Modeling Results of Crosslinking-Driven Refractive Treatment

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Questions about Crosslinking-Mediated Refractive Treatments

- Which types of refractive error could be treated?
- How much effect can be expected?
- Will it work, and how do we determine optimal patterns?
Approach to patient-specific modeling

Geometry

Material properties

FE Mesh

Simulation

Load

Stress/strain/shape & optical solutions

Refine surgical algorithm

Comparison to actual/desired outcome
Clue #1: Corneal displacement after 6D myopic LASIK with different elasticity

- High stiffness => overcorrection
- Low stiffness => undercorrection (± ectasia)

Sinha Roy and Dupps, JRS 2009
Clue #2: Reducing local elastic modulus simulates KC progression (steepening)

Roy & Dupps, IOVS 2011
Clue #3: Crosslinking flattens the cornea

- 23 eyes, progression halted, 70% regressed
- UVA/riboflavin, broad zone treatment

Wollensak et al, AJO 2003
Clue #4: Localized treatment can be leveraged for greater flattening effect

Roy & Dupps, IOVS 2011
Simulation-Based Studies of Crosslinking-Mediated Refractive Treatments

- **Purpose:** To test different patterned approaches to refractive treatment in patient-specific 3D FE models

- **Methods:**
  - *Generate 3D patient geometries* from Scheimpflug tomography, create 3D fiber-dependent anisotropic hyperelastic FE cornea-scleral model
  - *Simulate treatment* pattern representing the effective stiffening pattern in the cornea
  - *Assess refractive effect* estimated from resultant change in curvature
Myopia treatment (central 4mm)

Roy & Dupps, 2012
Hyperopic treatment
8-10-mm annulus, 1.5x stiffening
## Hyperopic treatment results

<table>
<thead>
<tr>
<th></th>
<th>1.5X stiffening</th>
<th>3X stiffening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preop K</td>
<td><strong>41.70</strong></td>
<td>41.70</td>
</tr>
<tr>
<td>3-4-mm</td>
<td>41.47</td>
<td>41.28</td>
</tr>
<tr>
<td>6-8-mm</td>
<td>42.24</td>
<td>43.27</td>
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<tr>
<td>6-7-mm</td>
<td>42.04</td>
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<tr>
<td>7-8-mm</td>
<td>41.91</td>
<td></td>
</tr>
<tr>
<td>8-10-mm</td>
<td><strong>42.47</strong></td>
<td></td>
</tr>
</tbody>
</table>

mean tangential curvature, central 3mm (D)
Patterned CXL treatment of astigmatic error

Rounded bowtie  butterfly  center-sparing  linear bowtie

Treatment axis is **OPPOSITE** the steep axis, specified 2x stiffening

Seven et al, JCRS 2014
Seven et al, JCRS 2014
Rounded bowtie pattern

Seven et al, JCRS 2014
Butterfly pattern

Seven et al, JCRS 2014
Center-sparing butterfly pattern

Seven et al, JCRS 2014
Linear bowtie pattern

Seven et al, JCRS 2014
## Astigmatism magnitude (sim K, D)

<table>
<thead>
<tr>
<th>Patient</th>
<th>Astigmatism 1</th>
<th>Astigmatism 2</th>
<th>Astigmatism 3</th>
<th>Astigmatism 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.99</td>
<td>-0.92</td>
<td>-0.48</td>
<td>-1.1</td>
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<tr>
<td>2</td>
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<td>-1.12</td>
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<tr>
<td>3</td>
<td>-1.01</td>
<td>-0.99</td>
<td>-0.53</td>
<td>-1.12</td>
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<tr>
<td>4</td>
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<td>-1.02</td>
<td>-0.55</td>
<td>-1.1</td>
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<tr>
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<td>0.81</td>
<td>0.37</td>
<td>-1.09</td>
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<tr>
<td>7</td>
<td>-0.1</td>
<td>0.69</td>
<td>0.24</td>
<td>-0.74</td>
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<td>8</td>
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<td>-0.58</td>
<td>-1.15</td>
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<tr>
<td>9</td>
<td>-0.79</td>
<td>-0.78</td>
<td>-0.45</td>
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<td>10</td>
<td>-0.32</td>
<td>-0.29</td>
<td>-0.34</td>
<td>-1.2</td>
</tr>
</tbody>
</table>

Seven et al, JCRS 2014
Effect of stiffening factor with linear bowtie: preop astigmatism 2.2D

Preop

Higher-Order Aberrations

Seven et al, JCRS 2014
2x stiffening (1.1D)

Postop k=2

Higher-Order Aberrations

Seven et al, JCRS 2014
4x stiffening (0.4D)

Postop k=4

Higher-Order Aberrations

Seven et al, JCRS 2014
6x stiffening (0.2D)

Postop k=6

Higher-Order Aberrations

Seven et al, JCRS 2014
Conclusions

- Localized flattening effect of stiffening can be leveraged to achieve refractive effects

- Myopic treatment has little astigmatic effect

- Astigmatic treatment demonstrates coupling, preserving spherical equivalent
Crosslinking-Based Refractive Treatment

- Stiffening is an attractive alternative or adjunct to incision, ablation, extraction

- Simulation-based approach lends well to
  - *In silico* testing of candidate treatments
  - Individualized customization of crosslinking patterns (FEA-based algorithm)