Chapter 3
Wavefront Guided Customized Ablation

3.1 Introduction

With over 1000000 laser vision corrective procedures performed each year, Wavefront-Guided (WFG) refractive surgery has become an increasingly valuable technological development that can be used to achieve a customized corneal ablation **(Liang J et al, 1994)**.

A traditional conventional excimer laser treatment corrects for spherical and cylindrical refractive errors, which are considered lower-order aberrations. In comparison, a WFG treatment takes into account measured lower and higher-order aberrations to create more precise ablation profile in an attempt to obtain better postoperative quality of vision. The theoretical potential to reduce all higher-order aberrations initially generated optimism that supernormal vision of uncorrected visual acuity of 20/15 or better could be consistently obtained **(Liang J et al, 1997)**.

3.2 Technique of wavefront guided LASIK:

In wavefront guided treatment besides the spherocylindric corrections, the ablation profile also includes higher order aberrations. Even though there are different systems for wavefront guided correction available; the basic principle is always the same **(Benjamin F et al, 2003)**.

First step, The refractive error is measured; most systems use the Hartmann-shack Sensor; less frequently, the Tscherning aberrometer is used **(Benjamin F et al, 2003)**.

Second step, The ablation profile for the excimer laser is calculated with the aid of the Zernike polynomials or with Fourier analysis **(Benjamin F et al, 2003)**.

Since the number of polynomials is infinite, approximating or defining the wavefront error becomes, like in Fourier analysis, more accurate the higher the number of Zernike polynomials. In clinical practice , mostly only the first 20 polynomials (2nd to 5th order)are used although recent studies showed that a higher number of polynomials may be useful to describe more deformed wavefront patterns **(Benjamin F et al, 2003)**.

Third step, Is the ablation of corneal tissue according to the profile calculated by the excimer laser.

Clinically, the third step does not differ substantially from the sphero-cylindric method **(Benjamin F et al, 2003)**.

Contrary to the earlier-generation excimer lasers (broad beam principle) laser systems used for wavefront guided treatment employ a beam with a small diameter that is being directed over the cornea by pivotable mirrors (flying spot principle) **(Benjamin F et al, 2003)**.

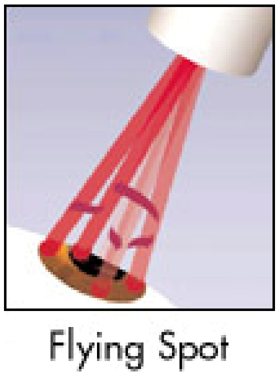

Figure (3.1) The broad beam and flying spot LASER

3.3 Indications of wavefront guided LASIK

Early data suggests that the 5-10 % of patients who demonstrate high-order aberration are the patients that will significantly benefit from Custom LASIK treatment; those with best corrected visual acuity less than 20/20 due to high aberrations **(Liang J et al, 1994)**.

Disadvantages and complications of wavefront guided LASIK:

Wavefront measurements are interesting and useful, but such highly customized treatment should not be used to correct every focusing abnormality. One concerns about these risk factors:

- Heightened expectations for 20/10 or 20/15 super vision may lead to frustration.
- Wavefront guided LASIK may reshape the cornea to compensate for aberrations that arise from the lens **(Christopher Kent, 2002)**.

But with time, most patients may develop normal lenticular changes and eventually have their cataracts replaced by plastic lens implants. Now unfortunately, their custom-shaped cornea will no longer coordinate with the spherical optics of their artificial lens **(Christopher Kent, 2002)**.

- The predominant higher order aberrations in non surgical eyes were third order aberrations, however, in postoperative symptomatic eyes fifth order aberrations, if present, tended to be accompanied by more severe visual complaints as changing the angle of an existing aberration is very disruptive **(Christopher Kent, 2002)**.

- Aberrations are not necessarily bad; and the differences were not statistically significant:

DR.Macrae reported that add a certain amount of spherical aberration to myopia can sometimes produce clear image. So in some cases, a higher Root Mean Square RMS may mean better acuity, not worse **(Christopher Kent, 2002)**.

3.4 Factors that influence wavefront sensing and wavefront guided customized ablation:

1) Physiological factors.

2) Ablation design and algorithms.

3) Flab creation.

4) Ablation delivery.

5) Biomechanics and wound healing.

This section will highlight some of the preoperative, intraoperative, and postoperative factors that may affect the outcomes of WFG ablations. Methods to map aberrations through wavefront sensing generate ablation maps from measured data, and apply the laser delivery to produce the planned ablation should be addressed to maximize correction of aberrations **(Huang D et al, 2001)**.

1) Physiological factors

A wavefront sensor captures a static measurement of a dynamic optical system. During the data acquisition, factors such as:

- Pupil size.
- Accommodation.
- Tear film can affect the wavefront aberration profile of eye.

Pupil size:

Essentially, the quality of the laser ablation is dependent upon acquiring an accurate assessment of the aberrations of the eye. The optical aberrations profile is highly dependent upon pupil size, whereas aberrations are at a maximum when the pupil diameter is largest, such as under scotopic conditions. Most laser platforms required data from a minimum of 5-mm pupil diameter to allow a WFG treatment **(WN Charman et al, 1989)**.

In an observational study to evaluate the effect of changing the pupil size on the corneal first-surface higher-order aberrations induced by different refractive treatments: standard laser in situ keratomileusis (LASIK), custom LASIK, and corneal refractive therapy **(Antonio Queiros et al, 2010)**.

This study used Eighty-one right eyes from patients with a mean age of 29.94 ±7.5 years, of which 50 were female (61.7%), were analyzed retrospectively at the Clínica Oftalmológica NovoVision, Madrid, Spain. Corneal videokeratographic data were used to obtain corneal first-surface higher-order aberrations for aperture diameters from 3 to 8 mm using the Vol-CT software (Sarver & Associates, Inc). Total Root Mean Square (RMS) and RMS for third- to sixth-order Zernike polynomials as well as spherical-like, coma-like, secondary astigmatism and spherical plus coma-like variables were calculated **(Antonio Queiros et al, 2010)**.

RESULTS:

1. We verified an increase in the higher-order aberration total RMS after treatments of 0.014 ± 0.025 μm, 0.019 ± 0.027 μm, and 0.018 ± 0.031 μm for standard and custom LASIK, and corneal refractive therapy, respectively, for 3-mm pupil diameter.
2. For the 8-mm aperture diameter, changes in total RMS increased by a factor of 50 compared with the variation for the 3-mm diameter up to 0.744 ± 0.731 μm, 0.493 ± 0.794 μm, and 0.973 ± 1.055 μm for standard and custom LASIK, and corneal refractive therapy, respectively **(Antonio Queiros et al, 2010)**.

CONCLUSIONS: The 3 techniques increase the wavefront aberrations of the cornea and change the relative contribution of coma-like and spherical-like aberrations. For a large aperture (>5 mm), corneal refractive therapy induces more spherical-like aberrations than standard and custom LASIK. However, no clinically or statistically significant differences existed for narrower apertures. Standard and custom LASIK did not display statistically significant differences regarding higher-order aberrations **(Antonio Queiros et al, 2010)**.

Accommodation:

Optical aberrations shift substantially with increase in accommodation, which appears to be age-related. In younger patients, spherical aberrations tends to change from a positive to a negative value with increasing accommodation, compared with patients around 40 years and older Miosis accompanying accommodation diminishes the effects of HOA and can result in an underestimation of the wavefront error in undilated eyes **(Radhakrishnan H et al, 2007)**.

Tear film:

Sequential measurement studies of HOA in relation to tear film dynamics demonstrate associated changes that may affect visual quality **(Koh S et al, 2007)** particularly in dry eye patients **(Koh S et al, 2008)**. Variable study results may be due to differences in definitions of dry eye and therefore differing degrees of dryness severity.

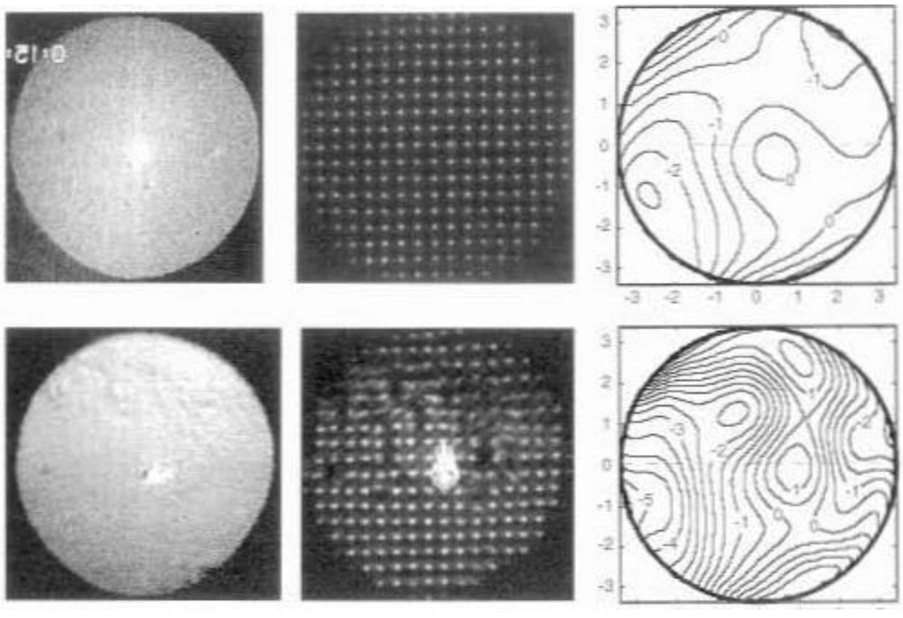

Figure (3.2) The optical effect of tear film disruption

The upper row of images was captured immediately after a blink; the bottom row of images was obtained after the subject had held his lids open for about 40 seconds. Left column contains images obtained by retroillumination of the pupil; the middle column shows the data images captured by the Schiener-Hartmann aberrometer; right column shows contour maps of the aberrated wavefront emerging from the eye captured from the SH data image. Contour intervals in the reconstructed wavefront are 1 micron and the wavefront phase at pupil center has been set to zero. Pupil coordinates are in millimeters **(Koh S et al, 2008 & Thibos LN et al, 1999)**.

Additionally, progressive age related changes of the lens and cornea result in alterations in wavefront aberrations, particularly spherical aberration and coma **(Amano S et al, 2004)**. As a result, modifying the Higher Order Aberration HOA profile through WFG treatment in a young patient may not remain optimal for that individual as age related changes occur.

2) Ablation designs and algorithms:

The optimal means for fitting and reconstruction of wavefront aberrations needs to be further studied, as there are advantages and limitations specific to analysis with **Zernike polynomials** or **Fourier transform analysis (discussed in chapter 4) (Ou JI et al, 2007)**.

Zernike polynomials uses **28** fitting parameters from Hartmann-Shack aberrometry lenslet measurements in comparison to **240** fitting parameters with Fourier transform analysis **(Ou JI et al, 2007)**.

As a result, analysis with **Zernike polynomials** may mask clinically significant **HOA** in an attempt to reduce noise, particularly in highly aberrated eyes **(Ou JI et al, 2007)**.

Another disadvantage is the optimal number of **Zernike order** and **Zernike coefficients** for each term are dependent upon pupil size **(Dia G, 2006)**.

For full wavefront reconstruction, **Fourier analysis** appears to be **more optimally** use slope information, utilize a faster algorithm, and better represent ocular aberrations in highly aberrated eyes compared with Zernike reconstruction **(Dia G, 2006 &Wang L et al, 2007)**.

Fourier transform was found to be more accurate than Zernike polynomials up to the 10^{th} order in fitting Hartmann-Shack lenlet data and corneal elevation data from virgin and post surgery eyes **(Wang L et al, 2007)**.

(Ou JI et al, 2007) showed a trend towards improved visual outcomes from myopic Custom Vue LASIK (AMO VISX S4, Santa Clara, California, USA) using Fourier treatment tables compared with Zernike treatment tables generated by Hartmann-Shack aberrometry, although the differences were not statistically significant and the sample size was limited. The HOA profiles were similar for both groups **(Ou JI et al, 2007)**.

3) Flap creation

A better understanding of surgically induced changes in wavefront aberrations is needed to optimize the WFG customized ablation. The increase in postoperative HOA after LASIK compared with PRK has been largely attributed to flap creation **(Porter J et al, 2003)**.

Biomechanical changes after **uncomplicated flap** creation with a hansotome **microkeratome without flap lifting** in 29 eyes resulted in significant changes in:

- Vertical coma.
- Horizontal coma.
- Spherical aberration.

- 90/180 degree astigmatism **(Porter J et al, 2003)**.

That was influenced by:

- Stromal bed thickness
- Flap diameter
- Total corneal pachymetry **(Porter J et al, 2003)**.

Both the IntraLase femtosecond laser and mechanical microkeratome flap creation change the profile of lower and higher-order aberrations, **with a significant increase in total HOA**, particularly coma and spherical aberrations, in the **mechanical micrakeratome** group compared with the femtosecond group **(Tran DB et al, 2005 &Montes-Mico R et al, 2007 &Buzzonetti L et al, 2008)**.

An increase in coma-like aberration can be attributed to the effect of the flap hinge. Induction of HOA increases with decentered flaps, particularly coma like aberration **(Buzzonetti L et al, 2005)**.

Induction of HOA due to flap creation affects HOA to a lesser degree than laser ablation and does not appear to significantly affect the post operative outcomes **(Potgieter FJ et al, 2005)**.

4) Ablation delivery

The efficacy and predictability of the WFG treatment are dependent upon:

- Accuracy.
- Speed.
- Precision of laser ablation **(Chernyak DA, 2005& Mrochen M et al, 2001)**.

Important laser platform parameters include:

- Laser beam shape and size.
- Ablation efficacy.

- Spot scanning rate and pattern.
- Eye tracking.
- Wavefront registration **(Chernyak DA, 2005 & Mrochen M et al, 2001)**.

Wavefront-guided and wavefront optimized platforms will have a compensatory function to account for peripheral ablation efficiency loss to reduce spherical aberration induction. Recent advances in registration and tracking maximize alignment and precision of wavefront ablation delivery, since cyclotorsion greater than 5 degree for non radially symmetrical treatments and lateral displacements greater than 20-100mm can be clinically significant for treating HOA **(Chernyak DA, 2005& Mrochen M et al, 2001)**.

Spot sizes of less than 1mm are needed to treat aberrations up to the 4^{th} order, that is, coma, trefoil, and spherical aberration, and produce a more leveled ablation than larger spots **(Guirao A et al, 2003& Ciccio AE, 2005)**.

Gaussian laser spots have better spot overlap than “top-hat” spots, fast scanning rates result in less tissue hydration, whereas non sequential ablation patterns in spot placement avoid heat buildup **(Guirao A et al, 2003)**.

Eye tracking of at least 200 Hz is ideally needed to track saccadic eye movement and for correct placement of the fast, small laser spots. In addition, radial compensation function, which accounts for the loss of fluence at the periphery of the laser ablation by increasing the number of peripheral pulses, was introduced as an additional feature of the wavefront-guided platforms, resulting in lower treatment-induced spherical aberrations **(Ciccio AE, 2005& Steinert RF, 2005)**.

Wavefront registration makes sure that the wavefront measured on the aberrometer matches point by point the wavefront treated when the patient is under the laser. To reach this goal, shifts in pupil position, in the vertical and the horizontal planes, as well as cyclotorsion, should be accounted for before and during treatment. To that effect, the CustomCornea system links the measured wavefront map to fixed references on the patient's eye; the surgical limbus and two marking dots ("sputniks") placed on the conjunctiva diametrically opposite on each side of the cornea **(Ciccio AE et al, 2005)**.

This process of registration was recently made automated saving time and improving accuracy **(Stienert RF, 2005)**.

The VISX Custom Vue in turn earned approval in late 2005 for **Iris Registration** technology (IR), a form of wave registration which matches reference points in the natural iris pattern to compensate for cyclotorsion and pupil centroid shift between the time of wavefront measurement and the ablation. The FDA approved Technolas 217z Zyoptix of Baush and lomb does not posses a registration system, although the new Zyoptix 100 released internationally in late 2003 relies on iris recognition technology, a form of iris registration.

Wave registration becomes very important in moderately to highly aberrated eyes, like post-LASIK eyes or postradial keratotomy, as shown by Durrie and associates **(Durrie DS et al, 2005)** on the Custom Cornea platform **(Durrie DS et al, 2005)**.

In an interventional study to analyze the predictive factors associated with success of iris recognition and dynamic rotational eye tracking on a laser in situ keratomileusis (LASIK) platform with active assessment and correction of intraoperative cyclotorsion **(Gaurav Prakash et al, 2010)**.

This study used Two hundred seventy-five eyes of 142 consecutive candidates underwent LASIK with attempted iris recognition and dynamic rotational tracking on the Technolas 217z100 platform (Techolas Perfect Vision, St Louis, Missouri, USA) at a tertiary care ophthalmic hospital. The main outcome measures were age, gender, flap creation method (femtosecond, microkeratome, epi- LASIK), success of static rotational tracking, ablation algorithm, pulses, and depth; preablation and intraablation rotational activity were analyzed and evaluated using regression models **(Gaurav Prakash et al, 2010)**.

The study concluded that Intraoperative cyclotorsional activity depends on the age, gender, and duration of ablation (pulses delivered). Femtosecond flaps do not seem to have a disadvantage over microkeratome flaps as far as iris recognition and success of intraoperative dynamic rotational tracking is concerned **(Gaurav Prakash et al, 2010)**.

5) Biomechanics and wound healing

In addition to flap creation, the ablation treatment, wound healing response (stromal remodeling, epithelial hyperplasia), and biomechanical changes of the cornea affect the result of the WFG treatment **(Potgieter FJ et al, 2005&Roberts C, 2000)**.

Corneal modeling studies have demonstrated that changes in the cornea occur outside the ablation zone, which can affect the central corneal shape. Therefore the removal of tissue based upon the WFG ablation profile is not the only factor to be considered in optimizing refractive outcomes **(Potgieter FJ et al, 2005 &Roberts C, 2000)**.

Clinical results:

Studies have confirmed the efficacy predictability, and safety of WFG customized ablation, based upon the profile of total ocular aberrations, resulting in very good to excellent outcomes for both primary ablation and enhancements. Previous studies have compared conventional and wavefront ablation with mixed visual outcomes, often based upon snellen visual acuity.

Differences in inclusion criteria, study design, laser platforms, and surgeon variables may explain the varied results. In general the change in postoperative HOA after WFG is less than for conventional, due to treatment of preexisting HOAs and less induction of new HOA. **(Lee MJ et al, 2007)** found that:

WFG LASIK resulted in a statistically significant smaller induction of HOA than:

A) Conventional LASIK

B) LASIK with the VISX S4 excimer laser; however there was no significant difference in postoperative Uncorrected Visual Acuity UCVA among the three groups **(Lee MJ et al, 2007)**.

Although the Uncorrected Visual Acuity UCVA and the refractive outcomes were similar between conventional and WFG LASIK with the AMO-VISX star 4 platform, **(Lee HK et al, 2006)** showed that WFG treatment had significantly better outcomes for contrast sensitivity, glare under mesopic conditions, and the subjective complaints than conventional LASIK. No correlation with the pupil size was found. Understanding the clinical relevance of HOA on quality of vision would increase the potential for better post operative outcomes **(Lee HK et al, 2006)**.

Wavefront optimized treatments to create an aspheric profile using certain preprogrammed corrections to better maintain the corneal shape and to induce less spherical aberration compared to conventional ablations have been devised, resulting in better visual outcomes. Spherical aberration is an important Higher Order Aberration HOA after laser vision correction that can adversely affect modulation transfer function and has been strongly correlated to undesirable visual symptoms, such as glare and starburst **(Chalita MR et al, 2004)**.

Several comparative studies have demonstrated highly effective refractive and visual outcomes with WFG LASIK (Alcon LADAR Vision or WaveLight Allegretto system) and wavefront optimized LASIK (Wave-light allegretto platform); however, WFG ablations resulted less induction of HOA than wavefront optimized treatment **(Brint SF, 2005 &Tran DB, 2006 & Padmanabhan P et al,**

2008). In a comparative contra lateral eye study by Padmanabhan et al **(Padmanabhan P et al, 2008)** the contrast sensitivity improved at low and middle frequencies in the WFG group and significantly worsened at all spatial frequencies in the wavefront optimized group **(Padmanabhan P et al, 2008)**.

A study **(Bababeygy SR et al, 2008)** of WFG LASIK for **moderate** (6.0 to 8.0 D, n=44 eyes) and **high myopia** (greater than 8.0 D, n=45 eyes) using the AMO-VISX S4 system with a **follow up** period ranging from **3 to 12 months** found that :

- 74% were within (±0.5 D)
- 94% were within (±1.0 D)
- All eyes had UCVA of 20 /40 or greater, and a small significant increase in coma and spherical aberration occurred.
- UCVA was 20/20 or better in 64% of eyes (71% of eyes with moderate myopia, 58% of eyes with high myopia) at 12 months.
- No eye lost two or more lines of best corrected visual acuity (BCVA).

These results were relatively similar to US Food and Drug Administration (FDA) data, confirming the effectiveness, predictability, and safety of WFG ablation for moderate to high myopia.

A retrospective study of **(Bababeygy SR et al, 2008)** of 316 eyes over a 3 years period found that WFG LASIK using **Technolas 217z** was highly effective for treating low to high myopia. The mean preoperative spherical equivalent was 4.91 (±1.38 D) in the low to moderate myopia group (n =172 eyes) and 9.41 (±2.4 D) in the high myopia group (n=144 eyes) for predictability:

- 85% of the low to **moderate myopia** eyes and 65% of the **high myopia** eyes were within ±0.5 D emmetropia.
- While 97% and 80% were within ±1.0 D emmeteropia.
- Under and overcorrections occurred more frequently in eyes with higher myopia.

- The **decrease in spherical aberration** at 12 months compared with preoperatively was statistically significant.
- Approximately 10% of high myopia eyes experienced symptoms of nighttime glare, but not in eyes with low to moderate myopia.
- No eyes lost Best Corrected Visual Acuity BCVA.

An advantage of this platform is the sparing of tissue ablation depth in the range of 20-25% which removes less tissue than standard laser treatment **(Bahar I et al, 2007)**.

3.5 Enhancements

Several studies have evaluated the safety and efficacy of WFG enhancements with LASIK or surface ablations to treat residual refractive errors, postoperative HOA and refractory LASIK flap striae in symptomatic patients **(Montague AA, 2006 &Kuo IC et al, 2008)** after previous keratorefractive procedures, as WFG treatment may be most beneficial in patients with highly aberrated corneas. In addition to good refractive and visual outcomes WFG enhancements resulted in reduction in HOAs **(Montague AA, 2006 &Kanellopoulos AJ, 2006)** and improvement in low contrast sensitivity and visual symptoms **(Kanellopoulos AJ, 2006)**.

A comparative study **(Alio JL et al, 2006)** of WFG versus conventional enhancement provided equivalent UCVA and refractive predictability, however; a significant increase in HOA RMS and decrease in contrast sensitivity was found in conventional group that was inversely correlated.

$$h_j = \int_{T_{ref}}^{T} C_{pj} dT$$

3.6 Customized ablation incorporating topographical data

In an attempt to overcome some of the limitations of ocular wavefront sensing , corneal wavefront aberrations are calculated from a spherical wavefront using corneal evaluation data , based upon the reference sphere at the exit pupil plane and the reference axis of the light of sight .

The corneal wavefront aberration is the major component of the total ocular wavefront aberrations profile and does not fluctuate like ocular wavefront aberrations can during data acquisition and overtime. There is no published study comparing WFG customized ablation based upon the total ocular wavefront aberration profile (traditional WFG) with the ablation profile based solely upon the corneal wavefront aberration profile. Preliminary results with corneal WFG treatment appear promising for myopia, hyperopia, and enhancement **(Zhou C et al, 2007 &Alio JL et al, 2008)**.

Topography-based profiles are calculated from a reference (ideal) spherical cornea using the videokeratography axis as the reference axis, not the line of sight. **(Vinciguerra et al, 2007)** compared WFG guided and topography guided PRK using the **NIDEK EC-5000 CX II** platforms (n=226 eyes) and found equivalent outcomes for predictability, stability safety and changes in mean total HOA.