation theory of cornea and biology effect by 193-nm ArF excimer laser are introduced. The ablation tracks model is put forward to make laser spots scan around cornea by many steps and many areas to change cornea curvature. The corneal average ablation curve is calculated by software so as to explain the feasibility of the ablation tracks model. By analyzing the actual ablation shapes of many arbitrary cornea sections, the optimal ablation method for deciding the random position of every laser spot in every ablation track is obtained. Experiments combining the ablation model with the device testify the energy stability of laser spots and the accuracy of rectifying anisometropia.

OCIS codes: 140.2180, 170.1020, 200.0200, 240.6670.

Nowadays, excimer laser's applications become more significant in R&D, industry and medicine owing to its special advantage of power level and photon energy not available from any other laser devices[1]. 193-nm ArF excimer laser has the characteristics of short wavelength and narrow pulse-width, it is used commonly in refractive laser surgery. Its single photon energy (6.4 eV) is far more than the combining energy of cornea tissue (3.4 eV)[1,2], thus it can cut off the chemical bond of corneal molecule easily with less damage around the cornea ablation incision[3]. On the other hand, 193 nm is near to the eyes maximum absorption wavelength 190 nm[4], one pulse can ablate corneal epidermis by 0.2-μm thickness or so. When laser spots scan across cornea, the energy will be absorbed within the distance of less than 5 μm, the effect to tissue can almost be neglected. For correcting myopia implemented by 193-nm excimer laser, combining with polymethyl methacrylate (PMMA) experiment, the topics of how to ablate corneal epidermis and what the ablation shape of an arbitrary imaginary corneal section across the cornea center is like are elaborated.

Laser *in situ* keraromileusis (LASIK) refractive surgery is accepted by more and more people, in which doctor cuts a very thin lamella — with about 8-mm diameter and 0.16-mm thickness — above cornea for ablation.

Figure 1 shows a perfect cornea section through cornea center. In theory, the aim of LASIK is to ablate the shadow proportion, changing the front cornea curvature radius from R_1 to R_q. After numbers of laser spots scanning across the cornea controlled by computer, the shadow part will disappear.

For convenience, suppose the cornea as a perfect sphere, then it is easy to get

$$H(x) = \sqrt{R_1^2 - X^2} - \sqrt{R_q^2 - X^2} + W,$$

$$W = \sqrt{R_q^2 - \frac{D}{4}^2} - \sqrt{R_1^2 - \frac{D}{4}^2}, \qquad (1)$$

where $R_q = \frac{n-1}{48.83+Q}$, Q is the needed correct diopter[5], n is the cornea media refractive index ($n = 1.376$[6]). The others parameters are defined in Fig. 1.

Figure 2(a) shows the ablation curves of -4D and -8D diopter got from Eq. (1).

In order to ablate the ϕ6 mm area of cornea and control laser spots' ablation routes, we adopt the laser spots' diameter of ϕ1 mm, and develop a new ablation model named as "ablation tracks", that is to say, divide the ϕ6 mm ablation area into several cirques. In Fig. 3, the cirques are just the so-called ablation tracks that distribute around the same cornea center equally. Six ablation tracks are taken here for convenience. The little circles represent the laser spot (ϕ1 mm), the spacing between two adjacent ablation tracks is 0.5 mm. Let every track have the scheduled spots number and distribute round the ablation track on average, the spot centers all lie in the ablation tracks (Fig. 3(a), the four spots lie in the second track). Now suppose there are 8 spots in the second track (Fig. 3(b)) and 12 spots in the third one (Fig. 3(c)), then after the two tracks overlap together, it will result in the effect of Fig. 3(d). The cases of laser spots lying in the other ablation tracks are not shown, but they follow the same principle.

In the same way, the ϕ6 mm ablation area can be divided into 10, 20, 30, 60 tracks, and so on. Therefore, the spacings between two adjacent tracks are 0.3, 0.15, 0.1, 0.05 mm, and so on. After all the scheduled spots scanning across the cornea, take an arbitrary cornea section A-A (Fig. 3(d), one of its ends is the cornea center,

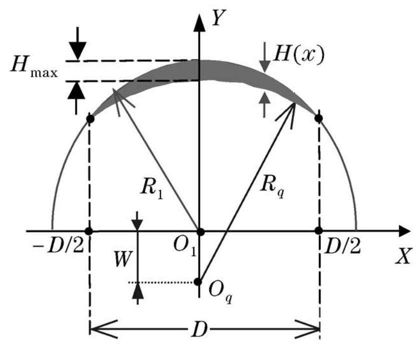

Fig. 1. The geometry relation of cornea sphere ablation thickness (the shadow proportion).

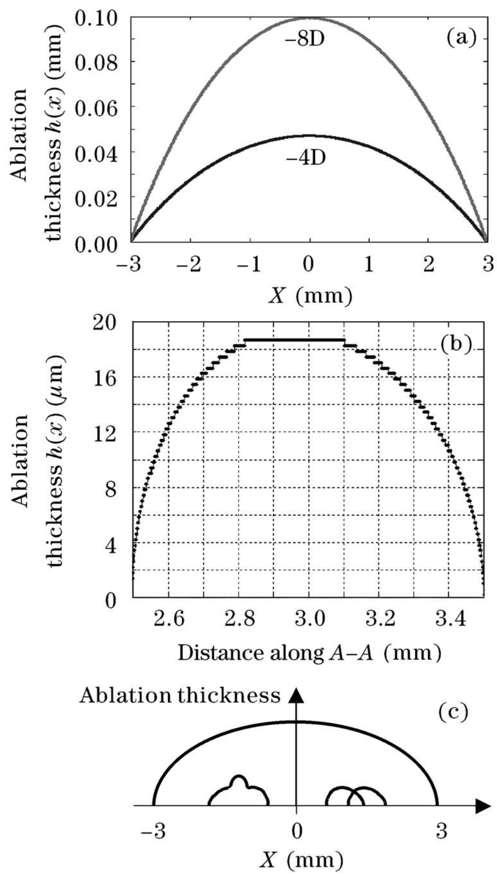

Fig. 2. Ablation curve. (a) Academic ablation curve of −4D and −8D diopter; (b) ablation thickness profile along A-A direction; (c) the overlap effect of spots.

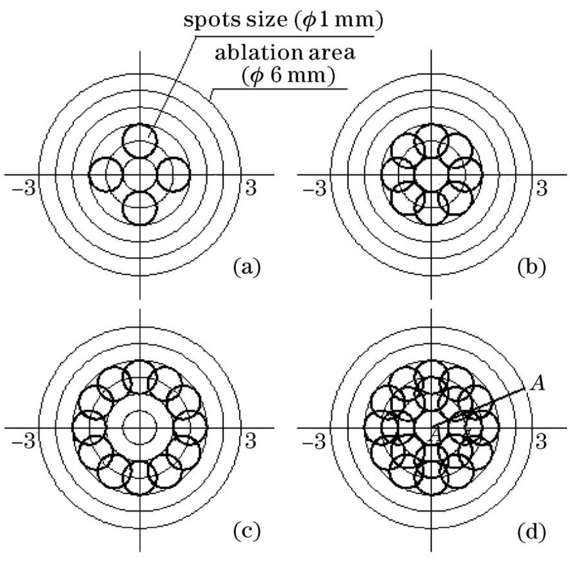

Fig. 3. Ablation tracks model.

the other is the edge of ϕ6 mm ablation area. It rotates round the cornea center clockwise.) to analyze whether the cornea section's ablation shape is near to the academic ablation curve shown in Fig. 2(a). When A-A lies in the horizontal x-axis (right side), the angle is defined as 0°, then it can be easy to get the angles of 1°, 2°, 3°, $\cdots$, 359°, or 0.1°, 0.2°, 0.3°, $\cdots$. Because the spots of every track are distributed averagely, 0° section shape has the representative characteristic of all other angle sections. As to one ablation track, with the help of Matlab software, the A-A section shape is like Fig. 2(b), it is askew toward the cornea center. Then when the other same shape overlaps with it, the ablation effect on the overlapped area will add up together (Fig. 2(c)). Therefore, the whole ablation curve is the effect of outline to add up.

Following the above steps, we take 60 ablation tracks for example. The spacing between two adjacent tracks is 0.05 mm, the position of spots can be considered as 12 cases: distance from spot center to cornea center (in millimeters) $R = 0$, $R = 0.05$, $R = 0.1$, $R = 0.15$, $\cdots$, $R = 0.45$, $0.5 \leq R \leq 2.5$, $2.55 \leq R \leq 3$. Figure 4 shows the $R = 0.45$ case of this ablation model.

To evaluate the ablation effect, radian contribution is considered generally. Take the ninth ablation track for example, see Fig. 4 ($R = 0.45$). When one spot scans on the ablation track, it will result in a small hole effect — 0.2 μm thick and 1 mm in diameter. Takes up 19 ablation tracks, each of them only possesses some proportion of the hole effect, thus define the proportion as the radian contribution measured by the short-wide arc lying in the middle of two adjacent ablation tracks. The radian, not 2π and acquired by two lines from cornea center to the two ends of arc, is equal to $\mathrm{arc}X(M) = 2 \times \arccos \frac{R^2+x^2-0.5^2}{2R\times x}$, x is the radius of the short-wide arc $\widehat{AC}$. Note that there is one 2π radian contribution. When the second spot scans on another position in the same ablation track, it also begets the same hole effect and radian contribution, then adds up the radian contributions for each of the 19 ablation tracks. In the end, each of the 60 ablation tracks has the accumulative total radian contribution $\mathrm{arc}(M)$ (M is from 1 to 60, $\mathrm{arc}(M)$ is the total radian of ablation track M), the corresponding ablation thickness of each track is equal to $hx(M) = \frac{\mathrm{arc}(M)}{2\pi} \times 0.2$ (μm) (0.2 μm is the ablation thickness of one laser spot).

Half of the whole ablation area's average ablation curve is shown in Fig. 5 (the left ablation curve is the same but symmetrical), for comparison, the actual simulation curve and the academic ablation curve educed from

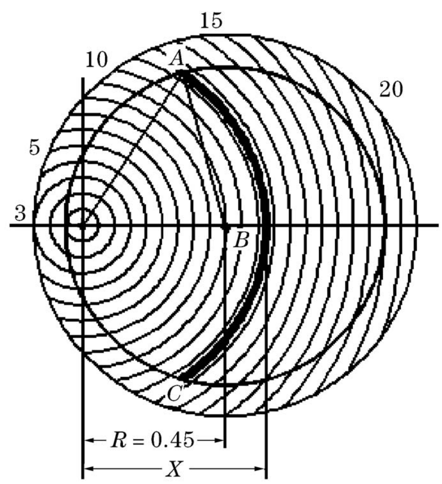

Fig. 4. Example of the 60 ablation tracks model.

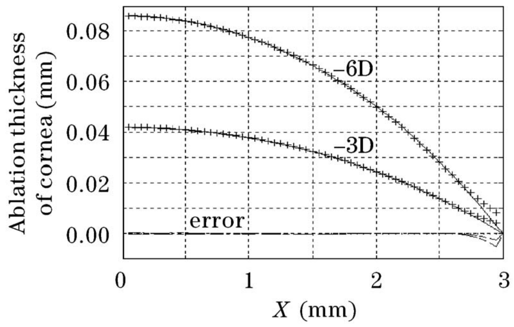

Fig. 5. Average calculation results (crosses) and academic ablation curves (solid curves) of −3D and −6D diopter.

Eq. (1) are given. Obviously, the simulation curve is very near to the academic ablation curve except for the narrow range of [2.65, 3]. So the ablation tracks model is feasible. In fact, patients' eyesight after LASIK has the trend of rebound[7,8], thus to ablate more cornea stroma in order to make up the eyesight rebound amount, that is to say, the simulation curve is permitted higher than the real line curve a little.

Actually, Fig. 5 only illustrates the average ablation effect, it is smooth but cannot reflect the actual section shape, and it also does not discuss the main problem how to arrange the scheduled spots for each ablation track. It is necessary, however, to look over if the arbitrary cornea sections' shapes stand or fall, which also decides the actual ablation effect smooth or not. Therefore, how to ascertain the position for each of the 60 ablation tracks' first spot becomes more important in cornea refractive surgery. There are two cases to account for this problem, one is that they all lie in the same horizontal line, the other is scanning at random.

Consider the case that all the first spots of ablation tracks lie in the horizontal line. It is known that the sections' shapes are symmetrical by the horizontal line, such as 1° and 359°, 90° and 270°, and so on. Take the example of −6D diopter to see the section's shape (other diopters are the similar cases). Figure 6(a) shows the two sections, shapes of 0° and 180°, Fig. 6(b) shows the eight sections' shapes of 0°, 10°, 20°, 30°, 40°, 50°, 60° and 90°. It is clear that the sections' ablation thicknesses near the 0° section are bigger than the academic ablation thicknesses, the shapes are not smooth, too, they fluctuate upon the academic ablation curve greatly, and their errors (the difference between academic thickness and actual thickness) are out of the range of ±5 μm. It is not the ideal ablation model.

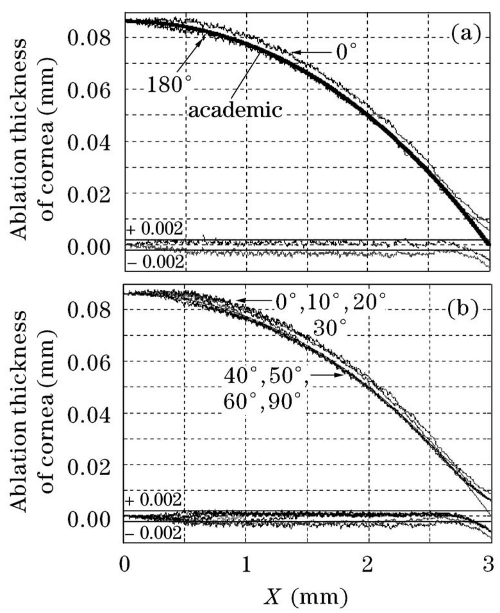

Fig. 6. Sections' shapes of −6D diopter.

Now consider the case of scanning at random. All the first spots of ablation tracks do not lie in the horizontal line, they distribute round their own ablation tracks at random. There are two lines concerned, one is from the spot center to cornea center, the other is the horizontal line. Then the angle formed by the two lines is just the radian to determine the spot's position at each track, the angle is a random number. There exists the problem that different random angles result in different shapes. Because ablation thickness is acquired by ϕ1 mm spots scanning across cornea and overlapping each other. After ablation, there will be a little step between two overlapped ablation areas, where there is more 0.2-μm thickness than the case of not overlapped. On the contrary, because of the 0.2 μm, the actual sections' shapes are not smooth. The key matter is still to improve the

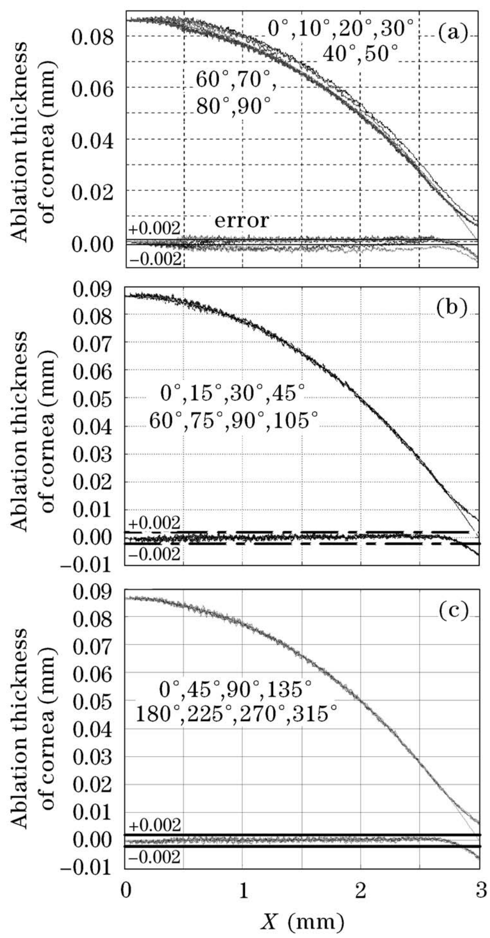

Fig. 7. Different random numbers result in different cornea section shapes. (a) Abnormal random numbers result in the unexpected sections' shapes of −6D diopter; (b) and (c) stochastic sections' shapes of −6D diopter.

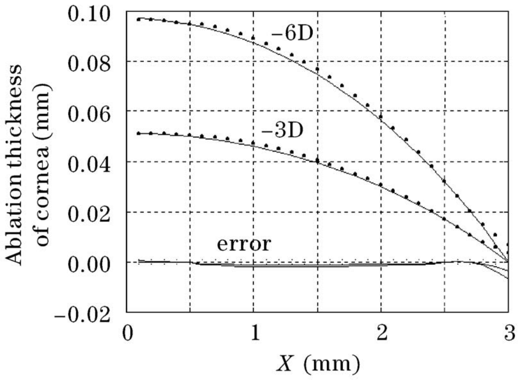

Fig. 8. Average ablation curves (dots) and academic ablation curves of −3D and −6D diopter of 30 ablation tracks.

sections' smoothness. If use the unreasonable random angles, the shapes will be like Fig. 7(a), the ablation errors are out of the permitted range of ± 2 μm greatly, too, they are not the anticipant sections' shapes.

After lots of careful and repeating experiments to decide the reasonable random angles (calculated by computer automatically), the reasonable shapes are obtained, as shown in Figs. 7(b) and (c). Obviously, they almost overlap together with academic thickness, all the errors are within the range of ± 2 μm and fluctuate little. It meets the demand of cornea LASIK surgery completely.

For comparison, we decrease the number of ablation tracks to 30. Because the ablation tracks are only half of the above case, it is inevitable to adjust the number of spots for each of ablation tracks. In Fig. 8, the average ablation curves of −3D and −6D diopter approach to the academic curves, respectively. The limitation is that the spacing between two adjacent ablation tracks is 0.1 mm, which results in the steps between two overlapped spots bigger than the case of 60 ablation tracks, and the smoothness is worse obviously. Besides, the average ablation curves are higher than the academic curves, that is the reason of making up eyesight rebound after LASIK.

Because of the feasibility of 60 ablation tracks model, it is used to the PMMA experiments to demonstrate its accuracy of rectifying anisometropia. From the data listed in Tables 1 and 2, it is clear that the results is perfect.

From the above discussion, as for each of the 60 ablation tracks' first spots positions, the case of spots scan at random is superior to the case of spots scan in the same horizontal line. Therefore, with the result of PMMA experiments, it becomes the preferred ablation scanning model for the following surgery experiments such as animal experiment and clinical experiment. Compared with some other refractive surgery technology and data[9,10], the above ablation model is easy to understand and the ablation precision satisfies the demand of rectifying anisometropia completely.

Table 1. Results of PMMA Experiments for Myopia

Inputting	Result				Rectified
Diopter	A	B	C	Average	Diopter
−1D	28	26	27	27	89.1
−2D	64	63	66	64.3	212.2
−3D	95	94	95	94.7	312.5
−4D	123	119	120	120.7	398.3
−4D	121	118	121	120	396
−5D	151	150	153	151.3	499.3
−6D	182	180	181	181	597.3
−7D	212	209	210	210.3	693.9
−8D	236	240	245	240.3	792.9
−9D	269	273	271	271	894.3
−10D	301	298	295	298	983.4

Table 2. Results of PMMA Experiments for Myopia and Astigmatism

Inputting Diopter	Result	Rectified Diopter
206DS/330DC	70DS(H)/155DC(V)	231DS/280.5DC
330DS/330DC	100DS(H)/195DC(V)	330DS/313.5DC

Z. Zhu's e-mail address is zzq781011@sina.com.

References

1. G. Deng, Y. Liu, and Z. Zhu, Acta Laser Biol. Sin. (in Chinese) **13,** 358 (2004).
2. L. Liu, *Modern Eyes Refractive Surgery Subject* (in Chinese) (People Army Surgery Publishing House, Beijing, 1995) p.209.
3. H. Jiang, Y. Yu, Z. Lu, and H. Zhou, Acta Laser Biol. Sin. (in Chinese) **7,** 249 (1998).
4. G. Deng, Y. Yu, N. Zhao, and Z. Zhu, Chin. J. Med. Phys. (in Chinese) **21,** 267 (2004).
5. Y. Hu and L. An, *Applying Optics* (in Chinese) (Publishing House of University of Science and Technology of China, Hefei, 1996) p.41.
6. J. Zhang, *Eyes Refractive Surgery Subject* (in Chinese) (He'nan Science and Technology Publishing House, Zhengzhou, 1996) p.51.
7. Z. Lin, J. Shen, and W. Liao, Laser Technology (in Chinese) **27,** 510 (2003).
8. X. Jin, J. Lian, D. Zhou, and K. Wang, Chin. J. Laser Med. Surg. (in Chinese) **11,** 37 (2002).
9. J. R. Jiménez, R. G. Anera, L. Jiménez del Barco, and E. Hita, Appl. Phys. Lett. **81,** 1521 (2002).
10. P. Homolka, R. Biowski, S. Kaminski, T. Barisani, W. Husinsky, H. Bergmann, and G. Grabner, Phys. Med. Biol. **44,** 1169 (1999).