Excimer Beam Considerations for Wavefront Surgery

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Overview

- Corneal ablation behavior
- Ablation efficiency
- Treatment fidelity
- Ablation byproducts
Ablation Behavior

- Most fundamental consideration for laser ablation is how much tissue does the laser remove per unit energy.
Ablation Behavior

- For organic materials there is a fairly consistent relationship over a large fluence range between the incident laser fluence and the ablation depth in the target:

\[ d = \frac{1}{\alpha} \ln \left[ \frac{F}{F_{TH}} \right] \]

- \( d \) = Ablation depth per pulse
- \( \alpha \) = Material absorption coefficient
- \( F \) = Incident laser fluence per pulse
- \( F_{TH} \) = Ablation threshold fluence
Example Ablation Behavior for Polyethylene Terephthalate
Ablation Behavior for Cornea

- Measuring the ablation rate in cornea directly is very difficult to do
- Based on composite results from many studies we estimate the behavior to be:

\[
d = (0.34 \mu m) \cdot \ln \left( \frac{F}{60 mJ/cm^2} \right)
\]

- This is consistent with results we see in clinical studies
Ablation Efficiency

- In performing laser surgery we want to be efficient with the laser beam (i.e., we want the “biggest bang for the buck”)
  - Minimize corneal exposure to UV radiation
  - Minimize procedure time

- This means we want to operate at a laser fluence that provides high efficiency:
  - Laser efficiency = Volume removed / pulse energy
Ablation Efficiency

- For a “top-hat” (uniform fluence) laser beam the efficiency is:
  \[ Efficiency_{Tophat} = \frac{\ln\left( \frac{F}{F_{TH}} \right)}{\alpha F} \]

- For a Gaussian laser beam (useful for reasons explained below) the efficiency is:
  \[ Efficiency_{Gaussian} = \frac{\left( \ln\left[ \frac{F_P}{F_{TH}} \right] \right)^2}{2\alpha F_P} \]
Ablation Efficiency Curves

![Ablation Efficiency Curves Graph](image)

- **Ablation Efficiency (pl/mJ)**
- **Peak Fluence (mJ/cm²)**

- **Gaussian**
- **Top Hat**
Ablation Efficiency

- It is interesting to note that commercial devices typically operate near the peak of the relevant efficiency curve.
- This adds credence to the basic assumption of the corneal ablation behavior.
Ablation Efficiency Curves

Ablation Efficiency (pl/mJ) vs. Peak Fluence (mJ/cm²)

- Gaussian
- Top Hat

Brands:
- Summit
- VISX
- Alcon
- WaveLight
Why Gaussian?

- Accurate ablations are possible with any ablation profile
  - IF enough pulses are delivered to the right places
- Highly overlapped Gaussian pulses yield particularly smooth treated beds
Why Gaussian?

- In addition Gaussian pulses operating near the peak of the efficiency curve are minimally affected by the corneal curvature.
Corneal Angle of Incidence

- Reflection losses are small under realistic angles
  - Corneal reflectivity goes down during ablation
- Peak fluence decreases with increasing angle of incidence
  - Peak ablation depth goes down
- However, irradiated area increases at the same time
  - Ablation volume minimally affected if Gaussian beam operates near efficiency peak
Spot Size

- Gaussian beam with ideal peak fluence can still be of any diameter
- A bigger diameter beam will complete surgery faster
- A smaller diameter beam will be able to perform more complex corrections
- What is the right diameter for realistic custom surgeries?
Higher Order Aberrations

6.5 mm analysis diameter

RMS Error (microns)

- Normal
- LASIK
- Symptomatic LASIK
- Keratoconus
- RK
Higher Order Aberrations

- For untreated eyes aberrations are trivial beyond $\sim 6^{\text{th}}$ order
- In some cases $\sim 8^{\text{th}}$ order terms may be significant
- Therefore treatment beam should be effective to $\sim 8^{\text{th}}$ order
- Mathematical modeling and test ablations in plastic indicate beam with FWHM diameter of 0.75 mm or less is suitable
8th Order Treatment Simulation
(6.5 mm OZ + 1.25 mm Blend)

$Z_8^0$  $Z_8^8$

Pre-Ablation

Post-Ablation
Ablation Byproducts

- The ablation event produces 2 things
  - Debris plume in the air above the eye
  - Some heating of the corneal bulk
- For accurate, safe surgery these cannot interfere with the treatment
Ablation Plume

- The ablation plume disperses on a millisecond timescale after the pulse
Corneal Heating
Ablation Byproduct Considerations

- By moving the laser beam around the cornea, and only periodically visiting any one site, we can avoid plume interference and prevent excessive heating.
- Doing this allows for Gaussian beam firing at >> 100 Hz.
- Operation at ~1 kHz or above may be problematic.
What is Achievable?

4 diopter ablation in plastic
Summary

- Many excimer beam considerations for refractive surgery
  - Energy, profile, size, speed, byproducts etc.
- Control of these parameters can result in a highly efficient beam optimized for clinical application