CHAPTER
73
Excimer Laser Instrumentation

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ELEMENTS OF AN EXCIMER LASER SYSTEM

The excimer laser emits UV light of different wavelengths ranging from 156 to 308 nm, depending on the gas mixture used to fill the chamber cavity. In corneal refractive surgery, only the wavelength of 193 nm is routinely used, which is obtained by mixing argon and fluorine gases. This laser is referred to as the ArF–excimer. The same spectral range can be emitted by frequency-multiplied solid state lasers; therefore, most of the technical considerations in this chapter also apply to those lasers.

An excimer laser station for corneal surgery consists of: the laser itself, as the light source; an optical delivery system, which modulates the laser beam; an eye tracker, to compensate for eye movements; and peripheral instruments, such as a corneal topographer and wave front analyzer (Fig. 73.1).

During the past 20 years, requirements for clinical excimer lasers have changed significantly, but a few criteria remained invariant and new entrants must fulfill the following five conditions.

PRECISION

The ablation depth must be guaranteed within ± 3% and should be calibrated before each treatment.

DURATION

A typical treatment (e.g., 6 D myopia) should be completed within 30–40 s to avoid dehydration of the corneal surface.

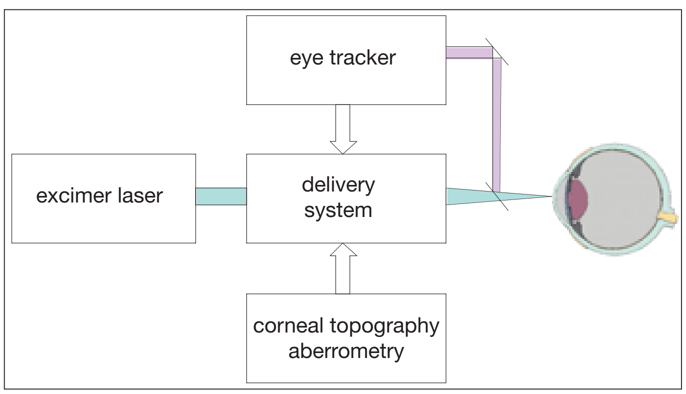

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FIGURE 73.1. Parts of a typical excimer laser station. The optical delivery systems forms and manipulates the beam emitted by the excimer laser.

ALIGNMENT

The centration of the treatment onto the center of the entrance pupil or any other reference point should be better than 0.07 mm.

SIZE OF ABLATION AREA

The standard optical zone is 6.5 mm in diameter for myopia and 7 mm for hyperopia surrounded by a blended zone, making the standard treatment zone at least 9 mm in diameter. Treatment zones of greater than 9 mm in diameter should not be attempted, because the cornea will reflect the UV light.

INTENSITY OF UV LIGHT

The ablation threshold for corneal tissue at a wavelength of 193 nm light is ~50–80 mJ/cm^2; however, to obtain stable photoablation of the tissue and minimize the influence of environmental factors such as humidity and temperature, the fluence at the cornea should exceed 120 mJ/cm^2.

Broad-beam lasers are classified by the diameter of the beam that reaches the cornea (ranging from 0.68 to 8 mm: the beam diameters of scanning-spot lasers range from 0.5 to 2 mm, whereas scanning-slit systems have a rectangular beam and a typical cross section of 2 × 9 mm. Specifications for the currently available excimer laser systems are listed in Table 73.1.

Correcting a standard myopia with a broad-beam laser is done by opening or closing the iris diaphragm, thus creating an amphitheatre-like keratectomy. With the scanning-spot-type laser, the laser spot travels across the cornea, but the focus stays more central than peripheral.

During a standard myopia correction, a convex–concave lenticule of stromal tissue is removed with a central thickness of a_o (Fig. 73.2).[1] This formula is routinely used to calculate the central keratectomy depth and is based on the diameter (d) in mm and the refractive change in diopters (P):

$$a_o = Pd^2 1/3$$

For a_o –6.0 D correction with an optical zone diameter of 6 mm, the central keratectomy depth (a_o) would be 108 µm. Assuming an ablation rate of 0.2 µm per pulse, a total of 540 laser pulses would be needed at the center of the cornea. A similar formula applies for making hyperopic corrections, where tissue is removed in the periphery of the cornea, sparing the central area.

THE EXCIMER LASER

The cavity of a laser is formed by two mirrors: one reflects 100%, the other reflects only 90–99%. A small percentage of

TABLE 73.1. Currently Available Excimer Laser Sytems

	Alcon	Bausch & Lomb	Nidek	Visx	Wavelight	Zeiss
Name	Ladarvision 6000	Technolas T217 Zyoptix	EC-5000	Star S4	Eye-Q	MEL 80
Type	Scanning spot	Scanning spot	Scanning slit	Broad beam	Scanning spot	Scanning spot
Profile	Gauss	Gauss	Gauss	top hat	Gauss	Gauss
Beam size (mm)	0.75	1–2	2 × 9	0.65–6.5	0.68	0.7
Rep rate (Hz)	60	50	60	10	400	250
Average fluence (mJ/cm^2)	200	120	140	200	200	200
Eye tracker respectively time	10 ms	7 ms	6 ms	20 ms	6–8 ms	6 ms
Customized treatment based on wave front (WF) or topography (T)	WF	WF, T	WF, T	WF, T	WF, T	WF

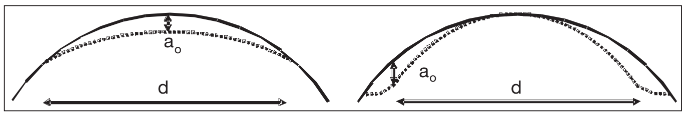

FIGURE 73.2. Changing the curvature of the cornea within the optical zone with the diameter (*d*) by removing stromal tissue in myopia correction (left) and hyperopia correction (right).

light escapes from the second mirror, which is what is emitted as 'laser light'. The cavity is filled with a substance that is capable of storing and releasing energy. In the case of the ArF–excimer laser, the laser medium consists of a gas mixture containing argon and fluorine gas and others that are preionized either electrically or by means of X-rays. The high-voltage current that is pumped in creates highly unstable, rare, gas-halide molecules (the stored energy), which when released emits the laser light (Fig. 73.3).

The lifetime of the 'excited dimers' of the excimer laser determines the length of the laser pulse emitted, which is in the order of 5–100 ns. The energy output per pulse ranges from a few mJ s as for the scanning-spot lasers up to 500 mJ s and more for the broad-beam lasers. The overall efficiency (laser energy/stored energy) is less than 1%. The repetition rate of the laser pulses is inversely related with the energy emitted per pulse. In clinically used excimer laser systems, the range is from 5 to 1000 Hz. In general, the higher the repetition rate, the smaller the energy emitted per pulse. The energy profile of the primary laser beam is somewhat Gaussian with an increased intensity in the center of the beam and a decreased intensity toward the edges. In many excimer lasers, the cross section of the primary beam is rectangular because of the geometry of the specific cavity design. One of the purposes of the optical delivery system is to reshape the beam profile to the desired energy configuration.

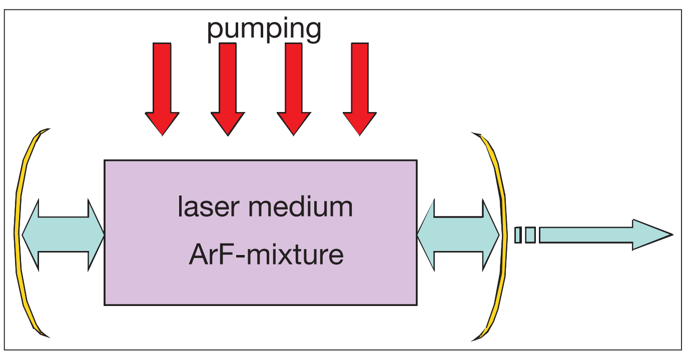

FIGURE 73.3. Schematic representation of a laser. In the case of the 193 nm excimer laser, the laser medium consists of a gas mixture and pumping is performed by means of an electrical discharge.

The use of laser gases in clinical setting, particularly fluorine, raises safety issues because of the associated dangers of these highly reactive substances. With modern systems, gases no longer need to be frequently replaced because the laser cavity is double-sealed in ceramic. Even at high-volume surgical centers, the gas will need to be changed only 1–4 times a year. Solving these safety problems eliminated one of the most important disadvantages of medical excimer lasers compared to solid state alternatives. Solid state devices have been marketed but none has gained clinical acceptance.

THE OPTICAL DELIVERY SYSTEM

Within the delivery system, the raw excimer laser beam is homogenized, shaped, scanned, and coupled into what amounts to a surgical microscope.

Beam homogenizers are optical elements consisting of prisms, lenses, mirrors, and even lenslet arrays-elements that are designed to level out irregularities such as cold and hot spots in the beam. At the same time, the energy distribution inside the beam is adjusted. There is a distinction between what is referred to as a 'top hat' and a 'Gaussian' beam profile (Fig. 73.4a). The top-hat profile was used in the early versions of broad-beam lasers and scanning-spot lasers. Figure 73.4b shows the result of small displacements of overlapping sequential laser spots on the ablation profile. It is obvious that Gaussian-profiled spots create a much more regular ablation pattern compared to top-hat spots. Even with the use of the most powerful eye tracker, small displacements of the spots are inevitable. In addition, one must consider that an area cannot be covered with a circular spot without some overlap. This is why most scanning-spot lasers use a Gaussian-like beam profile.

The advantages and disadvantages of broad-beam, scanning-spot, and scanning-slit lasers are still being considered. Although the majority of the new excimer laser systems are scanning-spot lasers, one scanning-slit and one broad-beam

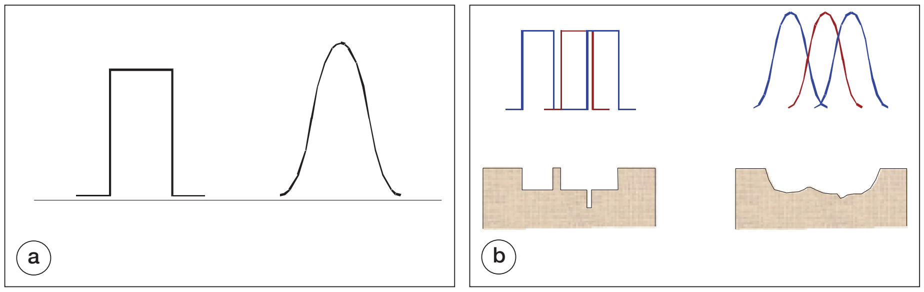

FIGURE 73.4. (**a**) Energy profiles of excimer laser beams. Top hat profile (left), Gaussian profile (right). (**b**) Adjacent spots produce the area of ablation on the cornea. Small displacements from the ideal spot location (middle spot) with top hat profiles produce more surface irregularity than is produced with Gauss profiles.

laser remain on the market (Table 73.1). Both of theses systems now include additional scanning spots so they can customize ablation patterns and procedures. In general for one of these systems to establish a broad homogeneous beam, the energy output of the laser has to be substantially higher than that of a scanning-spot laser. An 8 mm beam with a fluence of 150 mJ/cm^2 needs 75 mJ per pulse with a broad-beam or scanning-slit laser, while a scanning spot laser with the same average fluence, requires ~2 mJ per pulse. On the other hand, broad-beam lasers can work at low repetition rates (typically 10 Hz) to accomplish standard corrections in less than 30 s (see second condition), whereas a 2 mm-spot system needs a repetition rate of ~100 Hz and a 1 mm-spot system of at least 200 Hz to be as fast as the broad-beam laser. When the surgeon is only performing a standard myopic correction, a broad-beam laser is equivalent to a scanning-spot laser. However, the broad-beam lasers are bigger and heavier, which may be problematic in some clinical settings. For hyperopic corrections, a broad-beam laser needs to have a scanning mirror because the ablation of tissue is performed in the periphery of the cornea without touching the center.

A similar problem arises when aspheric ablation profiles are needed. Because of the curvature of the cornea, the UV light only hits the corneal surface perpendicularly near the apex of the cornea. Because of the oblique incidence, the ablation area of the beam is larger in the mid-periphery and the fluence (energy/area) decreases, resulting in an undercorrection in the periphery (Fig. 73.5). In addition to this purely geometric effect, the optical reflection of the UV light from the corneal surface increases with increasing obliqueness, which also reduces the photoablation.[2] To compensate for such peripheral undercorrections, an aspheric ablation profile is needed. Broad-beam lasers and scanning-spot lasers work well in this situation.

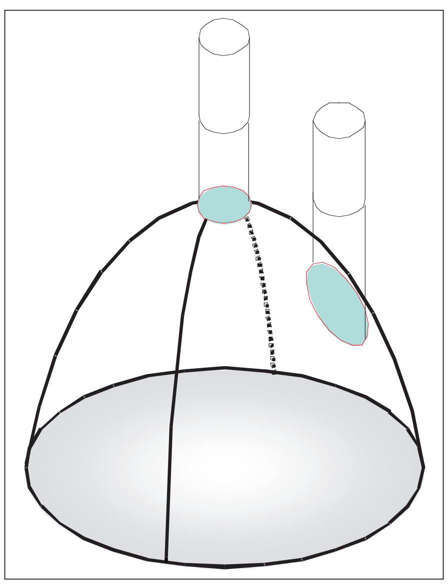

FIGURE 73.5. Decrease of the fluence in the periphery of the cornea due to the oblique ablation. The energy of the laser pulse spreads over a larger area.

With the advent of customized treatments, technical requirements are changing. Huang and co-workers showed that corrections of optical errors up to the fourth order require spot sizes of not more than 1 mm in diameter.[3] Recently published results of large studies confirm the superiority of wave front-guided customized laser treatment as proposed earlier.[4,5] This approach includes the correction of optical errors up to the fourth order, which means using a scanning-spot laser with a maximal diameter of 1 mm.

The optical apparatus of the delivery system is comprised of specialized quartz lenses and coated mirrors. To enhance the longevity of the optical system, the optical pathway is purged with nitrogen. This is to avoid contamination from oxygen in the air, which when ionized by UV light may erode the surfaces of the optics. Nevertheless, optics do age and must be replaced because of color centers created by the high-energy UV light inside the quartz

The accuracy of the energy output of the laser at the exit of the delivery system is crucial for the precision of a refractive procedure because the shot lists for a given correction assume a fixed ablation rate. Therefore, the energy output is controlled online in two loops-one sensor being placed at the entrance of the delivery system and one at the exit. In addition, the fluence is verified in the corneal plane at least once per operation day by metal foils or polymethylmethacrylate (PMMA) plates that are photoablated to a specific depth.

The scanning system consists of a pair of computer-controlled scanning mirrors, which are either galvanometric or piezoelectric. The resonance frequency of these mirrors must be considerably higher than the working frequencies and is typically on the order of 10 kHz. The position error of the spot at the cornea should be less than 10 μm compared to a target at rest. The scanning system needs to be tested and possibly calibrated each day with specially designed masks.

Finally, the excimer laser beam must be coupled into the surgical microscope so that the surgeon can look along the vertical laser beam axis (z axis). Various alignment systems (e.g., crossed pilot laser beams, projected slit images) have been developed to facilitate the appropriate alignment of the patient's cornea in the x, y, and z axes. Cyclotorsion may cause an undercorrection of an astigmatism and wave front errors; therefore, it is recommended that the surgeon meridionally align the eye to be operated on before the procedure. This can be achieved by marking the eye in the supine position and aligning it under the surgical microscope along projected reticules or automatically employing iris/limbus recognition.

All systems include suction devices for effluent removal because the plume can cause central steep islands and irregular ablations. The flow should be sufficient to remove the ablation effluent but not effect the hydration of the corneal surface.

THE EYE TRACKER

For a successful laser treatment, it is critical to have a precise overlap of successive laser pulses on the cornea. With broad-beam lasers, the concentric overlap throughout the procedure guarantees a symmetric postoperative shape to the cornea. In scanning-spot treatments, small variations of the spot locations may create an irregular corneal surface. During surgery, the patient is asked to stare at an identified target (usually a green LED mounted inside the delivery system coaxially with the excimer beam axis); however, once the flap is lifted, patients' sight is blurred and it is hard for them to fixate. It is inevitable that there will be small eye movements during the operation (Fig. 73.4b). Even saccades with a speed of 100° per second may occur when the patient has lost the target and tries to refixate. Eye jittering and drifts are observed especially during longer procedures (e.g., higher order corrections).

The basic principle of eye tracking is to recognize eye movements and to reposition the laser beam before the next laser pulse. A tracker can be linked to computer imaging of the entrance pupil position or to landmarks at the limbus. Recently, an iris recognition system has been introduced that compensates for cyclotorsion and shifts in the center point for a patient's pupil as the result of differences in pupil diameter. The eye tracker should be thought of as a closed loop regulation that is characterized by response time and the maximal compensated displacement.

The response time needed for an eye tracker to react properly is dependent on the repetition frequency of the laser, the spot size (which defines the tolerable displacement of a laser spot), and the maximally occurring eye movement speed. Currently, eye trackers offer response times of 3–10 ms, which corresponds to a maximal lateral displacement of the laser spot of 30–100 μm during a saccade. Since saccades are rare and normal eye movements are much slower, a response time of better than 10 ms appears to be sufficient in the majority of cases. Most eye trackers can compensate for up to 1 mm of lateral eye displacement.

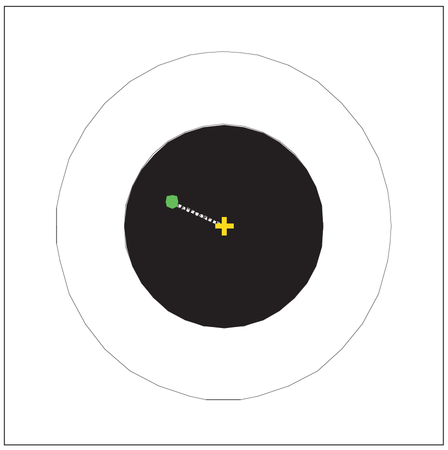

FIGURE 73.6. Surgeon's view of possible centration targets on the cornea. Cross: center of the entrance pupil; dot: first Purkinje-image of the fixation target.

A decentered treatment is one of the most severe complications in refractive surgery. It can result in asymmetric halos, increased glare, monocular diplopia, and visual loss. Eye trackers were originally developed to avoid the complications of eccentric treatments because they align the ablation field to a chosen reference point on the cornea. The challenge is in choosing the right center – the treatment must be centered on the visual axis, but its corneal intercept is not defined. The best estimate is that the visual axis may cross the cornea somewhere on the line connecting the center of the entrance pupil and the first Purkinje-image of the fixation target (Fig. 73.6).

To achieve a good visual outcome, the lateral alignment accuracy should be better than 0.07 mm and the torsional alignment held within 4°.[6,7] Most eye trackers center the photoablative treatment on the center of the entrance pupil but an option exists to decenter voluntarily in either the *x* or *y* direction.

SUPPLEMENTS FOR CUSTOMIZED ABLATION

The correction of refractive errors are usually based on the manifest or cycloplegic refraction and include spherical and astigmatic errors. However, even normal eyes have optical errors of higher order such as coma and spherical aberrations. Patients with previous ocular surgery, trauma, or corneal inflammation often have an irregular astigmatism. Only compensating for the refractive error fails to return unaided vision to normal levels. A customized ablation procedure should be considered to correct the higher order errors. Customized ablations can be planned based on preoperative wave front analysis or on corneal elevation maps approximated from Scheimpflug photography or corneal topography.

Two different methods can detect the ocular wave front, the Hartmann–Shak sensor and the Tscherning system. Both instruments provide a map that differentiates between the measured and ideal wave fronts. This 'differential map' is easily converted into a wave front-guided customized ablation pattern (Fig. 73.7). The maps are produced by software in the microcomputer of the laser, where Zernike-polynomials are used as the basis for creating shot lists. A shot list is available for each Zernike-polynomial.

A similar strategy is used for topography-guided customized treatments. For this treatment, an elevation map is calculated based on measurements from corneal topography. The map generated by the software in this system displays the differences between measured and desired aspheric shapes of the cornea. As with the wave front-guided technology, differences are approximated using Zernike-polynomials and transformed into a customized ablation pattern (Fig. 73.8).

Recently a third kind of customization has been introduced, the Q-factor customized ablation.[8] The preoperative asphericity factor Q of the cornea is taken from corneal topography and an

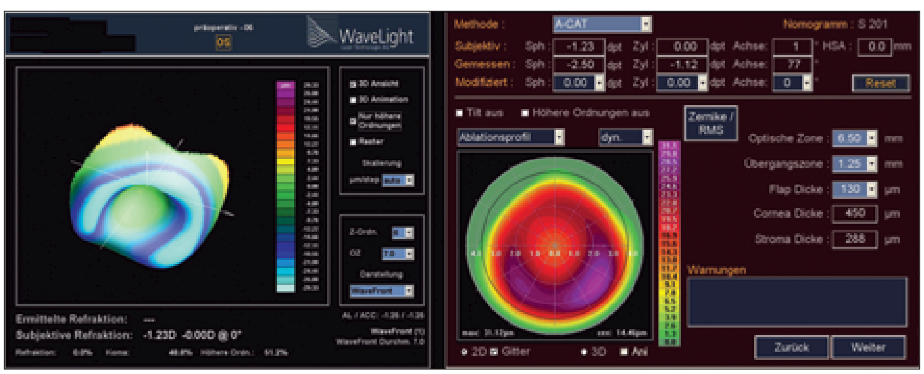

FIGURE 73.7. Wave front error (left) converted into an ablation pattern (right).

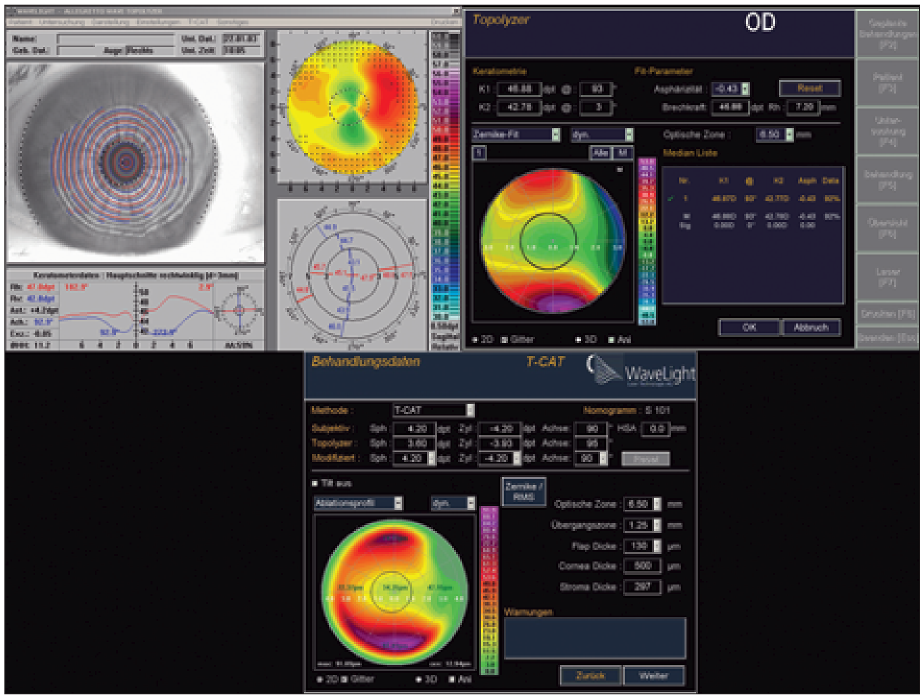

FIGURE 73.8. Topography of a cornea with irregular hyperopic astigmatism and corresponding differential elevation map. This map of the differences between measured and desired aspheric shapes of the cornea is converted into an ablation pattern.

ablation pattern created that aims on a desired postoperative Q-factor. During standard myopic corrections the preoperatively prolate corneal shape is turned into an oblate shape, which is thought to be responsible for a decrease in a patient's quality of vision. To avoid this side effect, a postoperatively negative Q-factor (prolate cornea) is necessary.

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