Phase-contrast optical metrology for depth-resolved corneal deformation measurements

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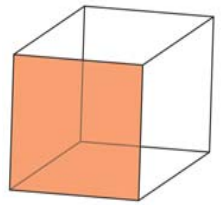
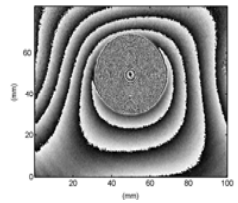
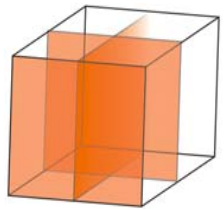
Outline

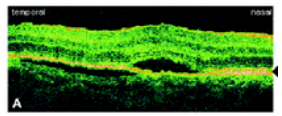
- Surface interferometry limitations



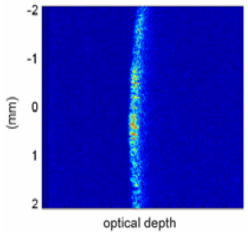


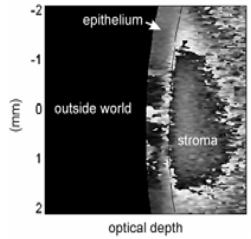
- Optical coherence tomography to image internal microstructure.



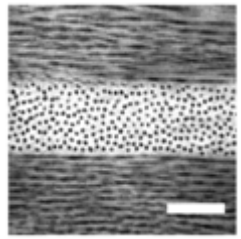


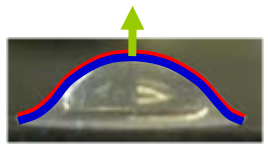
- New method that combines both worlds.
- Displacement fields through a cross section of a porcine cornea





- Comments on experimental challenges, corneal structure and phantoms towards identification of depth-resolved modulus





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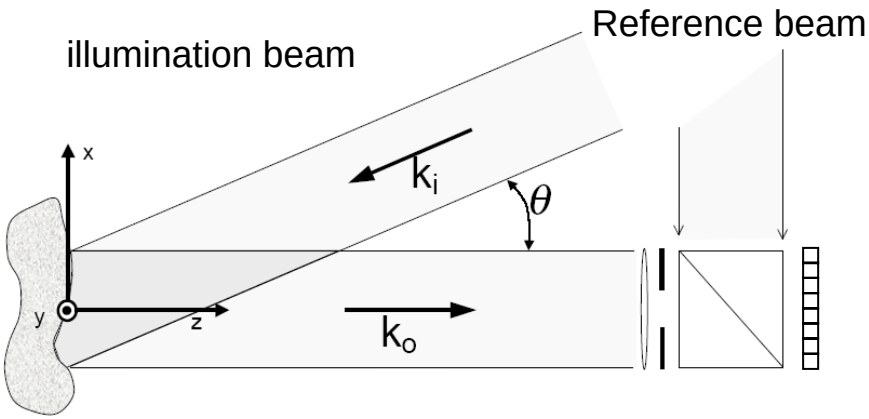
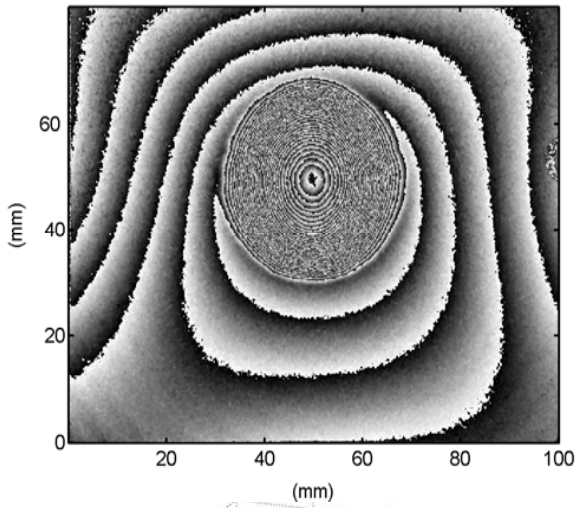
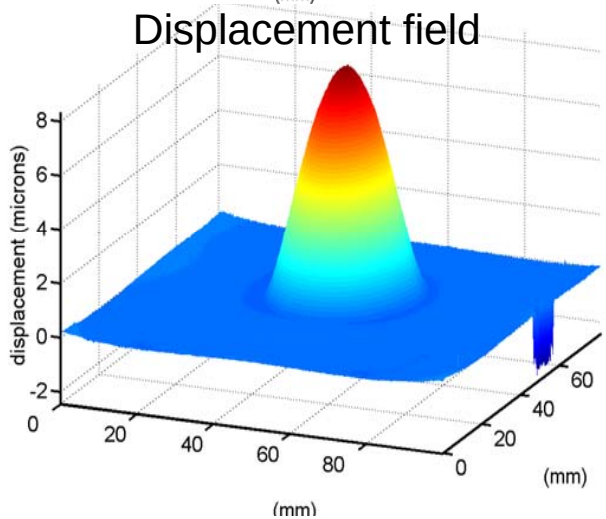
Surface interferometry



Wrapped phase



Displacement field



- Only surface displacements are obtained.
- Internal structure and strains difficult to estimate through inverse problem methods.

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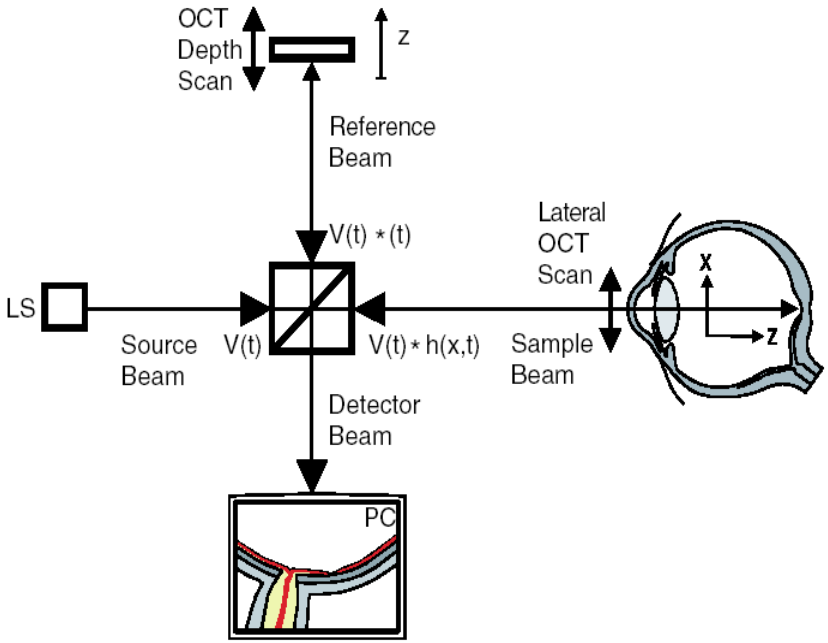
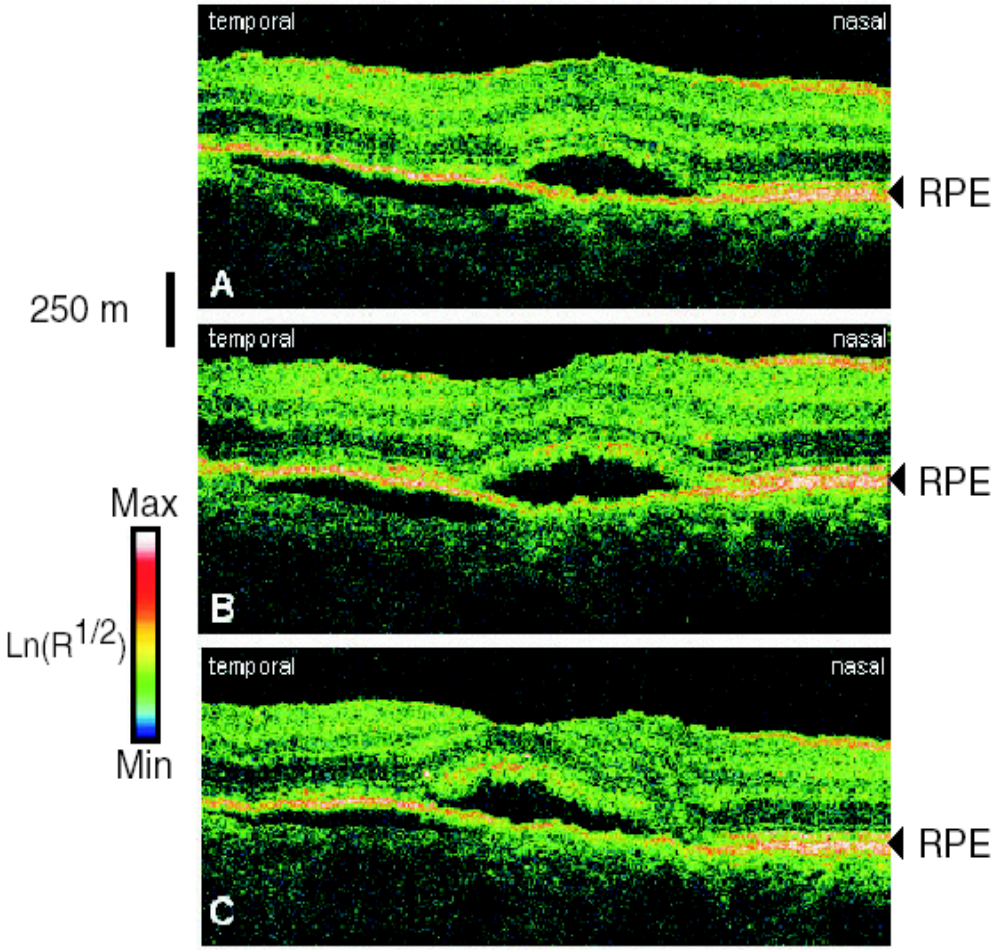
Optical coherence tomography





[Fercher et al. (2003) *Rep. Prog. Phys*. **66:**239–303]

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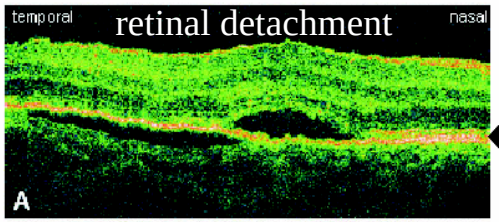
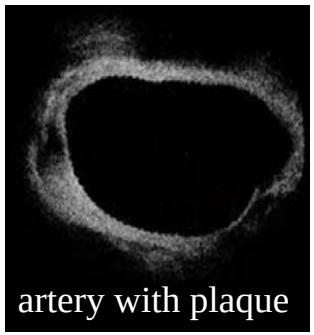
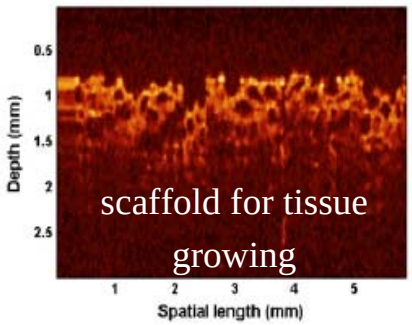
Structure and deformation

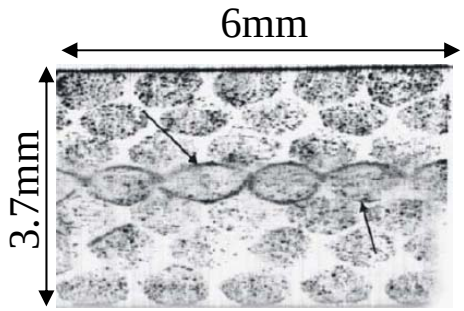
Structure

Optical Coherence Tomography







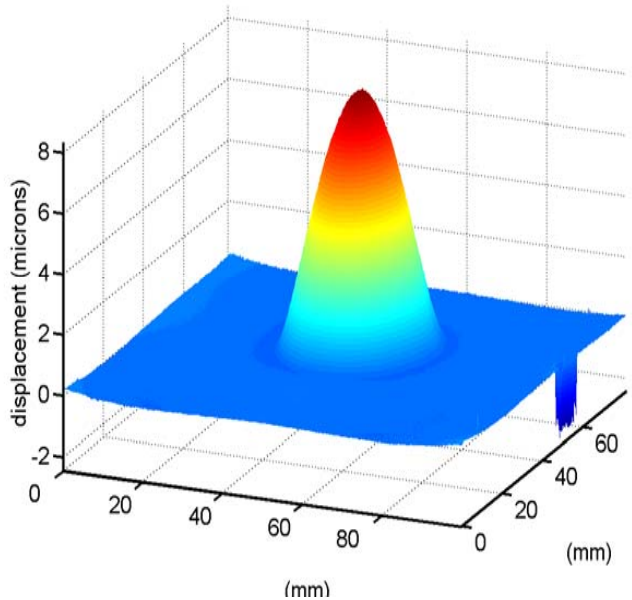


glass fibre composite

- Structure **through the thickness**

Deformation

Interferometry



- **Optical phase** based
- High sensitivity (~10nm)
- **Surface** measurements

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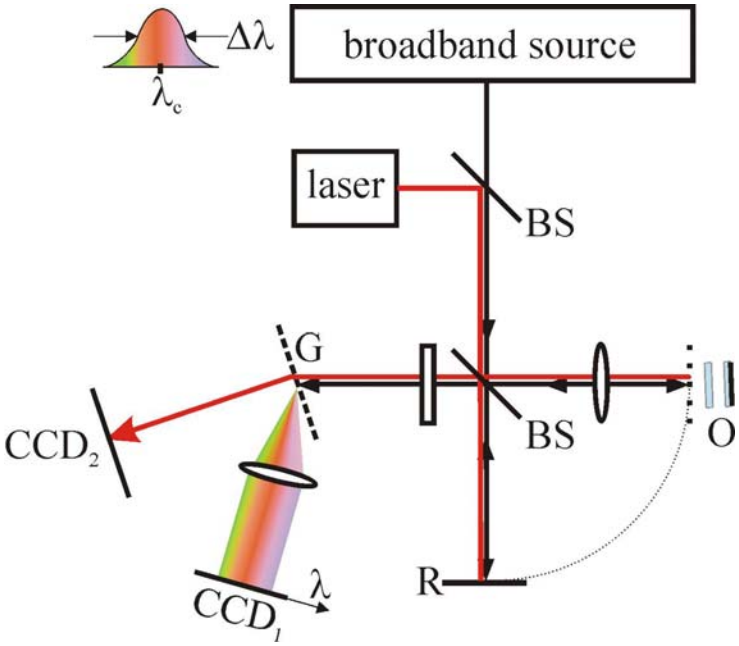
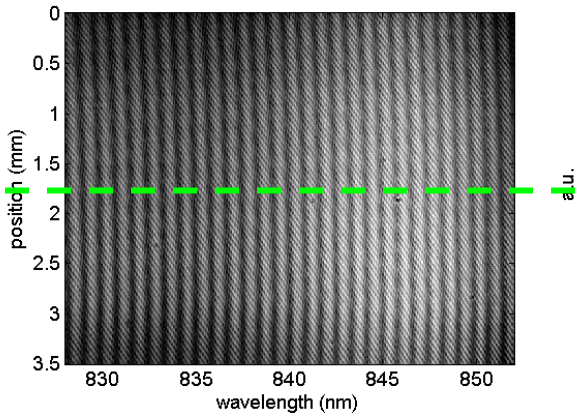
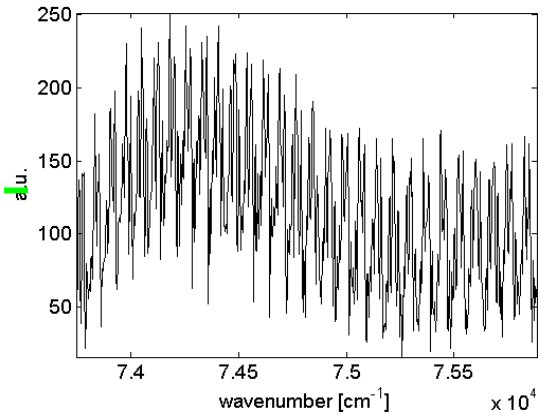
Spectral Optical Coherence Tomography

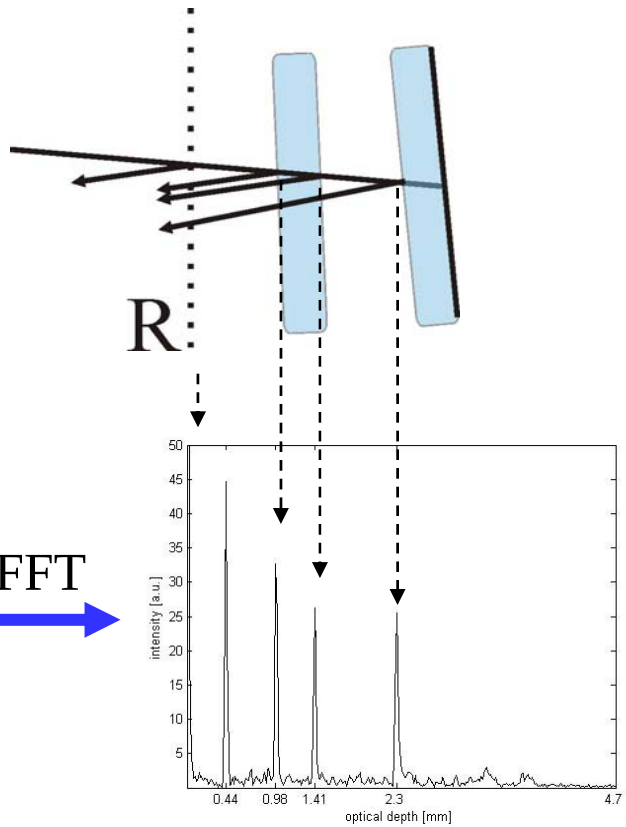


[M de la Torre-Ibarra, P D Ruiz and J M Huntley (2005), *Opt. Exp.* 14:9643-9356]





FFT



[M de la Torre-Ibarra, P D Ruiz and J M Huntley (2005), *Opt. Exp.* 14:9643-9356]

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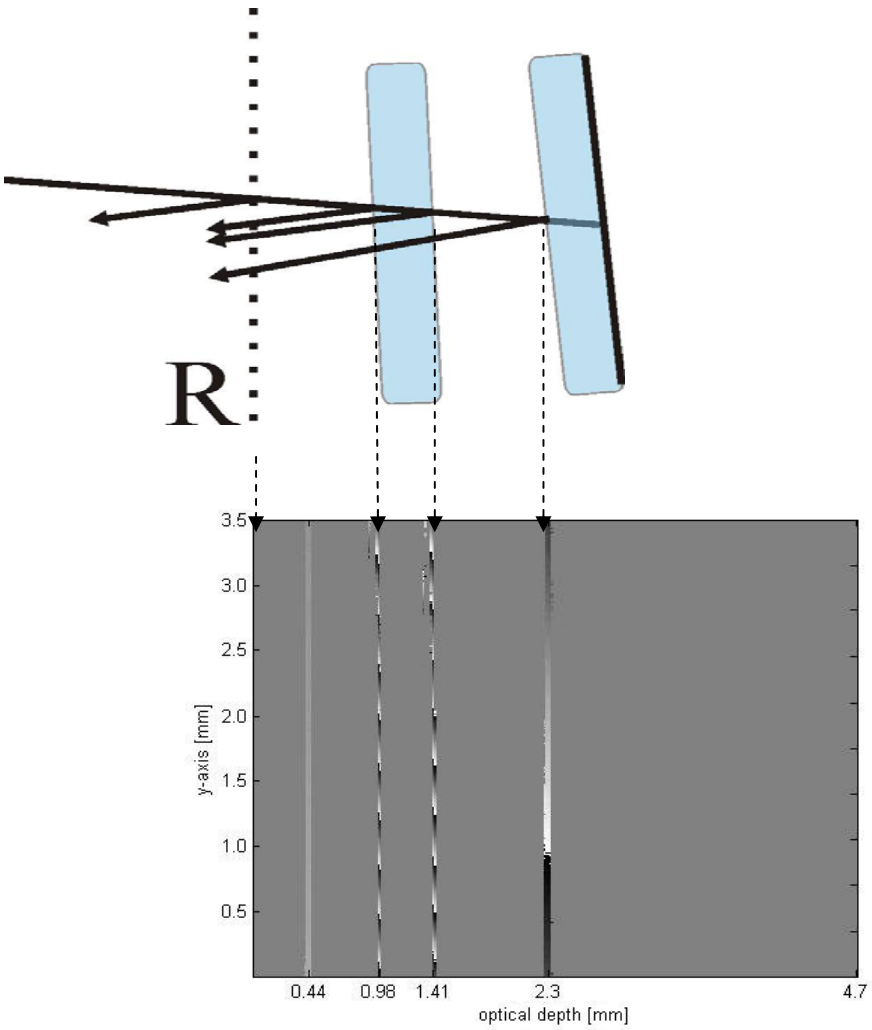
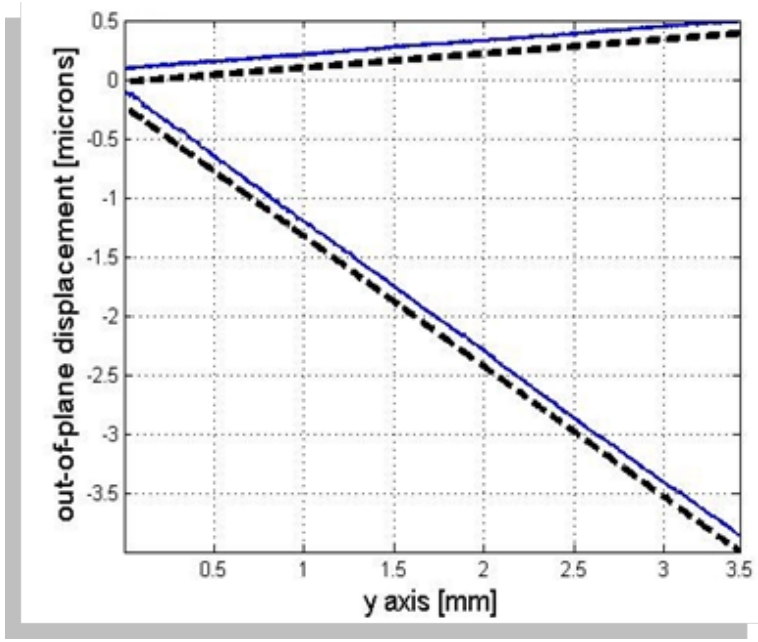
Depth-resolved displacement measurement



[M de la Torre-Ibarra, P D Ruiz and J M Huntley (2005), *Opt. Exp.* 14:9643-9356]



[M de la Torre-Ibarra, P D Ruiz and J M Huntley (2005), *Opt. Exp.* 14:9643-9356]

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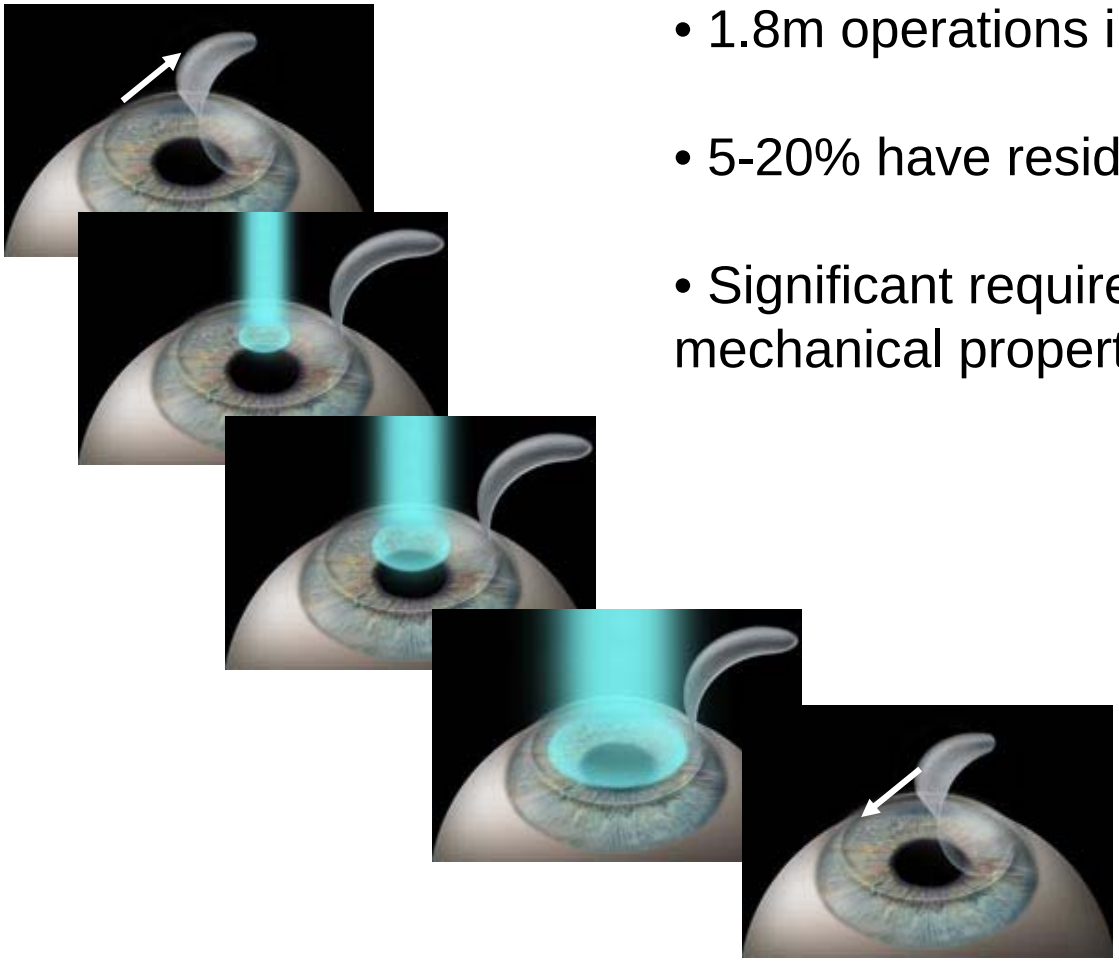
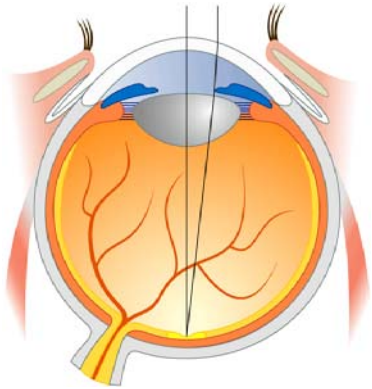
Refractive surgery / corneal biomechanics

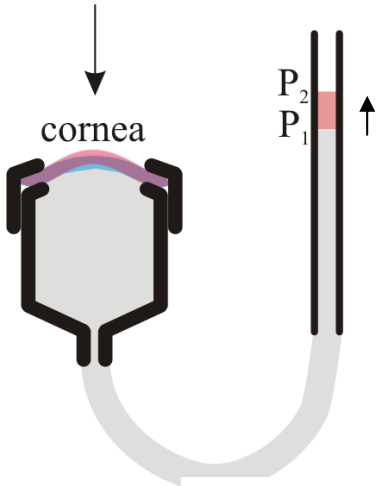


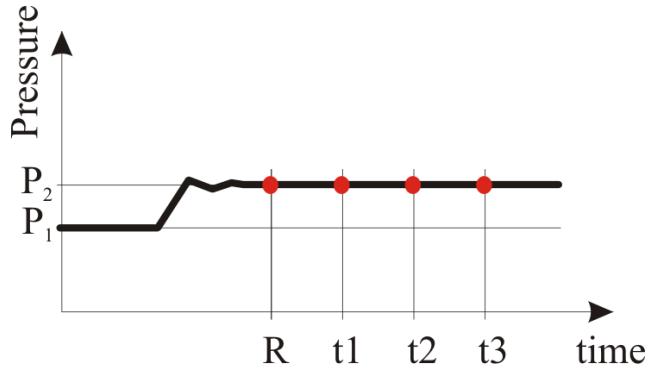
- 1.8m operations in 2001 in US alone
- 5-20% have residual refractive errors
- Significant requirement to measure internal mechanical properties of cornea

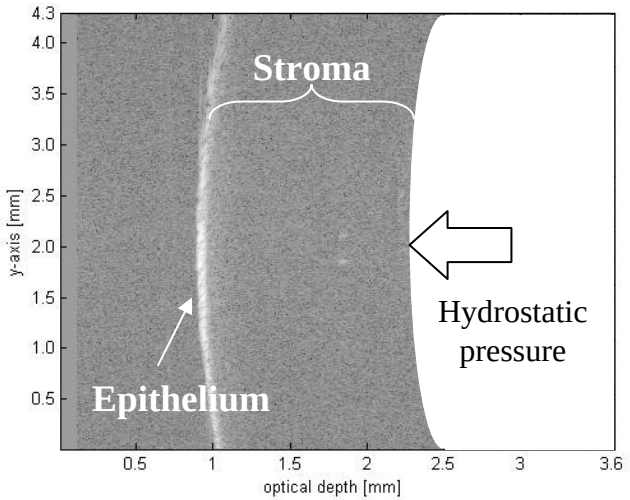
Images from JirehDesign and Capio Eye

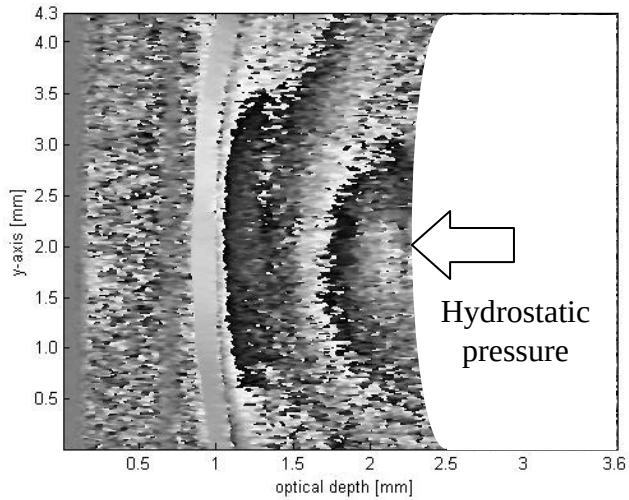
Depth-resolved corneal deformation











$$\delta z = \gamma \frac{\lambda_c^2}{\Delta\lambda}$$

$$\Delta z = \frac{N\lambda_c^2}{4\Delta\lambda}$$

magnitude **phase**

[M de la Torre-Ibarra, P D Ruiz and J M Huntley (2005), *Opt. Exp.* 14:9643-9356]

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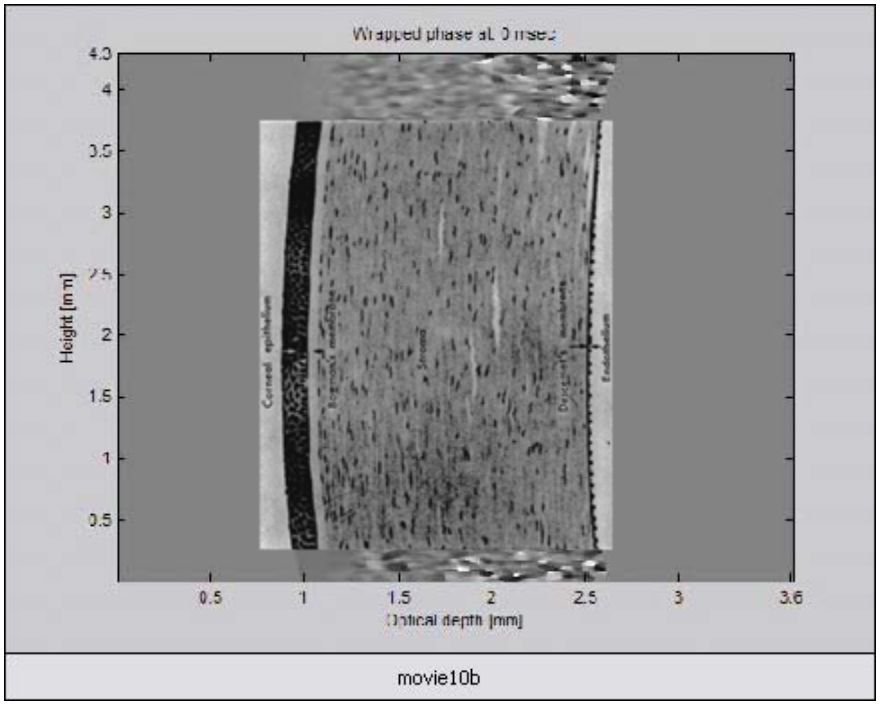
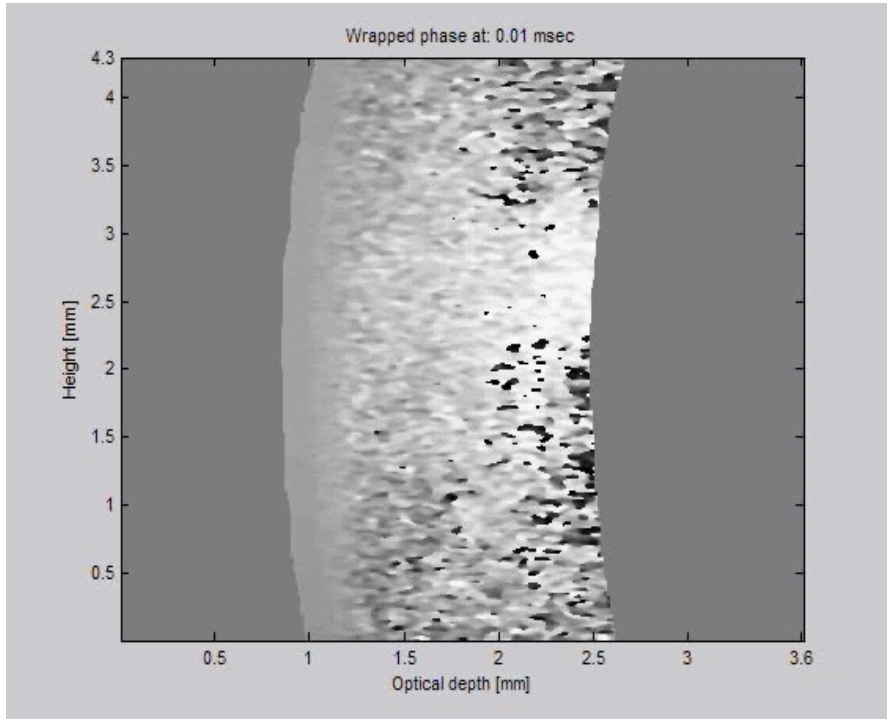
Case study: Depth-resolved corneal deformation





Out-of-plane sensitivity

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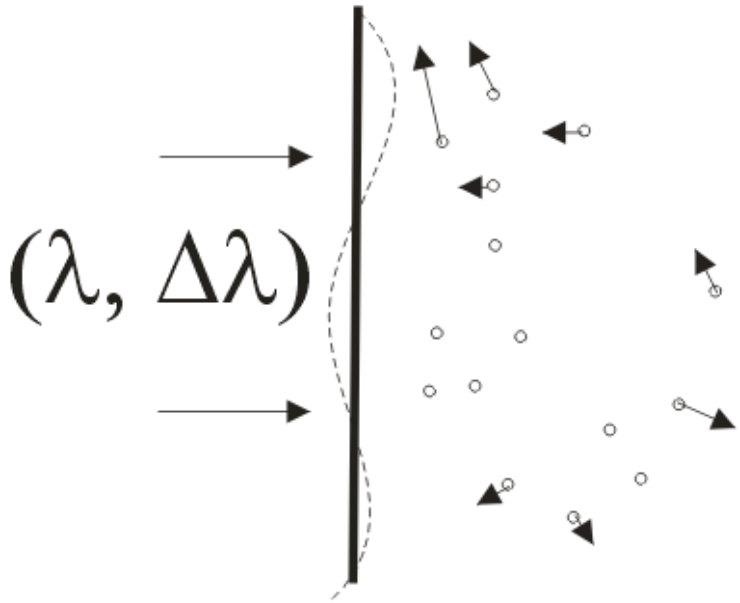
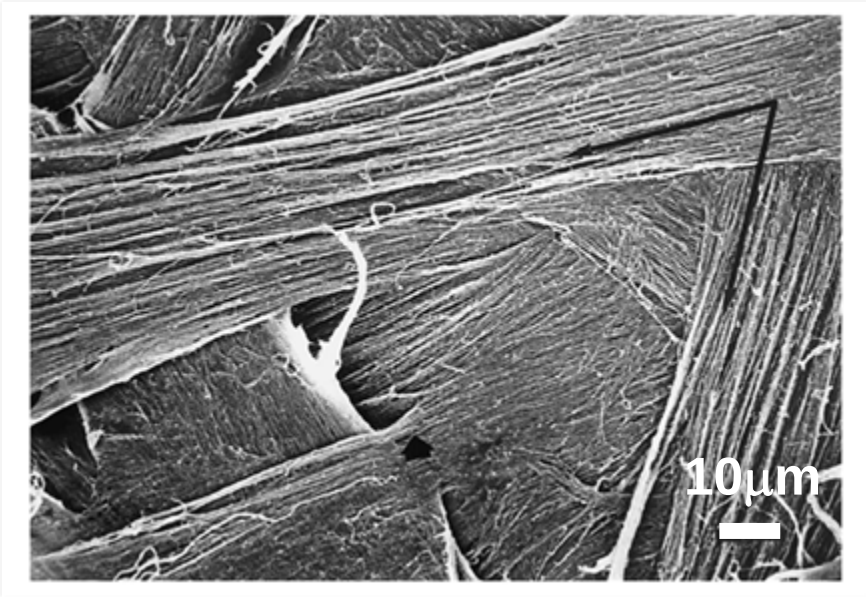
Sources of phase change

- Motion of scattering centres
- Surface curvature

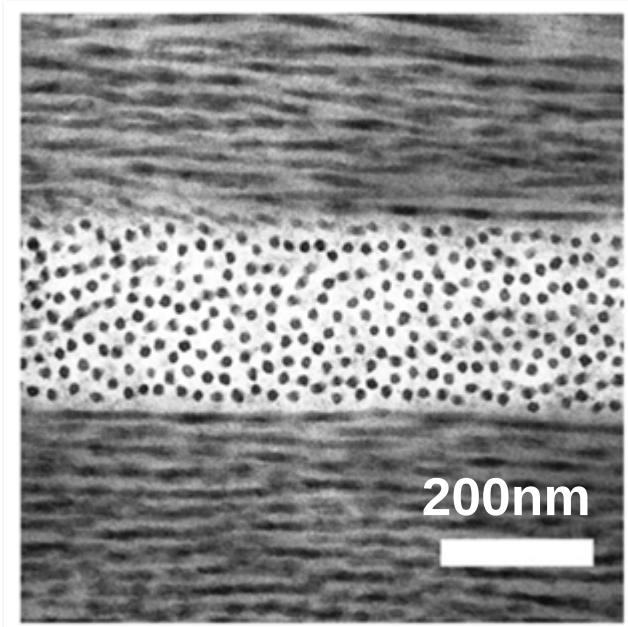


- Photoelastic effect n=n(strain)
- Non-uniform refractive index n=n(x,y,z)
- Dispersion n=n(λ)

Phantoms: start with something known



Collagen lamellae in the mid-stroma



Orientation of collagen fibrils in adjacent lamellae of the corneal stroma

[Meek and Fullwood (2001), Micron 32:261]
[Fullwood (2004), Structure 12:169]

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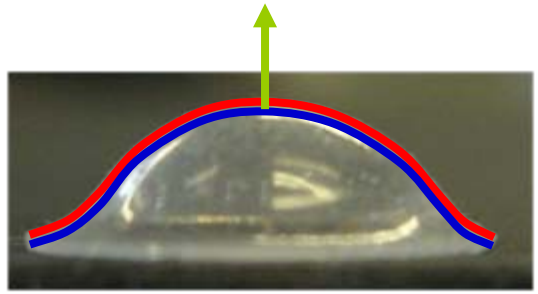
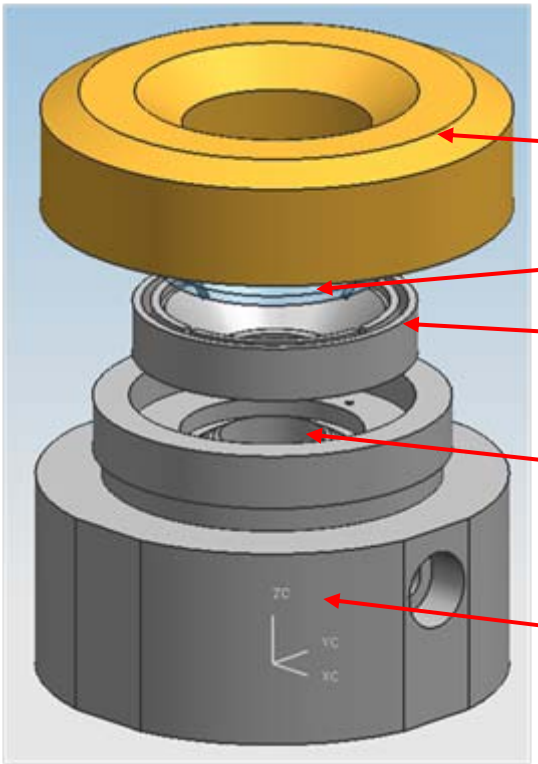
Phantoms: artificial corneal trephinates

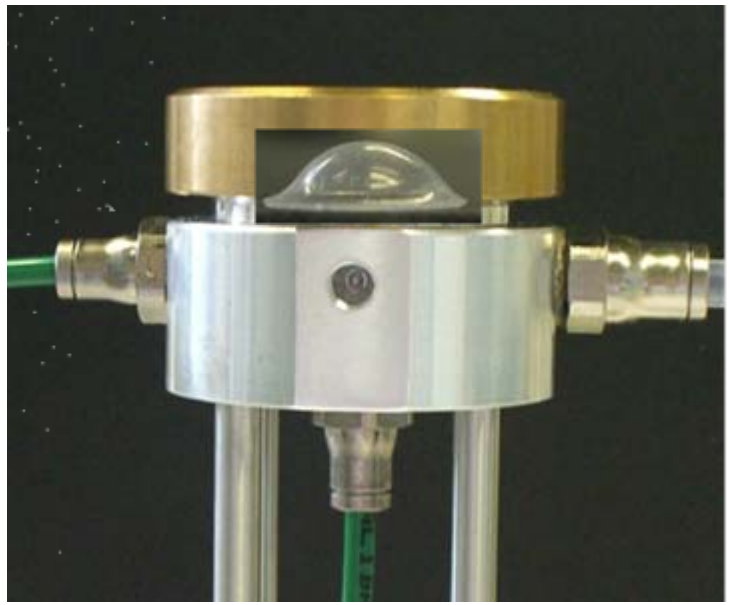
- Dimensions from Arizona's eye model
- Silicone rubber to match corneal effective modulus (0.1-0.9 MPa) at normal IOP
- Monolayer and bilayer (0.55 and 1.88 MPa)
- Bilayer with low and high moduli
- Inflation test to find pressure vs. apex displacement



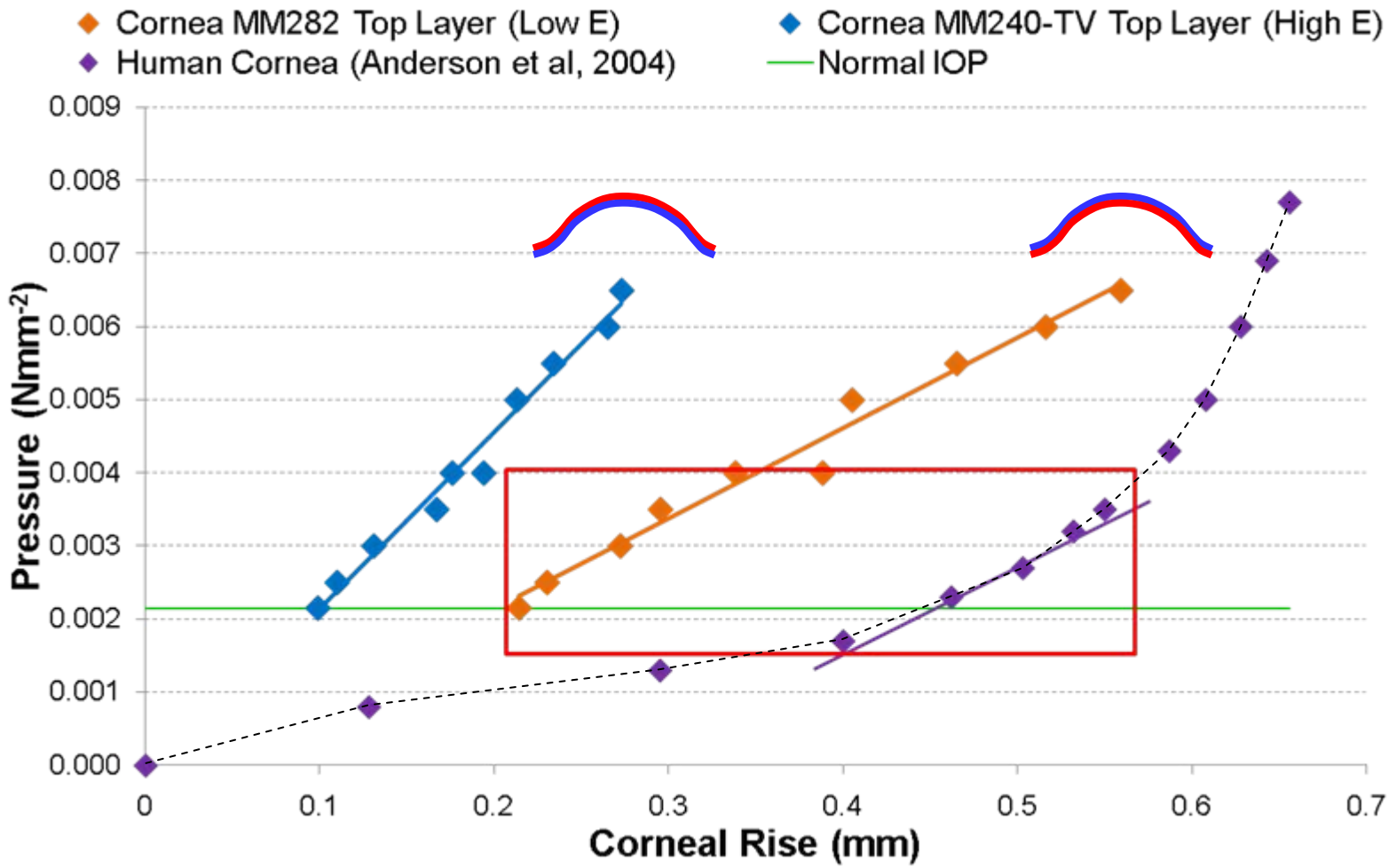
Phantoms: artificial anterior chamber

- Known geometry, boundary conditions, loads and material properties
- Used to validate experimental technique and test inverse methods





Corneal rise vs. ‘intraocular’ pressure



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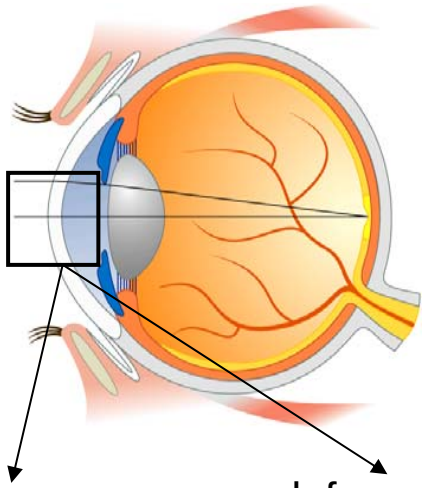
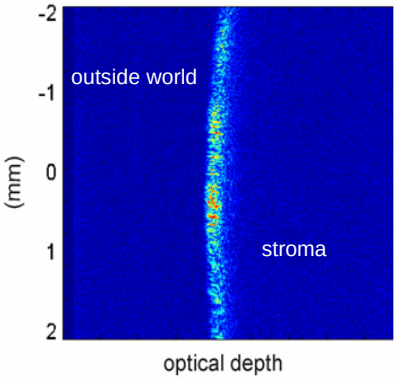
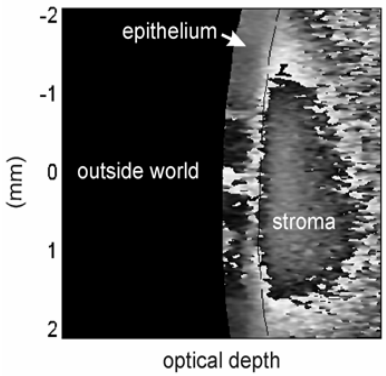
Summary: Phase Contrast OCT



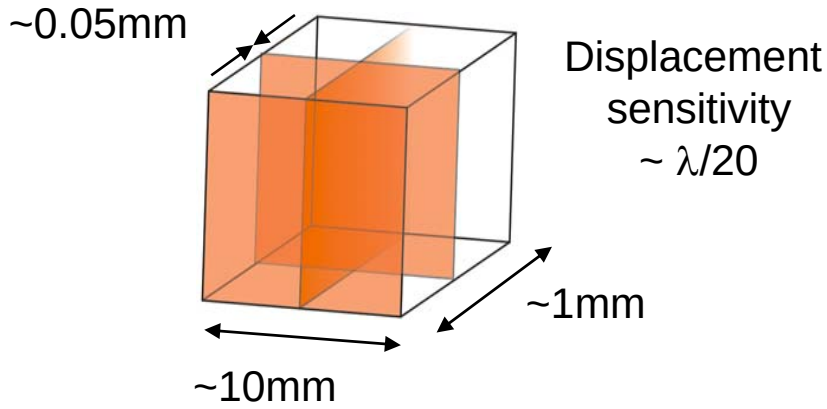
deformations encoded in phase contour map

structure





- Single-shot structure + depth-resolved deformations
- Displacement sensitivity 100-1000 times higher than depth-resolution
- Potential to estimate mechanical properties within the material
- Phantoms developed for validation



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Thank you for your attention