بسم الله الرحمن الرحيم

Course on “ Wavefront Customized Surgery”

Wavefront Customized Corneal Surgery (Present and Future)

Farid Karimian M.D

Labbafinejad Medical Center

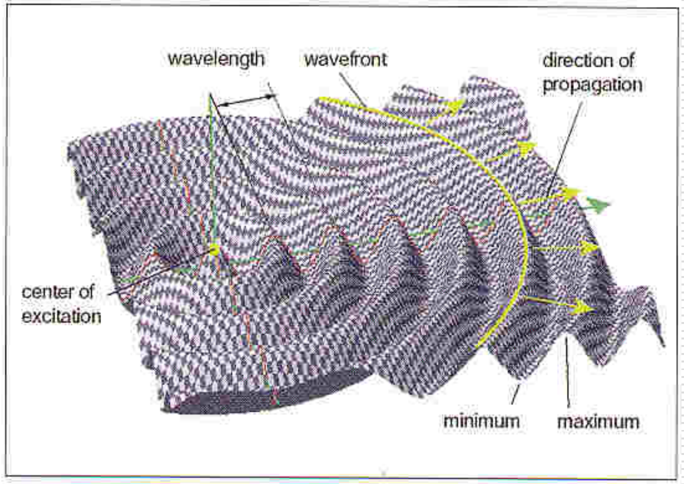
Negah Eye Center

XVth Congress of Iranian Society of Ophthalmology
October 2005

What is Wavefront?

Wavefronts:

- Are continuous iso-phase surfaces
- Are perpendicular to the directions of wave propagation
- Optical waves are 3-dimensional but wavefronts are surface



Wavefront Aberration

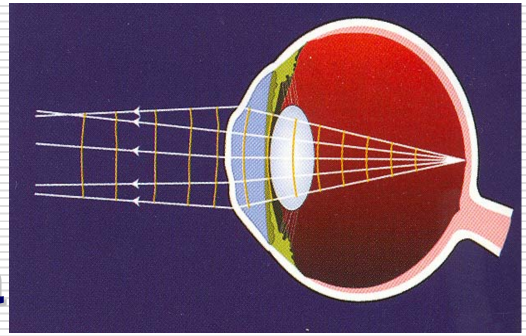
- Deviation of the actual wavefront from an ideal reference wavefront
- **Ideal eye** (aberration –free): ideal exiting wavefront is a flat plane
- **Real eye** (with optical aberrations):

  * Exiting wavefront deviates from plane wave

  * A plane wave entering the eye

  ⇩

  aberrated pattern on the retina



Principle:

- **Reversing direction and propagation of wavefront in the eye can show how it can be translated into ablation**

Aberration

- *Difference* that exists between the ideal image expected to be seen in the perfect optical system and what *actually achieved*

- *Zernike polynomials* ***are:***

  * Mathematical models of optic description

  * Defined on the circular shape basis (e.g cornea, pupil)

  * Deformation is sum of polynomials for all types of deformation

Aberration Groups

1) Chromatic:

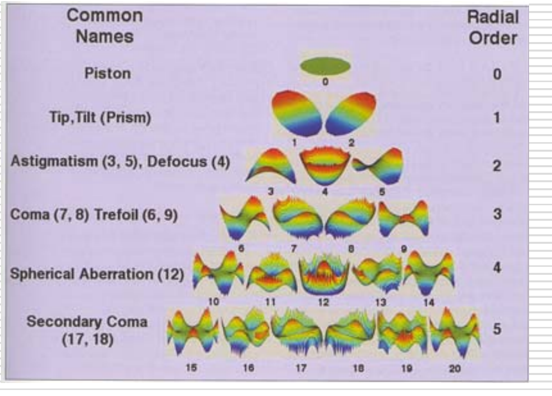
- Difference in distribution of incident polychromatic radiation throughout a medium
- Depends on light wave-length
- Normal eye chromatic aberration: 0.93 D
- Not correctable

2) Monochromatic:

- Aberration related to a specific wave-length

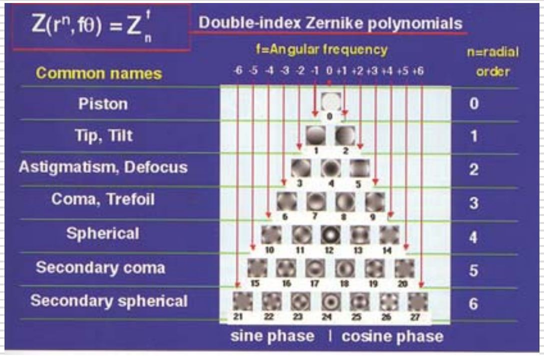
Zernike's Polynomials

- Zero order (no order)=axial symmetry, flat wavefront
- First order = linear aberration, tilting around a horizontal (x) or vertical axis (y)
- Second order = focus shift, spherical defocus or astigmatism
- Third order = corresponding to coma, triangular astigmatism
- Fourth order = spherical aberration, complex patterns
- Fifth-10th order = Irregular aberrations, important when pupil is wide dilated.



Main Aberration Types

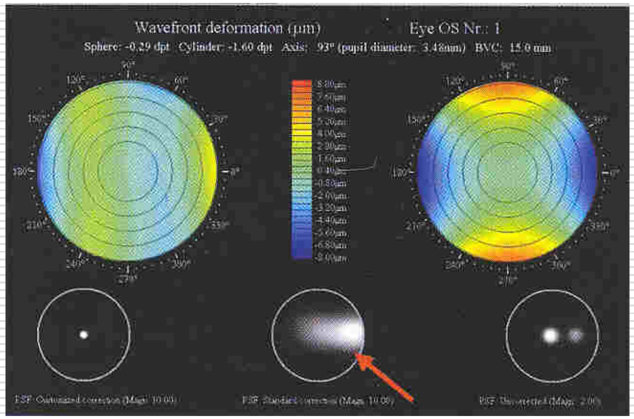
- ***Spherical refractive error (defocus):*** **simple form, myopic or hyperopic ametropia**
- ***Astigmatism:*** **different meridians focus on different planes**



- ***Spherical aberration:***
  - *** Marginal rays focus before the Para-axial rays do**
  - *** Normal eye:is about 0.50D**

Coma

- Extra-axial mono-chromatic aberration
- Incident radiation forms an angle with optical axis
- Retinal focal point (RFP) is like comet
- Astigmatism from oblique beams (or incidence):
  - extra-axial aberration, light source is not coaxial



- Distortion:- induces variable magnification of optical image in various zones of the image

Mathematical Properties of Zernike Polynomials

1- Completeness: **it can represent any aberration over a circular aperture**

2- Orthogonality: **Zernike terms can be manipulated and recombined**

3- Normality: **Zernike terms adjusted so that they contribute equally to root mean square (RMS)**

Fourier Transform

- More conveniently represent aberrations as superimposition of sinusoidal gratings of various spatial frequencies, orientations, and phases

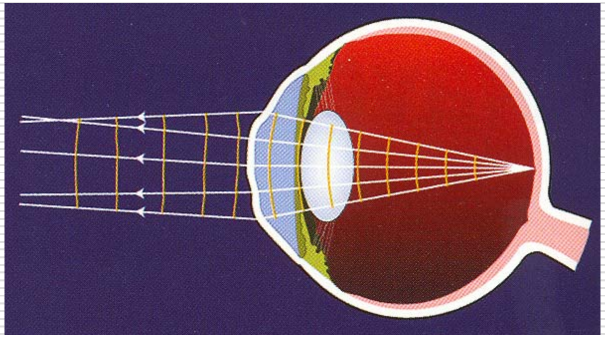
- Best describe linear aberrations (e.g scar) which Zernike is unable

Real eye with Aberrations

Considering refractive lens at corneal surface

Excimer etching by customized ablation

Converting wavefront to flat wavefront



Perfect focus on fovea

Ideal eye

Equation for Customized Corneal Ablation Depth

$$A(x,y) \times (n_{cornea} - n_{air}) = C - W(x,y)$$

n_{cornea} = corneal index of refraction

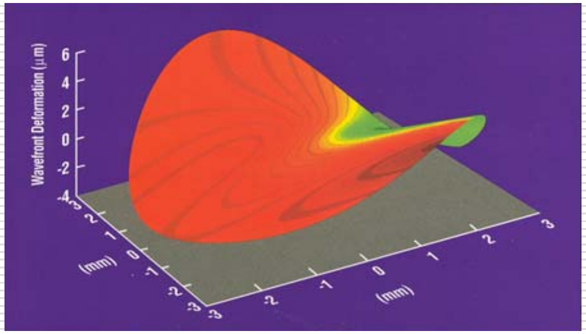
n_{air} = refractive index of air

- C= smallest constant depth needed to keep A (x,y) from becoming negative
- A(x,y)= can not take on a negative value, because ablation can not add tissue to the cornea
- Ablation of 1 micron reduces wavefront retardation by $n_{cornea} - n_{air}$ µm

Technology Requirements for Customized Ablation

Technology Requirements for Customized Corneal Ablation

- Accurate wavefront measurement device
- Precise and robust eye tracking
- Scanning Spot Laser Delivery
- Wavefront- Laser interface



Accurate Wavefront Measurement Devices

***Wavefront aberration information* is collected and measured by four different principles**

1. **Outgoing refractive aberrometry**
2. **Retinal imaging aberrametry (Tscherning)**
3. **Incoming Adjustable Refractometry (Scheiner)**
4. **Double pass Aberrametry (Slit Skiascopy)**

1- Outgoing Refractive Aberrometry

Shack- Hartman wavefront sensor

Low energy laser

↓

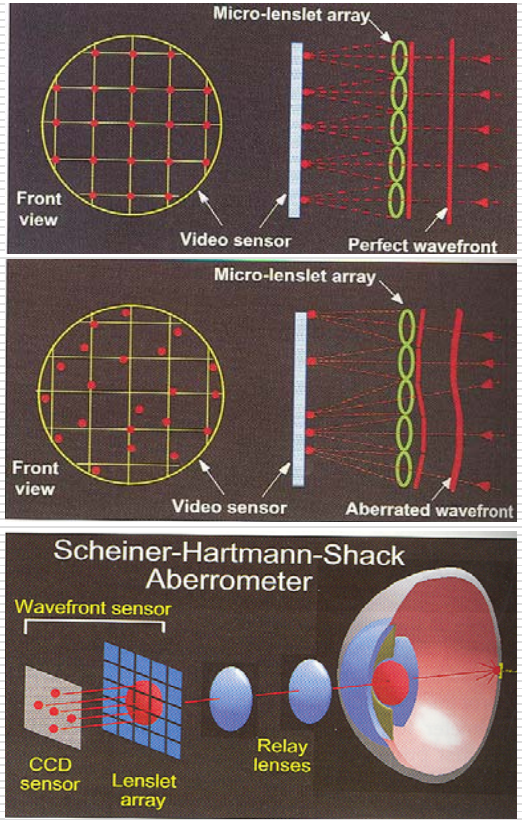
Reflection from fovea

↓

Optical structures of the eye

↓

Array of lenslets to a small spot each segment of focused wavefront



CCD detection array ↓ ⇒ ocular aberration

1- Outgoing Refractive Aberrometry

Limitations:

- Multiple scattering from subfoveal choroidal structures
- Crossover of focused spots in highly aberrated eyes
- Does not take quality of individual spots formed by lenslet array

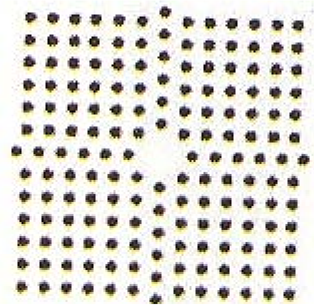
Shack-Hartman Devices

- Alcon LADARWave: 170 spots within 6.5 mm pupil
- VISX Wave Scan: 180 spots within 6 mm pupil
- Schwind aberrometer
- Bausch & Lomb Zywave: 70 spots within 6mm pupil
- Meditec WASCA: 800 spots within 7mm pupil

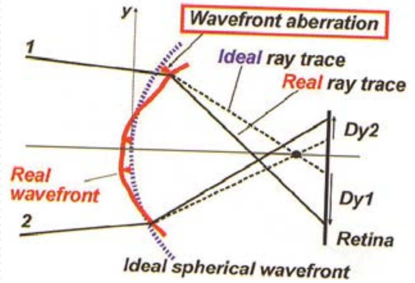
Note: *Approximately 200 spots within 7 mm pupil is adequate*

2- Retinal Imaging Aberrometry

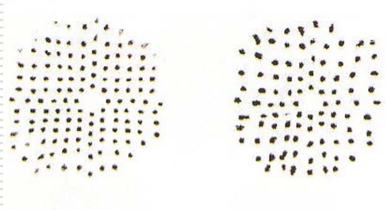
- **Tscherning and Ray Tracing: subjective measurement of monochromatic aberration**
- **Seiler used a spherical lens to project 1 mm grid pattern onto retina**
- ***Principle:* 13x13 spot grid (168 spot)**



Projection through 10mm cornea



100 spots within 7mm pupil



Paraxial aperture system

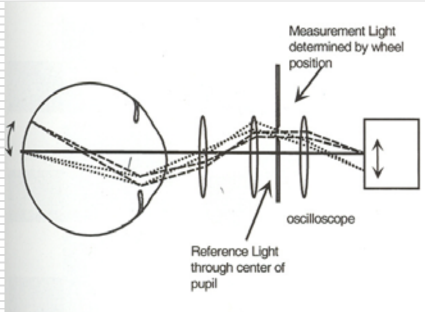
2- Retinal Imaging Aberrometry (cont)

- **Limitation:** Use of an idealized eye model (Gullstrand model I)
- **Ray tracing:** Nearly 100 sequential spots traced within 12ms within 7mm pupillary area
- **Examples:** Wavelight analyzer
  Tracey Ray Tracing

3- Ingoing Adjustable Refractometry (Scheiner)

(Spatially-Resolved Refractometer:SRR)

- **Subjective redirection of 37 peripheral beams of incoming light toward central target**



- **Limitation: time consuming procedure**

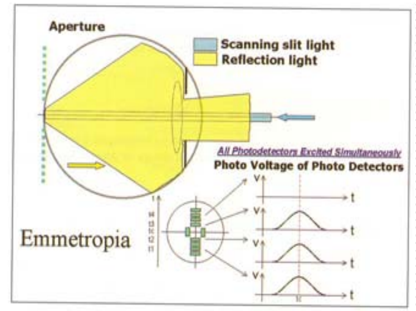
Example: **Interwave SRR**

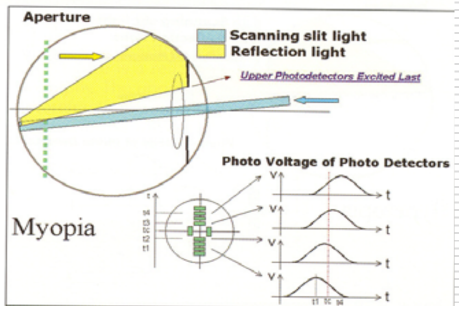
4- Double Pass Aberrometry (Slit Skiascopy)

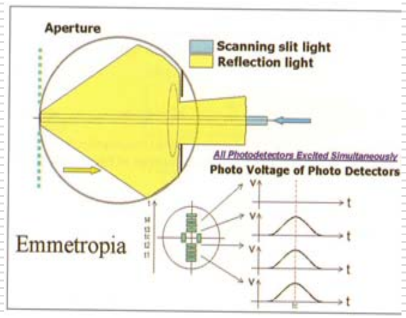
- **Considers passage of light into the eye + reflection of light out of the eye**
- **Rapid scanning a slit of light along a specific axis (Skiascopy)**

Captured fundus reflection: parallel photodetectors

- **360 meridia- 4 spot on each meridian=1440 data point**







4- Double pass aberrometry (Slit Skiascopy) (Cont)

Limitation:

- Small amount of collected axial information
- Sequential nature of capture

Example: **Nidek OPD-scan**

II-Scanning Spot Laser Delivery

1. Scanning spot size

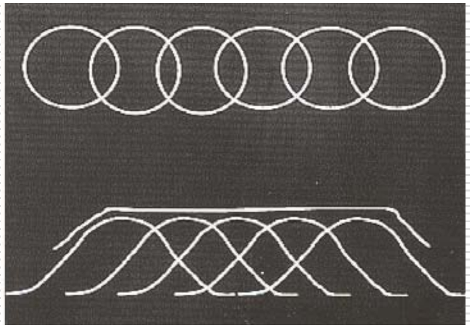
Huang et al:

- Treating up to 4th order aberrations requires a spot beam diameter of 1 mm or less
- Up to 6th order aberrations correction: requires 0.6mm spot size

Laser Device	Spot size (mm)	Scanning Rate (HZ)
LADARVision	0.8	60
Lasersight	0.6	200
Wavelight	0.95	200
Schwind	1.0	200
Zeiss Meditec (MEL 80)	0.7	250
B & L Technolas 217Z	2+0.8	100
VISX STAR S4	2+1	>10
Nidek EC-5000 CXII	2+0.8	200

2- Scanning Spot Shape (Profile)

- *Guassian Beam profile:* **LADARVision, Laser sight, Wavelight, Schwind, Zeiss Meditec**
- *Truncated Guassian beam:* **Bausch & Lomb Technolas 217**
- *Top hat beam profile:* **VISX STAR S4**
- **The most desirable profile is Guassian beam:**



*** very uniform overlap**

*** Avoids abrupt edges**

3.Scanning Spot Rate

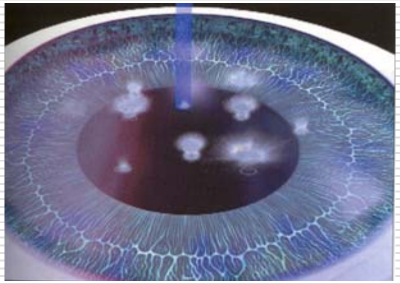
- Majority of small spot Gaussian profile lasers:

  200Hz
- *Alcon LADARVision:* 60Hz

  volume ablated per shot ablation time
- Importance of rate:

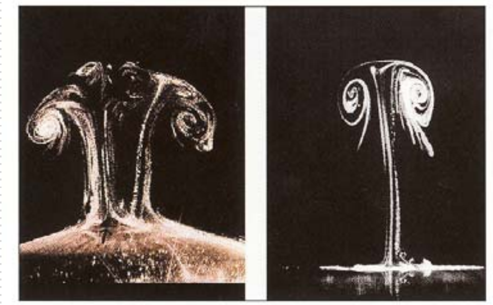
  * Slow rate stromal dehydration

  * Higher rate > eye tracking misplaced beams

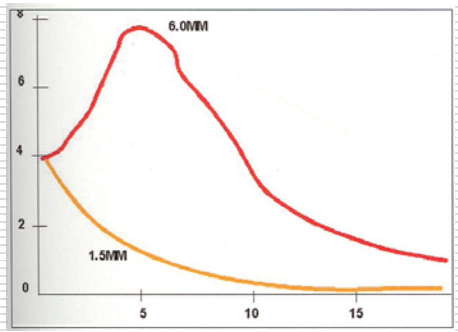


misplaced ablations

Advantages of Scanning Spot Delivery



- Reduction of steep central Island formation in respect to broad beam
- Increased surface smoothness due to perfect overlap
- Reduction in Stress waves:
  in broad beam lasers:
  * 40-80 atmospheres on cornea
  * Pressure focus 7-8mm posterior to endothelium



III- Fast Eye Tracking

Fixation- related eye movements:

Frequent saccadic eye movements

1- random

2- ~5/second

3- rapid distance traversed

III –Fast Eye Tracking… cont

Tracking Definitions

1. **Sampling rate:** Number of measuring the eye's location 60-4000Hz
2. **Latency:** * Time required to determine eye's location
   ↓
   required response calculation
   ↓
   laser tracker mirror move

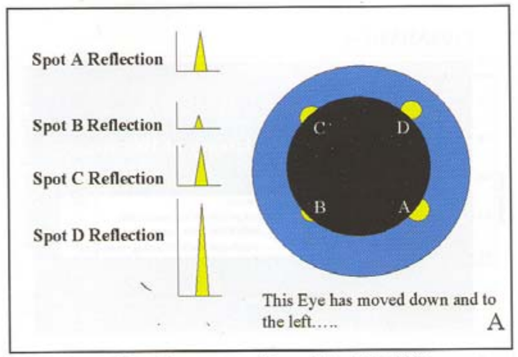
- Videocamera-based tracking 16.67ms (NTSC)to 20mS(PAL)
- Total processing delay: 33ms (NTSC) to 40ms (PAL)

3-Eye Tracker Types

Method of eye tracking	*Laser radar*	*Charged-coupled device (CCD)/infrared*
Laser system	**LADARVision**	**B&L Technololas (120)** **Nidek (60 to 200)** **VISX, Laser sight (60)** **Wavelight, Zeiss Meditec (250)**
Transmitted signal	**905 nm diode**	**None**
Detection frequency	**4000 Hz**	**60,120,250 Hz**
Response time	**3.0 ms rise time**	**50ms rise time**

4- Closed vs Open Loop Tracking

- *Open loop tracking* (Video) ⇨ new pupil image ⇨ comparison with old image
  ⇩
  single error calculation ⇨ *mirror movement*
- *Closed loop* (laser-radar) system ⇨ 905 nm laser signal ⇨ 4 (pupil) contrast boundaries
  ⇩
  variable sized spots
  ⇩
  Immediate readjustment



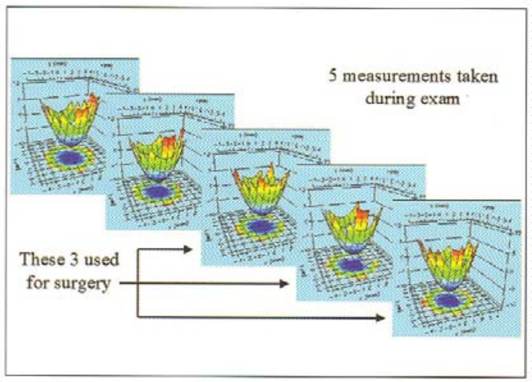
IV-LASER- Wavefront Interface

First step: Wavefront Capture & Comparion:

- Capturing the most accurate and reproducible wavefront
- Multiple captures → comparisons
  generation of a composite map
- In Alcon LADARWave aberrometer → 5 measurements

→ Three closest in agreement

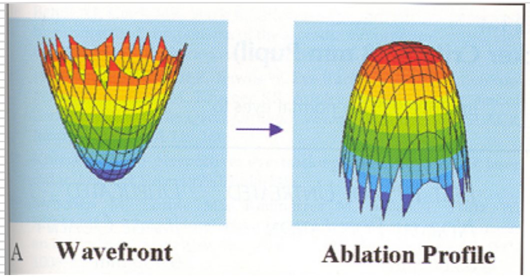
Composite profile



Second Step

Conversion to Ablation Profile:

- Ablation profile is fundamentally inverse of wavefront error map
- *Goal:* Correction of refractive error and higher-order aberrations
- Pupil diameter at least 0.5mm larger than scotopic
- Limbal marking for cyclotorsion detection



- Wavefront measurement + corneal curvature + biomechanics ⇒ ablation profile *complex*

Final Step: Dynamic Registration

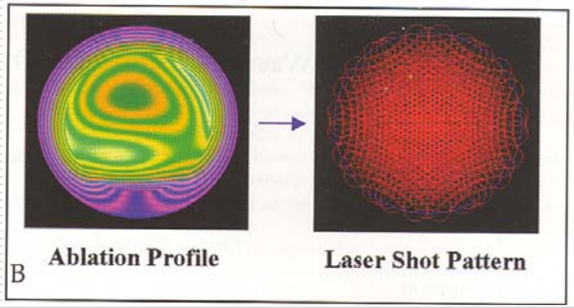
- *Ablation profile* → laser shot pattern

  ↓

  customized laser correction

  ↓

- Alignment with center of undilated pupil
- Dynamic registration → engagement of eye tracker



Dynamic Registration: Final Step
(Cont)

- First reticle → limbus ring alignment (X,Y)
- Second reticle → cyclotorsion alignment with limbal markings
- B&L Technolas 217z: iris detail used for registration and tracking

Process of Registration

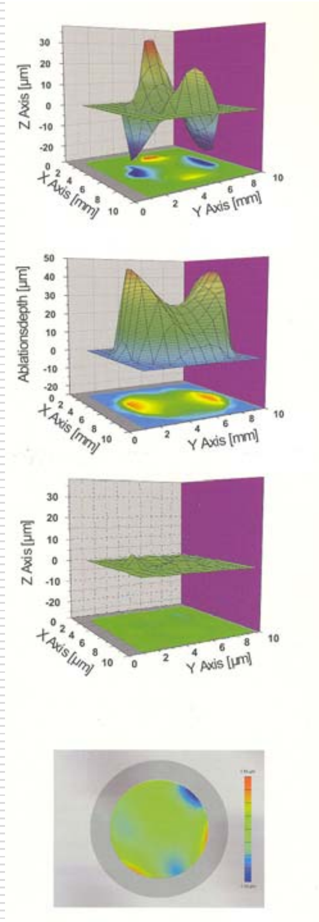
- **Most important technology requirement for customized ablation of HOA**
- **Required criteria for ideal registration and tracking:**

Lateral Decentration	*Torsional Alignment*
<50 μ	**1 degree for ideal wavefront ablation**
<200μ	**4 degrees: for achieving results consistent with best 10% of untreated normal**
<400μ	**10 degrees: only duplicate preop image quality**

What can be the Future of Wavefront Customized Corneal Surgery?

Future of wavefront diagnostics

- **Improving accurate measurement and diagnosis above current devices (6-10th Zernike order)**
- **Measuring corneal wavefront aberration and surface changes**
- **Measurement of aberrations by non-Zernike (Fourier?) algorithms**



The Future of Customization

- *"Zonal reconstruction":* **providing accurate representation of the underlying data set, minimize noise, take multiple measurements**

- **More sophisticated clinical aberrometer**
greater density of lenslets →
multiple sampling over time →
adaptive optic capabilities

Future of Customized Corneal Ablation

LASIK vs surface ablation

- Each microkeratome induces specific "flap only" aberration

  (flap size, thickness)
- Considering "flap aberrations" in total treatment calculations

Future of Customized Corneal Ablation … cont.

Surface Ablations:

- Show promising results with use of
- immunomodulating agents
- Better control of cellular and biochemical reactions
- Introduction of new drugs to better regulate wound healing and refractive outcome
- Gene therapy for better control of post laser keratocyte activation and wound healing

Multifocal Ablation

- Presbyopia: Customized multifocal ablation
- Aberrations may be induced when creating multifocality
- Potential loss of contrast sensitivity and quality of visual function
- Future results will be improved:

  * Wavefront mapping, sophisticated eye
    trackers corneal registration

  * Preoperative simulation of postop condition

Laser Delivery Refinements

- Correction of higher orders of aberration needs smaller spot delivery
- >5th order → requires 0.6-0.8mm spot size
- Smaller spot size needs faster and better eye trackers
- Smaller ablation depth per pulse provides ideal correction profile for higher orders

Laser Delivery Refinements

- **Katana solid state excimer laser: very small spot (0.2 mm), rapid laser delivery rate, rapid eye tracker (even rotational)**
- **Accurate registration: iris recognition by B&L Technolas, VISX**

Environmental- Interface Corneal Ablation Control

- **Environmental factors: temperature, humidity, physical variables of cornea**
- **Operating suite control: already done**
- ***Microenvironment* (around cornea) control: essential for outcome predictability**
- **Online pachy- and topography for intraoperative control: more precise**

Adaptive Corneal Correction

- **Intraoperative measurement of refractive and ablation profile of the eye**
- ***Not* possible with LASIK or surface ablation**
- **Adaptive LTK: real-time intraoperative measurement of wavefront errors**
- **Developing threshold for certain refractive and wavefront outcome: stop treatment when ablation corrected and goal reached**

Customized Corneal Ablation

- *Customized LASIK & PRK* **will dominate in next few years**
- **Speedy recovery, good quality of vision satisfactory outcome**
- *Disadvantage* **of conventional refractive surgery in some patients:**
  - * Increase in HOA
  - * Reduction in visual quality

Customized Corneal Ablation

Advantage of customized corneal ablation:

- Reduction of HOA
- Sharper contrast
- Superior visual outcomes

Customized corneal procedures seems to remain an option for next two decades

Wavefront Customized Visual Correction

Ocular wavefront sensing:

- Will be increasingly employed
- Will become routine in vision assessment

Wavefront customization is employed to optimize any refractive surgery procedure

Wavefront Customized Visual Correction (cont)

Future wavefront customized refractive procedures

- **Implantation of optimized IOL's e.g Technis aspheric lens**
- **Customized IOL's preinsersion, customized phakic IOL's**

Wavefront Customized Visual Correction (cont)

Customized IOL's post-insersion:

- **Calhoun laser adjustable lens**
- **Customized adaptive correction**
- **Accommodating IOL customization**
- **Capsular filling customization**
- **Customized corneal inlay/ on-lays**
- **Photophaco reduction and modulation**

Conclusion

- **Wavefront measurement devices and consequently wavefront correction procedures are still in process of evolution**

- **Achievement of *"supervision":* with advancement in current procedures will not be a dream in near future**

Thank You for Your Kind Attention!!