Customized Corneal Ablation and Super Vision

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ABSTRACT

PURPOSE: To review the early development of new technologies that are becoming available through customized corneal ablation techniques.

METHODS: The authors describe the early development of two diagnostic methods to perform customized corneal ablation as well as a variety of new treatment modalities in development.

RESULTS and CONCLUSION: Results using the wavefront sensors indicate that these techniques have the potential to be more sensitive than traditional refraction and keratometry. Subtle defects such as coma and spherical aberration can be detected and treated. A whole series of new technologies are being incorporated to treat patients with customized corneal ablation. [*J Refract Surg* 2000;16(suppl):S230-S235]

Customized corneal ablation and super vision represents an exciting new area of development that may have dramatic impact on the future of refractive surgery.

Over the past year, we have seen intense interest in the use of wavefront-guided ablation. On June 12, 1999, Theo Seiler, MD, PhD, treated the first patient with customized corneal ablation and improved the best spectacle-corrected visual acuity from a preoperative 20/12 to 20/10. Four months later, Marguerite McDonald, MD, treated another group of patients with customized ablation and was able to obtain subjective improvement in their vision compared to the contralateral control treated eyes.

These studies were based on findings by Liang and Williams[1] in 1997, who demonstrated that with wavefront analysis and adaptive optics, they were able to improve polychromatic high spatial frequency vision two-fold, particularly in low light conditions with the pupil dilated. Liang and Williams were able to improve vision to the 20/10 level reliably and create supernormal-type vision in normal subjects. These findings subsequently sparked early investigators and the laser companies to explore these techniques to see if they could improve vision beyond the 20/20 level using a refractive surgical laser. This article explores some of those diagnostic techniques and how they might be coupled to the excimer laser to improve excimer laser results.

PATIENTS AND METHODS

We used a Shack-Hartmann (Hartmann-Shack) wavefront sensor to evaluate wavefront error in a small group of patients.[2] The system (Fig 1) uses a

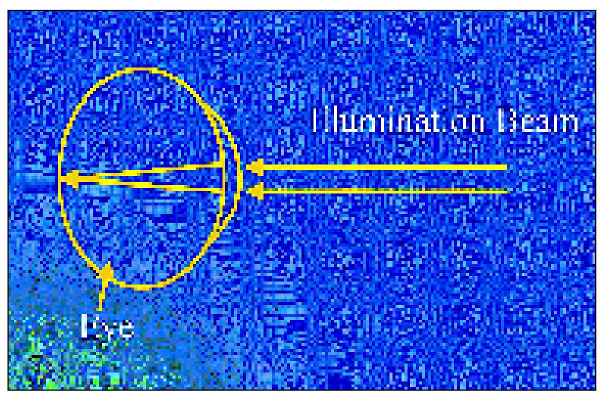

Figure 1. Shack-Hartmann wavefront sensing utilizes a narrow illumination beam going into the eye and focusing to a diffraction-limited point on the retina. The light scatters off the retina and back out of the eye.

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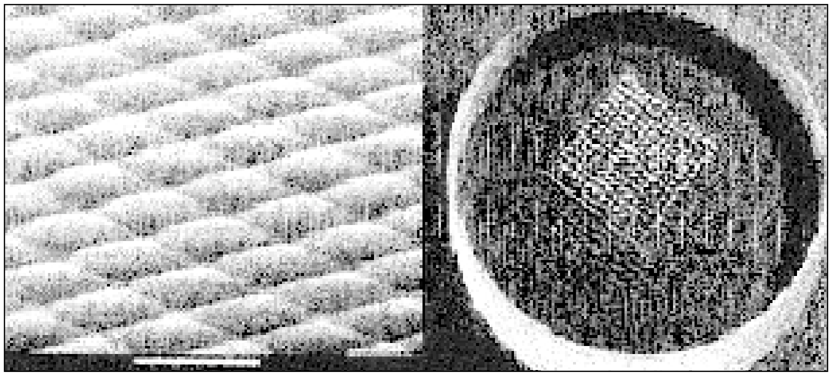

Figure 2. Demonstrates the tiny lenses or lenslet array that take the exiting rays of light and break them up into small points. The image on the left demonstrates a high magnification of the lenslet array. The magnification on the right is a lower magnification showing the tiny lenslet array.

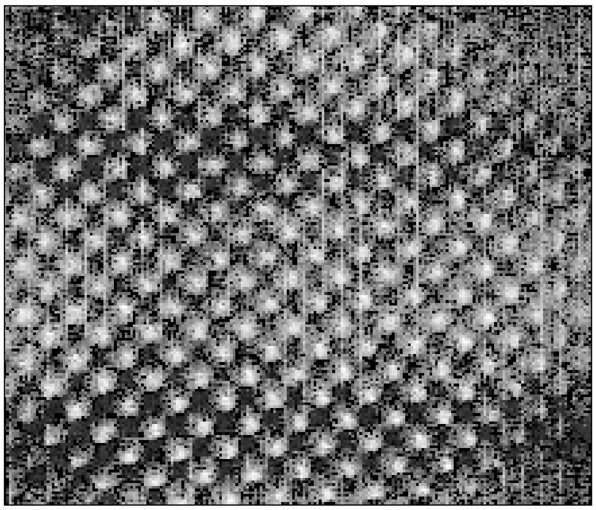

Figure 3. Actual captured video image of the light after it passes out of the eye and through the lenslet array.

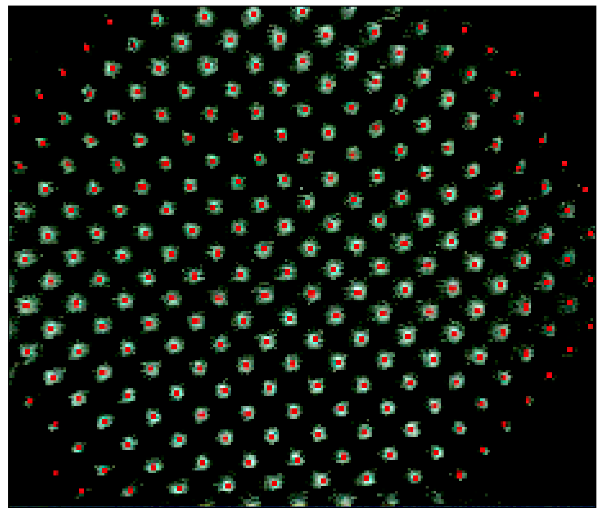

Figure 4. The center points of light in Figure 3 have been located and marked with red marks. X and Y coordinates are then identified and mapped. This pattern is compared to an ideal pattern, with no optical aberrations

narrow illumination beam that goes into the eye and focuses into a diffraction limited point on the retina. The light reflects off the retina and comes back out the eye.

The light exiting the eye is then passed through an array of tiny lenses (the lenslet array, Fig 2) and focused onto a video camera. Figure 3 shows the actual captured video image of the light after it passes out the eye and through the lenslet array. Small points of light appear in a symmetric grid under normal conditions. One can find the center of focus of each of these small points (Fig 4) and identify the X-Y coordinates of each. This pattern is compared to an ideal pattern with no optical aberrations. The ideal pattern can be shown and compared to the actual pattern (Fig 5).

Figure 6 (left) demonstrates the normal, regular pattern that one sees using the Shack-Hartmann instrument where there is a plain wavefront with a uniform grid pattern. Notice that the spacing is regular. In Figure 6 (right), one notices a slight irregularity which may be caused by either corneal or lenticular wavefront aberration. These cause aberrated wavefronts which secondarily cause a distorted grid pattern after the light passes through the lenslet array (tiny lenses).

Using this technique, we can compare a normal individual, shown in Figure 7 (left), who has a regular pattern with little spherical aberration or coma, with subject #2, who has a good pattern in the central 2 mm. But, as one moves away from the central 2 mm, there is increasing spherical aberration present (Fig 7 right). This is noted as the red points are further away from the blue points peripherally, indicating defocus. Figure 8 demonstrates that one can correct the optical aberrations of the eye either with a customized contact lens or corneal ablation. The color wavefront maps (Figs 9, 10, 12) demonstrate height deviations from a perfect planar wavefront (ideal) measured at the pupillary plane. The

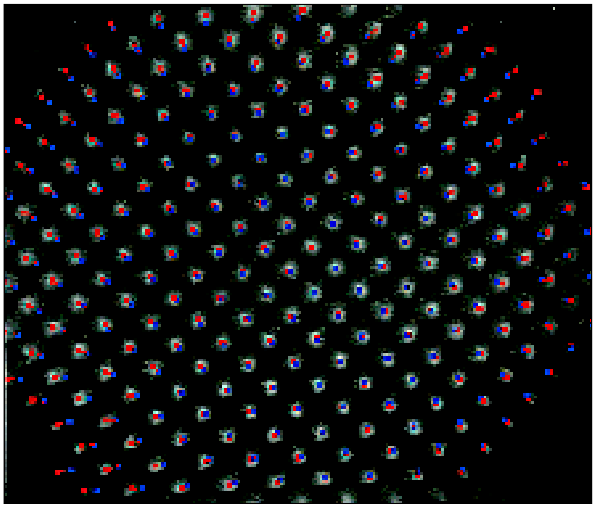

Figure 5. Demonstrates the center of the actual points of light shown in red compared to the ideal position if there was no optical aberration, which is shown in blue.

spherical equivalent refractive error is subtracted out to demonstrate higher order aberrations. The wavefront sensor-guided correction takes into account all the optical aberrations of the eye.

RESULTS

In our early work, we evaluated a number of different conditions with the Shack-Hartmann wavefront sensor. These are some examples of our early findings. Subject #1 (Fig 9) is a 31-year-old with no history of refractive surgery. The clinical refraction was -0.50 diopters (D) of spherical refractive error at the time of wavefront testing. The spherical error was subtracted out, leaving coma, spherical aberrations, and higher order aberrations. One can see the minimal wavefront error present. This is reflected in the smooth deep red pattern that indicates relatively little wavefront error over the central 6 mm of the exit pupil.

Subject #2 (Fig 10) had -5.00 D of spherical myopia before excimer laser surgery. The patient underwent an uneventful laser in situ keratomileusis (LASIK) and 4.5 months later, the refraction was -0.25 +0.75 x 70° which resulted in 20/20-1 visual acuity. The wavefront error map shown in Figure 10 demonstrates relatively little optical aberration in the central 2.5 mm. Beyond this, however, there is considerable spherical aberration. This patient was not particularly symptomatic under scotopic conditions, but this does point out the large amount of spherical aberration that is well demonstrated with wavefront testing.

We also evaluated a 22-year-old male with mild keratoconus. The patient's refraction was -5.50 +2.25 x 180° which yielded a visual acuity of 20/25. The corneal topography using the TMS Computed Anatomy System demonstrates the asymmetric bowtie pattern, typical of keratoconus (Fig 11). Figure 12 demonstrates the wavefront mapping which is relatively normal superiorly. As one moves inferiorly, however, there is elevation of the cornea and marked wavefront error, dominated by coma, consistent with moderate keratoconus.

DISCUSSION

The above cases represent early results using a Shack-Hartmann Wavefront Sensor. As this system becomes more refined, we believe more detailed data will be useful in guiding customized ablation.

There are two major new forms of customized ablation being performed (Table).[3] The first is

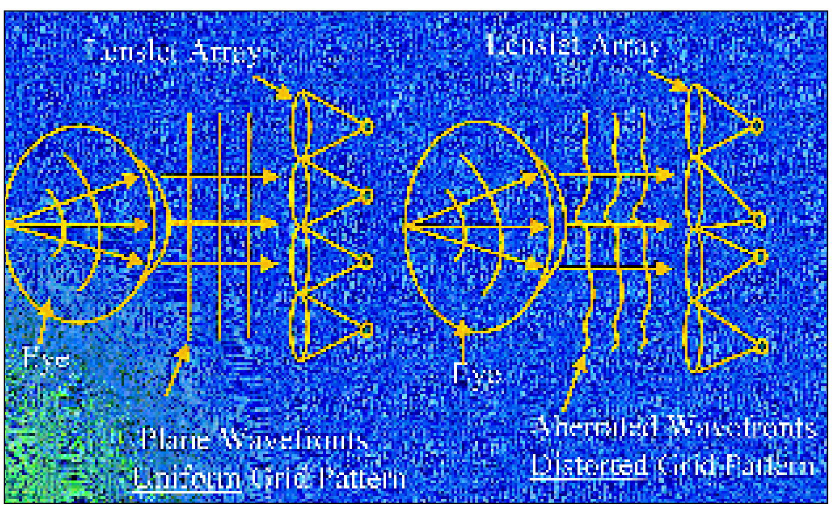

Figure 6. Left: Diagram shows the regular pattern one sees when using a Shack-Hartmann wavefront sensor in which there is a plane wavefront with a uniform grid pattern. The spacing of the light points is very regular. **Right:** Notice the slight irregularity of the light points caused by optical aberrations in either the lens or cornea. This creates a distorted grid pattern.

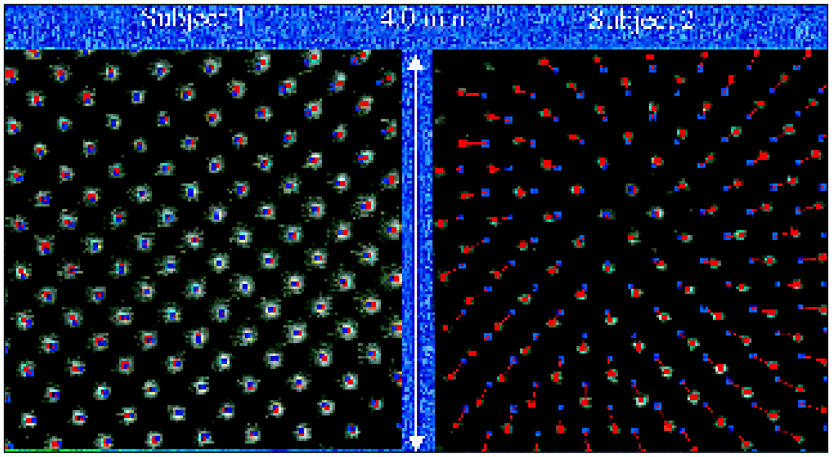

Figure 7. Left: Demonstrates a subject with a very regular pattern and little spherical aberration or coma. Note how the blue and red points mostly overlap. **Right:** A patient treated with LASIK has good superimposition of the light points centrally but there is separation of the red points (actual pattern) and the blue points (ideal pattern) as one moves peripherally, indicating spherical aberration.

Table
Current Customized Ablation Systems

Customization Based on Corneal Topography	Customization Based on Wavefront Measurements
VISX — CAP	Shack–Hartmann (Hartmann–Shack)
B & L — Orbscan II	Wavefront Sensing 1. B & L 2. Autonomous 3. VISX
Nidek — ARK-10,000	Aberrometer (Howland and Howland)
Lasersight — Orbscan	Tscherning Method (Seiler)
MEL-70: TOSCA - TSA	Slit Light Bundle Nidek ARK-10,000

customization based on corneal topography. There are a number of companies developing custom ablation based on corneal topography, including VISX, Inc. (employs a CAP method that uses the Humphrey Topographer), Bausch & Lomb, Inc. (employs topography-guided ablation using the Orbscan system), and Nidek, Inc. (employs the ARK-10,000, description follows). Lasersite employs the Orbscan for their Topographically Linked Guided Ablation. The Meditec system utilizes the Mel-70 with a system they call TOSCA-TSA. All of these systems use corneal topography in an attempt to calculate a height map. From the height map they can determine the deviation from a preferred uniform surface and direct the laser to subtract tissue from the relatively elevated areas.

The second form of customized ablation is based on wavefront measurements. There are a number of systems available, including the Shack-Hartmann (Hartmann-Shack), Cross-cylinder, and Tscherning Aberrometers, (as used by Dr. Theo Seiler), and the slit light bundle, used by Nidek. The Nidek System combines a slit light bundle sensor with a placido topography system for evaluation.

There are also two other systems that are not coupled to lasers at this time; TRACEY, a single pass system that uses a form of laser raytracing to detect aberrations, and the spatially resolved refractometer that can also detect irregularities and allows the patient to subjectively remove the irregularities using a hand toggle control.

Nidek ARK-10,000

The Nidek ARK-10,000 (Gamagori, Japan) uses a unique way to capture wavefront deviation information, employing a slit light bundle that scans onto the retina for each meridian. In 0.4 seconds, 1,440 measurements are taken. The reflected light is then detected by photo-detectors. The photo-detectors are located at 2.3, 3.2, 4.4, and 5.5 millimeters. This data is then converted to a refractive power map. There is also a placido-computerized corneal topography system built into the system. The placido rings are used to measure corneal topography simultaneously with slit light bundle data collection. The information from the Nidek ARK-10,000 can then be used in a simulation system called the "The Final Fit Software" (Fig 13). This simulates the postoperative shape from which one can calculate the ablation depth.

Nidek Segmental Small Area Ablation

One can then take this information and input it into the Nidek EC-5000 excimer laser segmental ablation program. The date and shot number can be calculated at each coordinate. The segmental ablation program can treat small area ablation of a millimeter or less. The Nidek segmental ablation

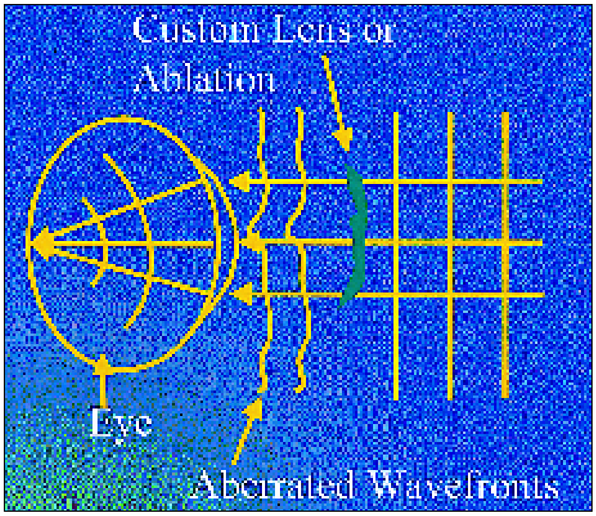

Figure 8. Representation of how irregular aberrations can be corrected either with a customized lens or a customized corneal ablation. The compensation that occurs for the aberration forms a diffraction-limited image on the retina. This results in better visual acuity and contrast sensitivity.

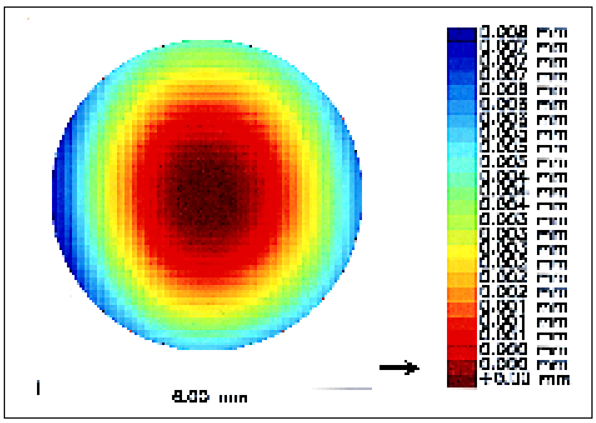

Figure 10. Subject #2 was treated for 5.00 D of spherical myopia with LASIK. This wavefront error test was done 4.5 months after LASIK. The patient's manifest refraction was -0.25 -0.75 x 70°, which resulted in 20/20 visual acuity. Note that there is little optical aberration in the central 2.5 mm of the map but outside this diameter, there is considerable spherical aberration as indicated by the blue color peripherally.

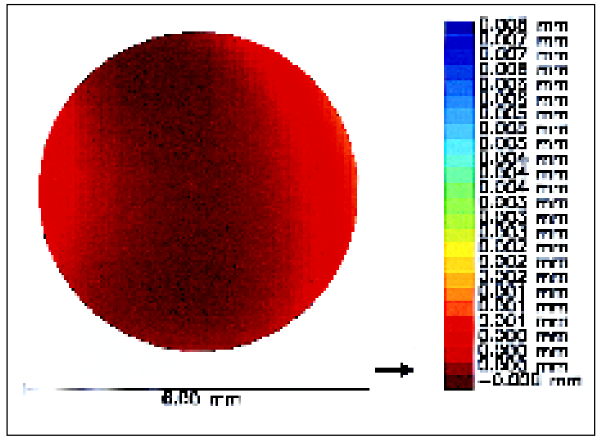

Figure 9. Subject #1, a 31-year-old with 0.50 D of spherical myopic refractive error at the time of wavefront sensing. There is minimal wavefront error present as indicated by the large area of dark red color. The dark red areas indicate that there is little deviation from an ideal pattern based on height mapping using the Shack-Hartmann wavefront data.

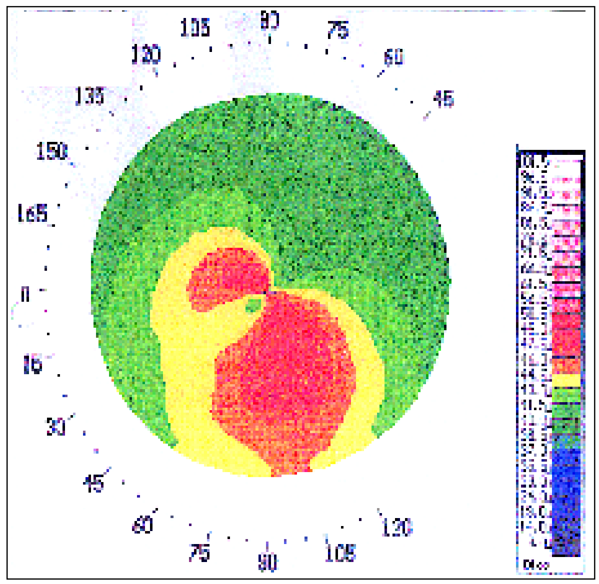

Figure 11. Corneal topography of Subject #3, a 22-year-old male with mild keratoconus. His refraction was -5.50 +2.25 x 180° with a visual acuity of 20/25. The topography demonstrates asymmetric astigmatism typical of keratoconus.

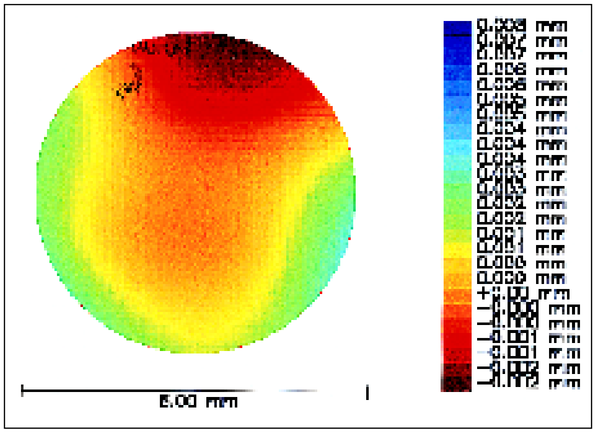

Figure 12. A wavefront map of Subject #3 (see Fig 11) with keratoconus. Notice that the superior portion of the wavefront map is relatively normal. The inferior portion shows significant optical aberration, dominated by coma.

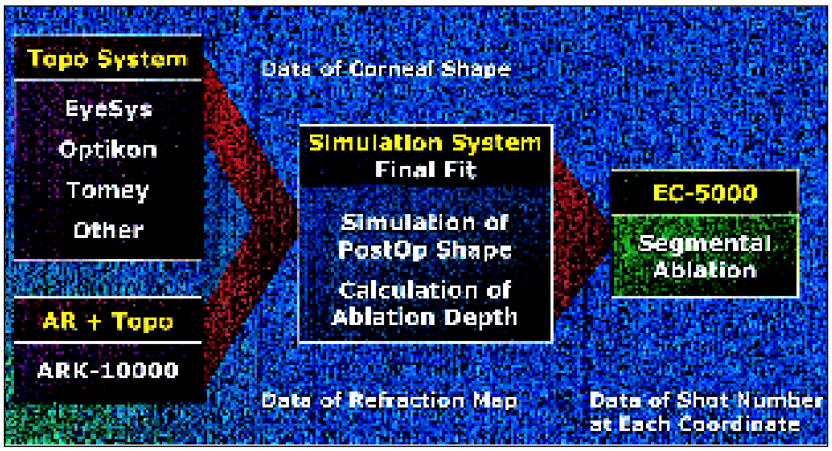

Figure 13. Data flow for the Nidek final fit custom ablation sofware. This system can take corneal topography information from various corneal topography units or the Nidek ARK-10,000, or refractive power data from the ARK-10,000, and integrate this information into a computer simulation that calculates the depth of tissue removal. This can then be input into the Nidek EC-5000 excimer laser to be used with segmental small area ablation.

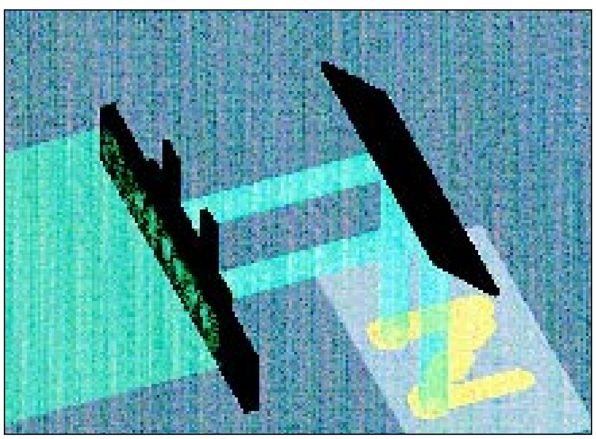

Figure 14. Representation of the Nidek EC-5000 excimer laser segmental small-area (1.0 mm) ablation system. The segmental ablation system has six apertures, 1.0 mm in diameter. Several apertures can be used simultaneously for more efficient treatment.

uses six apertures that give a 1-mm spot size (Fig 14). Several apertures can be opened simultaneously for more efficient treatment across the treatment zone. The treatment zone is 10 mm. The segmental small area ablation can treat either spherical or aspheric patterns. It can also treat subtle irregularities and aberrations to create customized ablation.

We think these types of wavefront testing systems are a valuable tool to assess a patient's aberrations to a much finer degree than was formerly possible, and point the way to a truly customized ablation. Each of these systems has advantages and disadvantages in terms of detecting wavefront error and surface abnormalities. In the future, it will be critical to assess which system performs better under a variety of clinical conditions.

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