Transferring planned profiles into corrections

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Historical perspective

1980’s
Munnerlyn’s equation for spherical corrections
Small optical zones
Visual symptoms

Early 1990’s
Aspheric ablation profiles by adjustment of Munnerlyn’s equation
Complicated eyes could not be treated
Topography based treatments
Mid 1990’s
Maintain the physiological aberrations without inducing new aberrations
Wavefront optimized profiles
Unsatisfying results
Uncorrected higher order aberrations
End 1990’s
Each profile has it’s specific indication
Wavefront guided ablation profiles

Clinical indications

• Wavefront optimized ablation profiles
  Maintain the physiological condition
• Q – value adjusted ablation profiles
  Hyperprolate cornea for enhanced monovision
• Wavefront guided ablation profiles
  Improve the optical quality of the total eye
• Topography guided ablation profiles
  Therapeutic treatments for vision enhancement

Wavefront – based ablations

Wavefront
Ablation profile
Wavefront-based ablations

Pre-OP  
Post-OP 6 months

Total wavefront
Wavefront of higher orders

Ablation profile used!
“classical” ablation profile

Make sure your indications are right!

Effectiveness of correction evaluated by indirect measures:

Goal of refractive surgery: Eliminate refractive errors by applying changes to corneal curvature

→ overlap pre- and post-operative corneal topographies

Effective amount of corneal tissue removed?

Optical zone

- Peripheral fluence loss
- Corneal hydration changes
- Laser fluence variations
- Eye movements
- Post-op corneal smoothing
- Biomechanical changes
Overlap of topography data is not trivial.

Subtraction of pre- and post-operative topographies often yields large amounts of profile tilt and highly asymmetrical structures.

Problem of ablation or overlap?

Method: 3-D profile matching

Analysis of the effective tissue removal yields valuable information on the quality of the refractive laser platform.
Results
Mean relative difference between attempted vs. achieved profiles

Platform 1
ERROR > 23%

Platform 2
ERROR < 8%

Results
Mean difference between attempted vs. achieved profiles

Platform 1
ERROR > 7 µm

Platform 2
ERROR < 3 µm

Results
Mean absolute difference between attempted vs. achieved profiles

Platform 1
ERROR > 7 µm

Platform 2
ERROR < 4 µm
Discussion

VISX SA = 0.2 Micron

Expected targeting precision of VISX laser

Yellow: Defocus of -2.7 D

Superimposed spherical aberration of medium magnitude ($C_{12}=0.2 \mu m$)

Platform 1 ERROR > 7 µm

WaveLight SA = 0.2 Micron

Expected targeting precision of WaveLight laser

Green: Superimposed spherical aberration of medium magnitude ($C_{12}=0.2 \mu m$)

Platform 2 ERROR < 4 µm

Discussion

VISX SA = 0.5 Micron

Expected targeting precision of VISX laser

Yellow: Defocus of -2.7 D

Superimposed spherical aberration of medium magnitude ($C_{12}=0.5 \mu m$)

Platform 1 ERROR > 7 µm

WaveLight SA = 0.5 Micron

Expected targeting precision of WaveLight laser

Green: Superimposed spherical aberration of medium magnitude ($C_{12}=0.5 \mu m$)

Platform 2 ERROR < 4 µm
Optical outcomes after WFG

6 mm pupil

Take home message

Make sure that your laser is delivering what you have planned!

Misalignment – undesired influence factor

Centration: A task with 6 degrees of freedom

The coordinate systems used in the measurement (M) and the treatment (T) have to coincide exactly!
**Required Accuracy**

Treat 95% of normal eyes to:

<table>
<thead>
<tr>
<th></th>
<th>Diffraction limit</th>
<th>10th percentile of rms of normal eyes</th>
<th>Same image quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torsional alignment</td>
<td>3 mm</td>
<td>3 deg</td>
<td>6 deg</td>
</tr>
<tr>
<td></td>
<td>7 mm</td>
<td>1 deg</td>
<td>4 deg</td>
</tr>
<tr>
<td>Lateral centration</td>
<td>3 mm</td>
<td>0.21 mm</td>
<td>0.41 mm</td>
</tr>
<tr>
<td></td>
<td>7 mm</td>
<td>0.07 mm</td>
<td>0.22 mm</td>
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</tbody>
</table>

**Centration**

- Precise lateral and torsional centration is required for high precision in customized treatments.

**Misalignment of entire Ablation profile**

Each pulse can be misaligned from the ideal incident position.

**Reasons?**

Profile is approximated by overlapping a finite number of single laser pulses (Gaussian or top hat intensity profile).

**Scanning-spot lasers**

Ablation profile

Treatment zone

Optical zone

Laser pulses
Residual surface roughness within the optical zone.

Roughness reduced by:
- Gaussian Beam Profile
- Small Pulses (Diameter)
- Small Ablation Depth / Pulse

Contour limit: ± 1µm

Desired ablation

Actual ablation

C7 = 0.5µm
The illumination problem

Fluence losses

\[ \text{Fluence losses} \]

\[ F = 150 \text{mJ/cm}^2; R = 6.5 \text{ mm} \]
\[ F = 150 \text{mJ/cm}^2; R = 7.0 \text{ mm} \]
\[ F = 150 \text{mJ/cm}^2; R = 7.8 \text{ mm} \]
\[ F = 150 \text{mJ/cm}^2; R = 8.3 \text{ mm} \]

The illumination problem

Fluence losses

Surface heating – 1000 Hz Laser

Myopic correction of -3 dpt / 6.5 mm OZ

Surface heating – 1000 Hz Laser

Myopic correction of +4 dpt / 6.5 mm OZ
Different tool paths

- Line scan
- Ring scan
- Random scan
- Gaussian distribution
- Standard scan
- Minimum thermal load

Problem of coherent tool path algorithms

Max. Temperature

- Time sequence used to place the laser spots onto the cornea has a significant impact on the corneal heating and surface quality.
- Intelligent algorithms are required for ideal time sequences in high repetition rate laser refractive surgery.
Eye movements
- Parallax Error
- Limited accuracy (Resolution)

Latency
- Limited accuracy
- Static misalignment

How does latency cause positioning errors?

Image Acquisition → Image Transfer → Image Processing → Position Control → Ablation

Eye Tracker → Scanner Device

Eye - tracking

The eye moves during treatment
Eye Motion during Latency => Positioning Error

Eye movements & Latency

No compensation, Freq 250 Hz
SID: 100 microns

Movement artefacts
Latency: 100 ms
SID: 60 microns

Example: 4D myopic correction (Spot 500 / 0.5 microns)

Compensation with 0 ms latency
Compensation with 100 ms latency

Example: Irregularity radial order n=4 (Spot 250 / 1.0 microns)
(Primary spherical aberration)

Ideal ablation profile
Ablated w 0 ms latency
Ablated w 100 ms latency
Influence of laser spot parameters

<table>
<thead>
<tr>
<th>Diameter (µm)</th>
<th>Ablation Depth (µm)</th>
<th>Latency (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>0.25</td>
<td>2, 5, 30, 100, No eye-tracing</td>
</tr>
<tr>
<td>250</td>
<td>1.0</td>
<td>2, 5, 30, 100, No eye-tracing</td>
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Keep in mind

- Each spot configuration (diameter & ablation depth per pulse) requires an adequate small latency for the scanning / eye-tracing module

Summary

- Each ablation profile has its specific indication.
- The accurate tissue removal stands for the quality of the refractive laser platform.
- Precise lateral and torsional centration is required.
- Intelligent algorithms are required to avoid significant corneal heating and to achieve good surface quality when using high repetition rate excimer lasers
- Each spot configuration (diameter & ablation depth per pulse) requires an adequate small latency for the scanning / eye-tracing module

Conclusion

- Discussions about the right ablation profiles are not sufficient, if the delivery of the planned profile is still the largest source of error in corneal laser surgery
Thank you