Technology Requirements for Summit-Autonomous CustomCornea

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With the recent surge of interest in wavefront sensing technology as a new diagnostic tool in refractive surgery[1,2], the concept of wavefront customized correction has now come to the forefront. [3,4] Among the companies leading this effort, the Summit-Autonomous Technologies provides a technology platform within CustomCornea which can be used as a model for wavefront ablation requirements.

Although the technology requirements for wavefront guided ablation are unique to a given laser and wavefront sensing device, the essential components can be summarized in part by using the example provided by a specific company and a specific technology platform, namely CustomCornea.

SCANNING SPOT DELIVERY

Spot Size and Shape

Although many of today's commercially available excimer laser systems have beam diameters which vary in size and profile shape, it is the small scanning spot of guassian shape that is the essential first requirement for wavefront customized ablation. A gaussian beam allows for very uniform overlap in the creation of a smooth customized ablation profile.

This is in contrast to a top-hat beam created by concentric iris apertures, which produce sharp ablation edges that may overlap in the laser vision correction profile. Additionally, the size of the spot must correspond to the resolution of aberrations being treated. Mathematical calculation of the spot ize required to correct fourth order aberrations within an optical ablation zone diameter of 6 mm require a spot size of ≤1 mm (unpublished data). Therefore, scanning spot lasers larger than 1 mm would not adequately treat the most common of higher order aberrations, namely spherical aberration and coma.

In a study of small spot scanning, a 2 mm top-hat beam profile results in performance degradation of both low and high spatial frequency during custom ablation.[5] This is in contrast to a 1 mm gaussian beam, which shows good performance when treating both high and low spatial frequency aberrations.[5] The Summit-Autonomous LADARVision laser uses a 0.8 mm gaussian spot during both its conventional and CustomCornea ablations.

Spot Scanning Rate

The majority of the small spot gaussian profile lasers use a spot scanning rate of approximately 200 Hz. The Summit Autonomous LADARVision laser, however, uses a spot scanning rate of only 60 Hz. Even though the spot frequency for the LADARVision system is considerably slower than the other small spot scanning lasers, the actual ablation time is shorter with the LADARVision (8 seconds per diopter) than when using the LaserSight LSX system. This is because of the slightly higher fluence and volume ablated per shot with the LADARVision system.

The frequency of spot placement is important with regard to hydration changes, as treatments that take too long, can adversely affect tissue hydration. The scanning spot, however, must not be more rapid than a rate which can be adequately followed by the tracking system. This will be discussed in the next section.

Finally, a scanning spot must also be nonsequential in its pulse placement (one spot not directly placed next to the following spot), to avoid thermal buildup and improper plume evacuation during treatment. Figure 1 presents the nonsequential spot placement of the LADARVision system.

The Three S's of Scanning Spot

Despite the fact that CustomCornea requires a small, scanning spot, additional benefits of scanning spot technology are evident in the "Three S's" which

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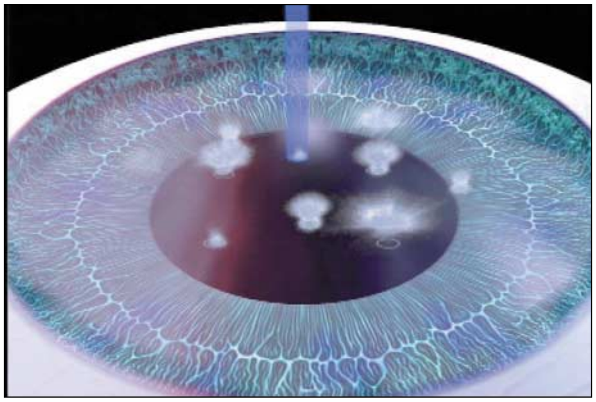

Figure 1. Nonsequential spot placement of the LADARVision system demonstrating adequate space to avoid interference with the evacuation plume and thermal build up between pulses.

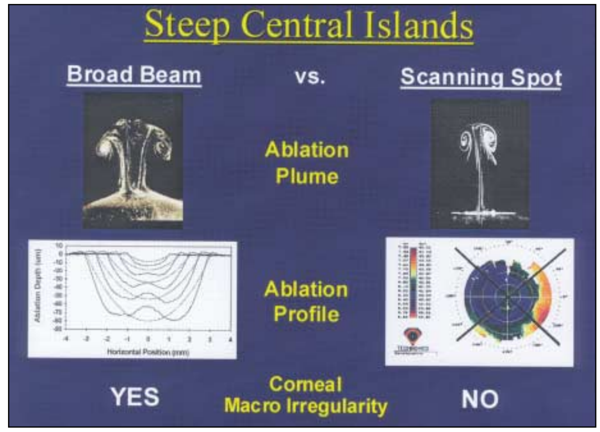

Figure 2. Ablation plume with a broad beam laser delivery demonstrating a central vacuum (arrow) which traps the effluent and shields the subsequent pulse (top left). This is in contrast to the ablation plume with scanning spot laser delivery which does not trap particles or shield subsequent pulse placement (top right). As a result the profilometry of broad beam ablation in plastic (PMMA) demonstrates peripheral overcorrection and central undercorrection (bottom left) leading to the formation of a steep central island. Scanning spot delivery does not lead to steep central islands (bottom right).

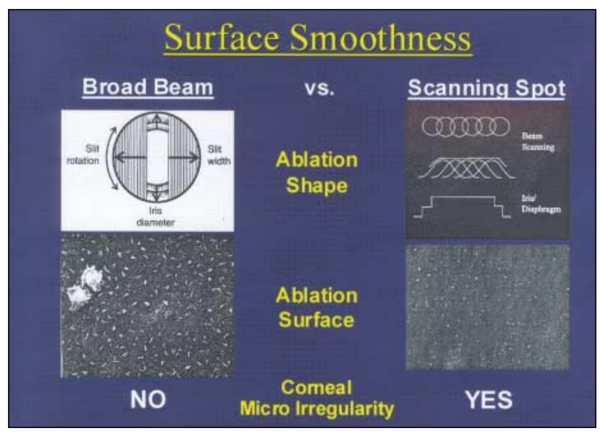

Figure 3. Scanning electron micrographs (SEM-1000X) of the ablated surface of paired fresh human cadaver eye corneas treated with a) Summit Autonomous LADARVision laser and b) VISX 20/20B. Note the smoother surface when using the scanning spot laser in comparison with the broad beam delivery.

in turn further support the safety and precision of CustomCornea.

Steep Central Islands—When using a broad beam laser, steep central islands have been found to occur in as much as 80% of eyes treated with photorefractive keratectomy (PRK).[6] The unwanted formation of steep central islands led to the development of special ablation software to compensate for their formation. Yet even after implementing anti-central island software, they frequently still occur.

The proposed mechanism for steep central island formation has been attributed to a micro explosion phenomena on the corneal surface during photoablation. This occurs due to a central shielding of subsequent pulses from trapped particles within the center of the broad beam, as well as the accumulation of central fluid.[7] Figure 2 demonstrates the ablation plume with a broad beam, which causes a central vacuum (arrow), trapping the plume particles and shielding subsequent pulse placement. The narrow plume with a small spot laser does not show any central attenuation. Profilometry of broad beam ablation in plastic demonstrates peripheral overcorrection with central undercorrection.[8] Since this profilometry was performed in plastic, the total explanation of central islands being due to accumulation of fluid would here be unsubstantiated.

The formation of steep central islands does show the presence of a macro irregularities with broad beam treatment, which are not present when using a small scanning spot.

Surface Smoothness—Concern over microscopic smoothness of the beam has been a long-standing issue. Broad beams are noted as having a variety of inhomogeneities and hot spots within the beam. Scanning spot ablation with perfect overlap when using eye tracking demonstrates no inhomogeneities or hot spots. This results in the greater smoothness of scanning electron microscopy (SEM) after LADARVision treatment versus that of a broad beam laser (Visx 20/20B) as noted in Figure 3.

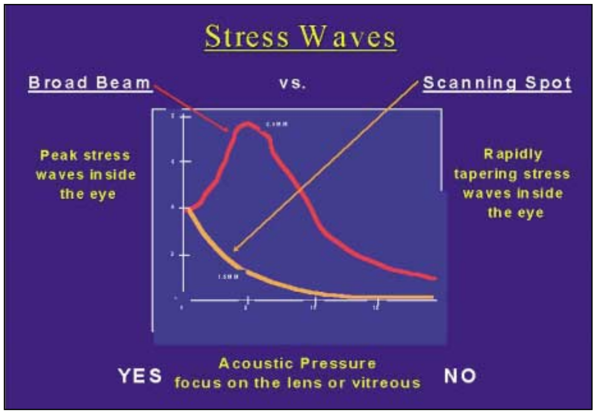

Figure 4. Stress wave amplitudes as measured with a hydrophone within a porcine eye treated with differing excimer laser beam diameters (1.5 mm to 7.5 mm). Note that with a 1.5 mm beam the stress wave quickly dissipates as it travels through the eye, while beams >3 mm develop a pressure focus. This pressure focus is 7 to 8 mm posterior to the cornea (posterior lens/anterior vitreous) in human eyes.

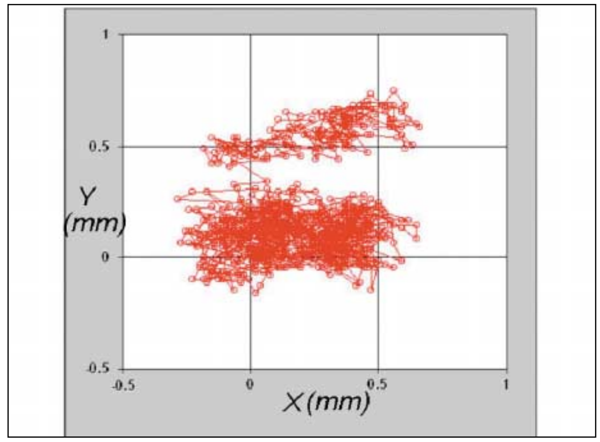

Figure 5. Recorded tracing of fixation-related eye movement during LADARVision tracking which demonstrates multiple saccades extending greater than 0.7 mm both horizontally and vertically from the point of fixation.

Recently, unpublished studies by Yee and colleagues confirm this observation (Richard Yee, MD, American Society of Cataract and Refractive Surgery, 2000). Smoother surfaces are believed to result in better healing and outcome, but this idea has not been substantiated. Smoother surfaces, however, would certainly be predictive of greater precision in wavefront customization, which is another benefit of scanning spot delivery.

Stress Waves—The impact of excimer laser photoablation on the cornea produces a stress wave, which propagates through the eye[9] as well as an ablation plume projected away from the eye.[10] The energy and speed of particulate ejection from the cornea is matched by an equal but opposite energy directed into the eye.

The magnitude of this excimer laser induced stress wave is approximately 40 atmospheres at the plane of the cornea.[9] With a small spot ablation (<1.5 mm) this energy quickly dissipates beyond the corneal endothelium. However for larger spots (>3 mm), a pressure focus is found 7 to 8 mm behind the corneal endothelium at the level of the posterior lens or anterior vitreous (Fig 4). For a 6 mm diameter beam, the magnitude of the pressure focus is approximately 80 atmospheres.[9] This additional acoustic stress at the anterior vitreous and lens may lead to vitreoretinal or lens abnormalities. Although the incidence of retinal detachments after PRK or LASIK is no greater than the general population11, a case of bilateral giant retinal tears with detachment has been recently reported after bilateral LASIK bringing the impact of this acoustic effect into question.[12] Once again we see the potential benefit of scanning spot delivery.

Very Fast Eye Tracking

Fixation-related Eye Movements—During patient fixation frequent saccadic eye movements have been recorded which are random, about 5 times per second, and at a rapid rate proportional to distance traversed.[13] These characteristics of fixation-related saccadic eye movements make careful treatment of patients requiring laser vision correction impossible without the aid of a sophisticated eye tracking system. Typical fixation related saccades traverse a distance of 1 to 10° (0.1 to 2.0 mm) at a rate of 100 to 800 degrees/second (22 to 170 mm/second).[13] An example of the extent of random movement noted with fixation during laser vision correction is shown in Figure 5. This figure shows translational movements extending greater than 0.7 mm in both the X and Y direction from the point of original fixation. The fastest saccadic eye movements are recorded and measured at greater than 10° (2.0 mm) at a rate of up to 800°/second (170 mm/second).[13-15] The speed of this movement is fast enough to allow the globe to rotate greater than twice within the orbit for each one second. Only a very fast eye tracking system can follow this type of movement during laser vision correction.

Eye Tracking of Significant Eye Movements—To adequately follow and track saccadic eye movements during fixation, a 100 Hz closed-loop

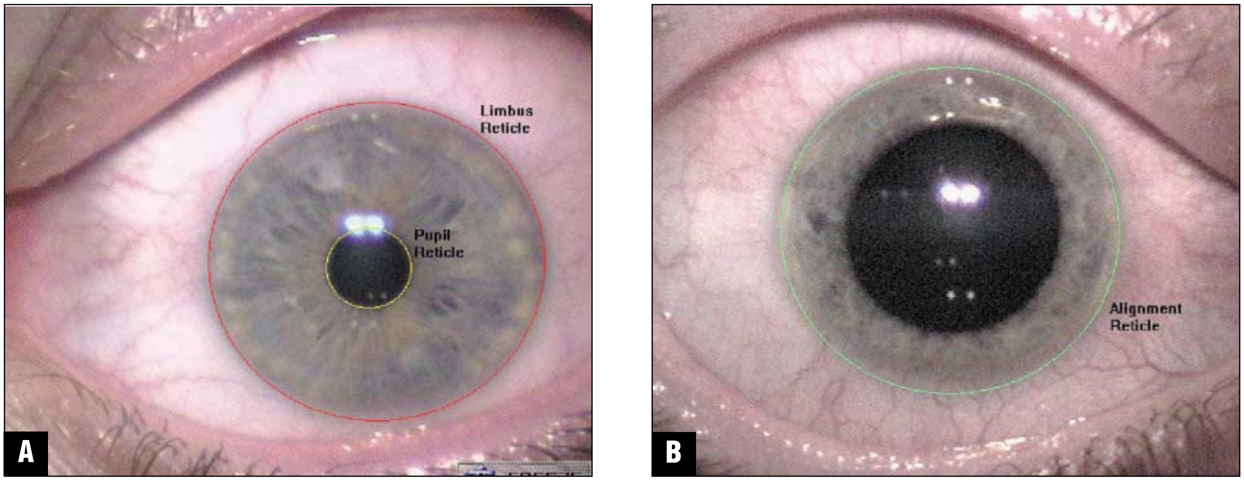

Figure 6. A) Centration step outlining and recording the undilated pupil (yellow circle) relative to the limbus (red circle). **B)** Alignment step, overlaying the limbus reference mark (green circle) over the actual limbus during laser radar eye tracking. Centration from the undilated pupil relative to the limbus is achieved by tracking the dilated pupil margin relative to the limbus.

bandwidth tracker is required. To understand what this means in relation to the tracker sampling rate, the closed-loop tracking frequency (sampling rate) must be approximately 10 times the desired tracker bandwidth (10 X 100 = 1,000 Hz). At present, LADARVision is the only tracker in which the sampling rate (4,000 Hz) exceeds 10 times the optimal tracker bandwidth.

LADARVision tracking compensates for saccadic eye movements by laser radar. This works by implementing two subsystems: detection and response.

The detection subsystem utilizes a 905 nm diode laser signal which is transmitted and received 4000 times each second, locating the position of the dilated pupil margin. This detection subsystem is intimately connected to the tracking servo-mirrors, which are repositioned quickly in less than 10 milliseconds. Hence the closed-loop bandwidth response time of the tracker mirror assembly combined with the laser radar signal is greater than 600 radians/sec or about 100 Hz.[16,17]

The laser radar device senses the position of the pharmacologically dilated pupil margin after capturing the position of the undilated pupil in reference to the limbus using the graphical user interface of the laser's computer. Figure 6 demonstrates the centration step (Fig 6A) outlining the undilated pupil in reference to the limbus, as well as the alignment step (Fig 6B) redefining the position of the limbus on the graphical user interface prior to engaging the eye tracker. Once engaged, the eye tracker locks onto the dilated pupil margin and the tracked image verifies that the laser sees an unwavering image of the eye even during fixation related saccades and nystagmus.

Comparison of Laser Radar and Video Camera Eye Tracking

The closed loop bandwidth tracking frequency of 100 Hz achieved by the LADARVision system can be compared with various infrared video camera tracking systems only in part because most video camera tracking systems are described as open loop when considering their bandwidth frequency. This means that for each observed change in the position of the pupillary reflex in the video camera based tracker, the servo-mirrors have an opportunity to respond or

Table
Comparative Features of Eye Tracking in Scanning Spot Excimer Lasers

Features	LADARVision	Video Camera
Laser system	Autonomous	Technolas (120) Nidek, Visx (60) Lasersight (60) Wavelight (250)
Method	Laser radar	CCD/Infrared
Transmittal signal	905 mm diode laser	none
Detection frequency	4,000 Hz	60, 120, 250 Hz
Response time	3 ms rise time (100 Hz bandwidth)	50 ms rise time (6 Hz bandwidth)

not respond to that change. For many of these systems the scanning rate of the laser matches or may be slightly faster than the tracking frequency. The most frequently used video camera tracking rate has been 60 Hz, being limited by the frame rate of the camera. Faster, more sophisticated video camera technology has allowed this to be expanded up to 120, 250, and 300 Hz in some systems. When considering that a tracker sampling rate needs to be 10 times the actual tracker bandwidth frequency, these video camera based trackers at best achieve a 6 Hz to 30 Hz tracker bandwidth frequency. The Table outlines the comparative features of eye tracking in scanning spot excimer lasers.

Although the VISX Smooth Scan is considered a broad beam laser with modified scanning features, it is considered in the table for comparison. Although the table makes a comparison of the tracker detection frequency and bandwidth frequency, this only applies if the eye tracker is a closed loop system. Open loop systems can only respond to an individual sample without truly locking on to the position of the eye. Many video camera based tracking systems are only available internationally outside the United States, and even in these locations, are intermittently used or not used at all.

In a study of ablation centration after active eye tracking during PRK and LASIK, a mean decentration of 0.33 mm (PRK) and 0.35 mm (LASIK) was consistently observed despite the use of an eye tracker (50 Hz Schwind Multiscan).[18] The conclusion was that active eye tracking alone did not ensure good centration and that patient cooperation and fixation were important. This conclusion, however, does not consider the magnitude and frequency of fixation-related eye movement found despite the cooperation of the patient, nor does it consider the limited tracking frequency studied, and the need to evaluate a more sophisticated eye tracker such as LADARVision.

Clinical Benefit of Very Fast Eye Tracking

The laser associated with the fastest eye tracking system (LADARVision) has recently also demonstrated the fastest and most broad ranging FDA approval rate. FDA approval for myopia, myopia with astigmatism, hyperopia, hyperopia with astigmatism and mixed astigmatism have all been recently granted with outstanding clinical outcomes during the U.S. investigational clinical trials. These

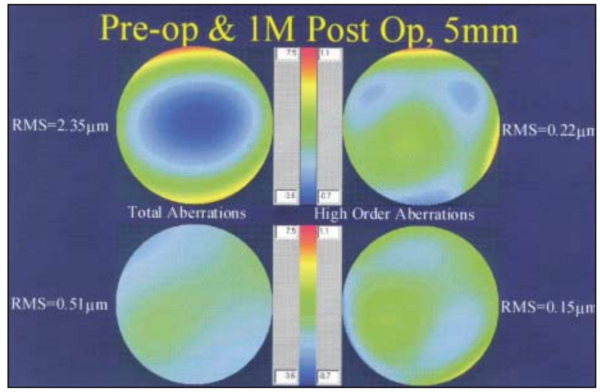

Figure 7. CustomCornea refractive image maps (2-dimensional) demonstrating a reduction in the RMS error after tracker assisted CustomCornea LASIK for both the total refractive profile, including sphere and cylinder (left; preop above, postop below), as well as just the higher order aberration including coma, spherical aberration, etc. (right; preoperative above, postoperative below). The reduction of aberrations substantiates the benefit of very fast eye tracking (LADARVision) in performing CustomCornea LASIK.

approvals have all been granted exclusively for use with the laser radar eye tracking system, which is an essential component to the LADARVision laser treatment.

At present, the LADARVision system is under US FDA investigation of CustomCornea with the goal of reducing ocular aberrations. Ocular aberrations are typically greatly increased during conventional LASIK.[19] Figure 7 illustrates the wavefront sensing map of a patient treated with CustomCornea. On the left, total aberrations, including sphere and cylinder, are markedly reduced after surgery. On the right, high order aberrations are shown and are also notably reduced after surgery, being the first time that laser vision correction has not increased ocular aberrations.[4] This reduction of ocular aberration improves not only the uncorrected but also best corrected visual acuity after surgery.

The improvement of best corrected vision and reduction of ocular aberrations, however, has not been exclusively observed with the Autonomous LADARVision system. Reports using the Wavelight Allegretto Laser and its 250 Hz video tracker system have also demonstrated an improvement in the RMS wavefront error in isolated individuals. Approximately 16% of 30 custom treated eyes achieved “supervision” outcome of 20/10 best corrected visual acuity or better. (Theo Seiler, MD, PhD, International Society of Refractive Surgery, July 2000, Miami FL). The improvement in vision and higher order RMS wavefront error has been recorded in the peer reviewed literature in three patients treated with the Wavelight Allegretto laser.[3] The 250 Hz tracking system used by this laser verifies that video based tracking systems can also be used to effectively perform wavefront customized corneal ablation in selected cases. But once again, very fast eye tracking is required.

A final example of the success and utility of very fast eye tracking with laser radar is demonstrated in two patients with congenital nystagmus. Each patient had a preoperative best corrected visual acuity which was limited because of both amblyopia and refractive error limitations in fixation with glasses. In each case, the postoperative uncorrected visual acuity at one day was better than the preoperative best corrected vision by at least 1 to 5 lines of visual acuity (personal communication, Brian Will, MD, May 2000). Here, even during random large amplitude eye motion such as nystagmus, sophisticated eye tracking with LADARVision successfully follows nystagmus saccades producing a good outcome. Very fast eye tracking is an important requirement for achieving the full potential for improved visual acuity with wavefront customized corneal ablation.

WAVEFRONT MEASUREMENT DEVICE

Corneal Topography vs Wavefront

Customized corneal ablation in refractive surgery has come to mean one of two things: topography guided custom ablation or wavefront guided custom ablation. The former utilizes information presented by computerized corneal topography instruments to change irregularities in the corneal shape into a smoother, more uniform pattern that improves the uncorrected or best corrected visual acuity.

The second meaning for customized corneal ablation has been more recently assigned to wavefront guided ablations. One of the essential components for wavefront ablation or CustomCornea is a wavefront device or CustomCornea measurement device (CCMD). Wavefront pattern measured by such a device gives a two dimensional profile of refractive error much in the same way as computerized corneal topography gives a two dimensional mapping profile of keratometry. Implementing the CustomCornea measurement device (CCMD) in customized ablation can be much more precise than corneal topography by attempting to achieve not just a smooth corneal surface, but a sharp focus of all corneal points on the retinal fovea.

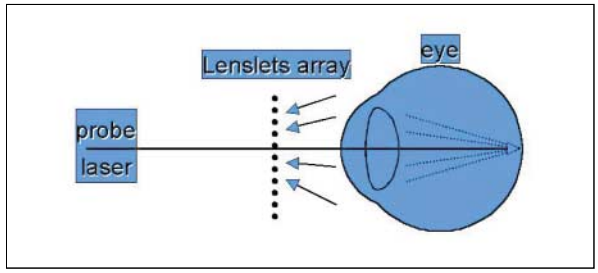

Figure 8. Principles of Shack-Hartmann wavefront sensing: Low energy laser light reflecting off the retinal fovea passes through the optical structures of the eye creating an outgoing wavefront. The wavefront passes through the lenslet array to define the deviation of focused spots from their ideal, which mathematically characterizes the wavefront pattern.

Principles of Wavefront Measurement Devices

Much in the way that a number of computerized corneal topography devices became available in the market during the past decade, so too, now as we enter a new decade, there are a number of different types of wavefront measurement devices in addition to that of the CCMD. Although it is often difficult to adequately categorize new products in an understandable fashion, there appears to be three different principles by which wavefront aberration information is collected and measured. The first type, which includes the Summit-Autonomous CCMD as well as others, is the most widely implemented and will be covered in greater detail.

Outgoing Reflection Aberrometry (Shack-Hartmann)—At the turn of the past century, Hartmann first described the principles by which optical aberrations in lenses could be characterized.[20] This was later modified by Shack, and found practical application in adaptive optics telescopes to eliminate the aberrations of the earth's atmosphere for the past 20 years. It was finally introduced to ophthalmology by Liang and Bille in 1994, where it was used to objectively measure the wave aberrations of the human eye. Adaptive optics to eliminate the aberrations of the human eye was first implemented in viewing retinal structures with greater detail than ever before. In 1996, images of cone photoreceptors were viewed in the living human eye by adaptive optics defined by a Shack-Hartmann wavefront sensor.[21] This first attempt at customizing the

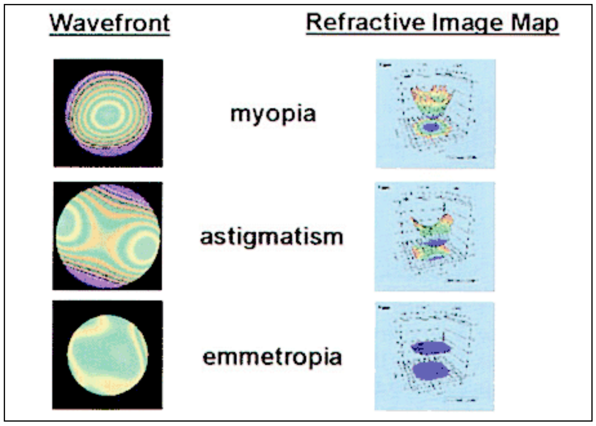

Figure 9. Wavefront fringe pattern and refractive image map (3-D) of myopia, astigmatism and emmetropia. The refractive image map demonstrates the shape of the wavefront coming out of the eye (bottom to top direction), such that myopia is bowl shaped (rays perpendicular to wavefront converge to a focus) and emmetropia is flat (rays perpendicular to wavefront are parallel).

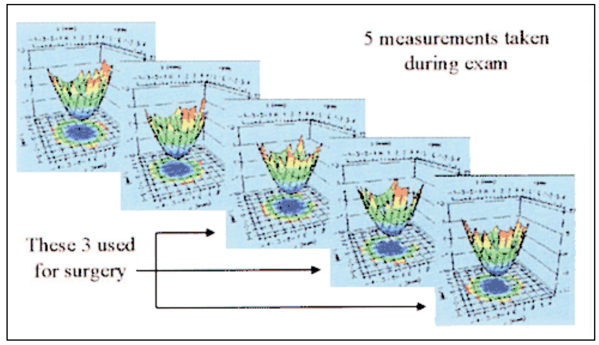

Figure 10. Capture and comparison of five consecutive wavefront maps in a myopic eye before CustomCornea laser surgery. The three in closest agreement were used to generate a composite profile map to be used in creating the wavefront guided laser ablation profile.

optics of the eye to increase the resolution of structures within it, in turn defined the need for measurement specificity in achieving better resolution when viewing structures outside of the eye. This in turn led to the beginning steps of Autonomous Technologies in introducing CustomCornea as a way of measuring and ultimately correcting the higher order aberrations of the eye. Although the exact parameters of the CustomCornea Mesaurement Device are not disclosed, a typical Shack-Hartmann wavefront sensor utilizes >100 spots, created by (>100) lenslets which focus the aberrated light exiting the eye onto a CCD detection array (Fig 8). The distance of displacement of the focused spot from the ideal very accurately defines the degree of ocular aberration. Figure 9 demonstrates the wavefront fringe pattern and corresponding refractive image map for myopia, astigmatism and emmetropia using the CustomCornea Measurement Device

Retinal Imaging Aberrometry (Tscherning & Ray Tracing)—The next type of wavefront sensing was first characterized by Tscherning in 1894, when he described the monochromatic aberrations of the human eye.[22] Tscherning's description, however, was not supported by the leaders of ophthalmic optics, including Gullstrand, and was not favorably accepted. It wasn't until 1977 that Howland and Howland used Tscherning's aberroscope design together with a cross cylinder lens to subjectively measure the monochromatic aberrations of the eye.[23] Seiler using a spherical lens to project a 1 mm grid pattern onto the retina more recently modified this same concept. This, together with a para-axial aperature system, could visualize and photographically record the aberrated pattern of up to 168 spots as a wavefront map.[1] A modification of this type, Tracey, uses a sequential projection of sixty-four spots onto the retina which are captured and traced to find the wavefront pattern within 12 milliseconds.

Ingoing Adjustable Refractometry (Spatially Resolved Refractometer)—The final method of wavefront sensing is based on the 17th Century principles of Scheiner and described by Smirnoff in 1961 as a form of subjectively adjustable refractometry.[24] Peripheral beams of incoming light are subjectively redirected toward a central target to cancel the ocular aberrations from that peripheral point. This was modified by Webb and Burns in 1998 as a subjective form of wavefront refractometry of the human eye.[25] The spatially resolved refractometer utilizes approximately 37 testing spots, which are manually directed by the observer to overlap the central target in defining the wavefront aberration pattern. The limitation of this technique is the lengthy time required for subjective alignment of the aberrated spots. An objective variant of this method is based on a form of slit retinoscopy (skiascopy), which is rapidly scanned along a specific axis and orientation. The fundus reflection is then captured to define the wavefront aberration pattern.

Laser/Wavefront Interface

Capture and Comparison—The first step to properly linking up the CustomCornea (wavefront) measurement device with the actual laser treatment is

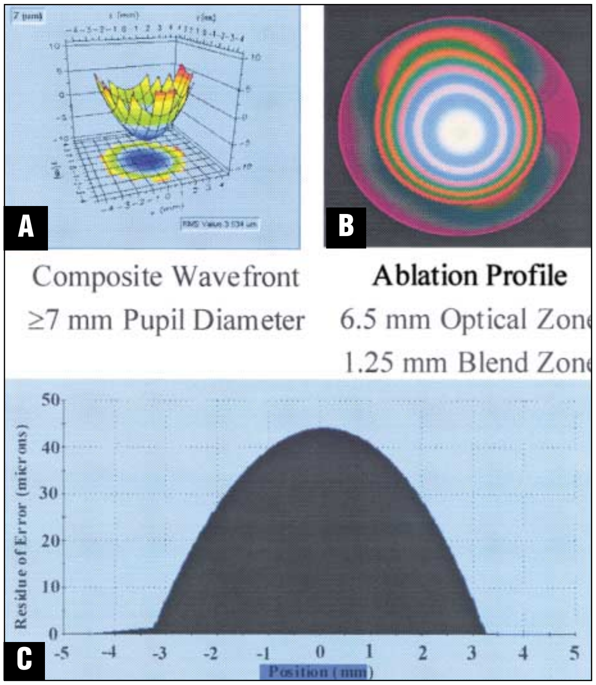

Figure 11. A) Conversion of the CustomCornea wavefront map, **B)** into the ablation profile represented by interference fringes, and **C)** ablation depth.

to assure that the most accurate and reproducible wavefront has been captured and implemented. In the US FDA trials of CustomCornea, using the LADARVision laser, the first step to this process of the laser/wavefront link-up is the capture of five consecutive wavefront measurements on the day of surgery. These five wavefront maps are then compared statistically and the three in closest agreement are used to generate a composite profile (Fig 10). This new composite wavefront map is then used to create the wavefront guided laser ablation profile and spot pattern.

Conversion to the Ablation Profile—The next step in the process is converting the wavefront measurement into an actual ablation profile of tissue that needs to be removed from the cornea to correct the refractive error and high order aberrations. When implementing this step it is important to have a wavefront measurement which has been captured through at least a 7 mm diameter pupil. To achieve a pupil diameter of this size, pharmacological dilation is necessary. However subtle variations in the wavefront pattern have been demonstrated with the use of pharmacologic agents, and this needs to be considered when forming the wavefront composite to be used during surgery.[26]

The conversion of the measurement profile into an ablation profile is a complex mathematical inversion of the 3-dimensional profile of wavefront error. The ablation profile used by the LADARVision laser is defined by a 6.5 mm optical zone together with a 1.25 mm blend zone for a total ablation diameter of 9 mm. Figure 11 demonstrates the conversion process for the Summit Autonomous CustomCornea interface. Here the wavefront composite with a greater than 7 mm pupil is converted into an ablation profile as demonstrated by the interference fringes and 2-dimensional profile of ablation depth.

Before transferring the ablation profile to the laser, a final step is determining the excimer laser shot pattern. The ablation profile map which measures the depth or elevation of corneal tissue that needs to be removed must be broken down into a calculation of the position of each excimer laser pulse to achieve the ablation profile. This step requires knowledge of the fluence and approximate ablation depth for each pulse as well as the proper gaussian overlap to achieve a smooth uniform ablation profile.

Transfer, Tracking, and Alignment—The next step in linking up the wavefront with the laser is the actual transfer of the wavefront ablation information to the computer assisted input of the laser. At the present time the link-up is achieved by a computer disc which downloads the information from the wavefront device, and a computer which calculates the excimer laser spot pattern to the computer interface of the excimer laser. This information that is transferred by way of a floppy disc includes the orientation data gathered during the wavefront measurement.

The LADARVision tracker can than be engaged to align the laser pulse positioning with the movement of the eye, but more importantly, a step of XYZ alignment is necessary to assure that the wavefront determined pulsing sequence corresponds with the exact position of the aberrations as seen at the level of the cornea. The Summit Autonomous LADARVision laser has eye tracking which is maintained by locking onto the edge of the dilated pupil but aligned by the position and landmarks of the limbus. For the CustomCornea study specific markings are made along the limbus in four quadrants using a dye or light thermal cautery for orientation of the wavefront map with the eye during surgery. The graphic user interface on the LADARVision system demonstrates the alignment of the limbus and overlap of the orientation marks while the tracker follows the movement of the dilated pupil margin.

Algorithm Development—The last step of interfacing the wavefront ablation profile to the laser requires understanding the variables of the ablation process. Just as current excimer laser correction procedures utilize a carefully developed nomogram for the optimal visual outcome; so too, complex nomograms, considering the multiple variables associated with wavefront guided treatment, need to be developed and refined in order to successfully reduce the ocular aberrations. Complex ablation considerations need to be considered in order to try to improve upon these results. The following parameters outline a preliminary menu of variables that need to be further considered with wavefront guided laser vision correction.

1. Corneal topography (Shape). Even though the wavefront map fully characterizes the aberrations within the optical system of the eye, subtle shape changes in corneal topography may have a bearing into the proper placement of pulses onto the cornea.[27] Corneas that are unduly flat or steep may impact the way in which the wavefront guided ablation pattern successfully remolds the cornea.

2. Corneal Biomechanics (Structure). Besides the shape issues as defined by corneal topography, there are also structural issues regarding the individual biomechanics of the cornea during laser vision correction. Corneas of differing thickness and corneal elasticity will likely have a different biomechanical impact on ablation.

3. Flap Biomechanics (Surgery). The wavefront measurement profile, which is highly sensitive to the structure and orientation of the cornea, will likely change after making a corneal flap. The biomechanical changes of the cornea secondary to flap creation and positioning of the hinge are not thoroughly understood. Initial studies with the CustomCornea measurement device have demonstrated induced coma along the axis of the hinge after making a corneal flap (personal communication, Christy Stevens, OD, June 2000). Further analysis of wavefront profiles after making a flap alone will need to be analyzed and factored into the ablation nomogram.

4. Healing Process (Remodeling). Another large variable in the ablation considerations is the healing of the corneal stroma and epithelium following wavefront guided laser vision correction. The correction of subtle aberrations can, in part, be undone by filling in by the epithelium or remodeling of the stroma. The biologic variability of laser vision correction makes it very difficult to achieve full optical quality when performing laser vision correction, and attempts at controlling wound healing has already been an important area of research in refractive surgery. Pharmacological or gene manipulation of biologic processes, such as keratocyte apoptosis, may help us to reduce the wound healing response after refractive surgery and thereby further control our outcome.[28] Ablation algorithms and nomograms will need to be developed to consider the wound healing aspect of wavefront guided laser vision correction in its current state as well as with our further control of wound healing in the future.

5. Environmental Issues (Humidity, Temperature, etc). Another large variable that we currently face with laser vision correction is the hydration of the cornea, which is in part dependent on the humidity, temperature, technique and length of treatment time. Uniform corneal hydration will be an important consideration in order to get a uniform pattern that fully corrects the wavefront error.

As with all complex systems appropriate algorithms or nomograms will need to be developed to achieve the optimum optical result. Wavefront guided laser customization, as with the CustomCornea platform offers a unique new application to refractive surgery that will hold a great deal of research interest and attention in the years to come. Potential to correct not only the refractive error but the higher order aberrations has already been well demonstrated in physical applications such as the Hubble Telescope, and even of correcting the ocular aberration pattern when viewing cone photoreceptors in the retina. The promise of perfect optical quality after laser vision correction would be a well-received addition to our current techniques of laser vision correction. As we further explore this technology, its requirements, as outlined in this article, will likely be expanded upon. Nonetheless, the technology requirements outlined here serve as a foundational basis in our understanding of wavefront guided customization and specifically the technology requirements of Summit-Autonomous CustomCornea.

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