Effect of Numerical Modelling Assumptions on the Simulated Corneal Response during Goldmann Applanation Tonometry

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Introduction and Background

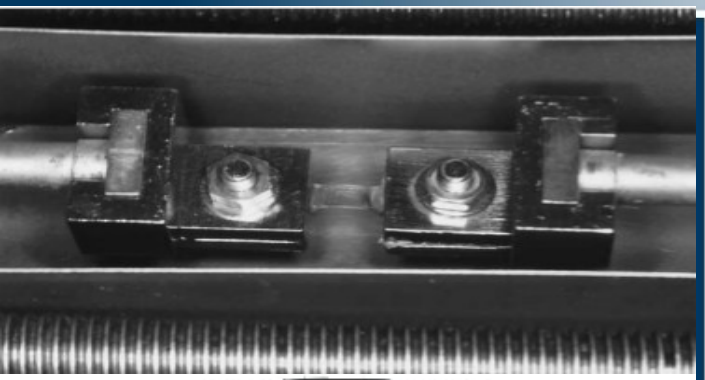
Ateshian and Friedman[1] on earlier studies of biomechanics:

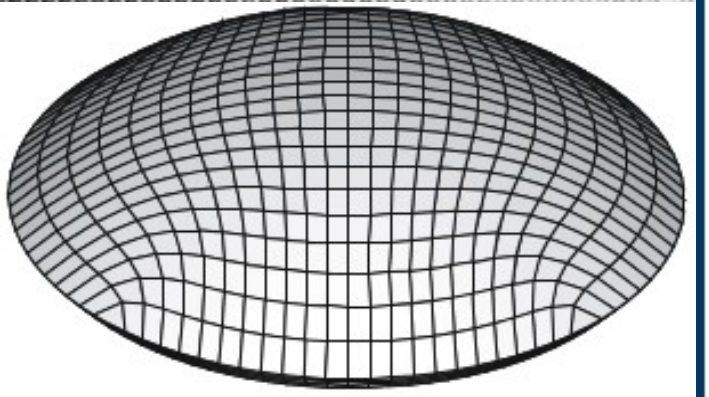
"one of the most pressing needs was to characterize the mechanical properties of various tissues in relation to their structure, to better understand their function."

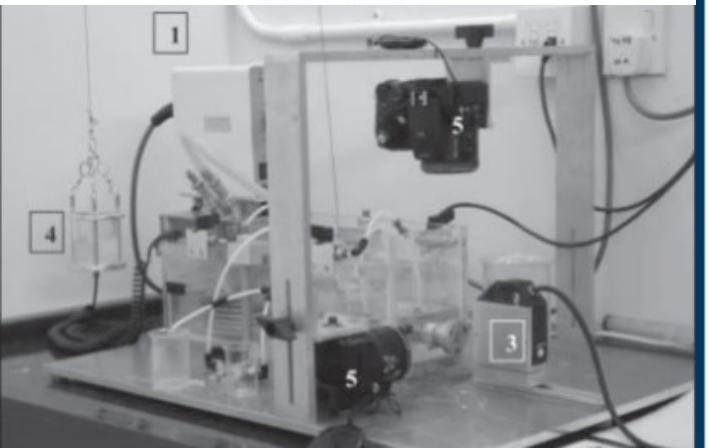
- To understand the behaviour/response of a structure it is necessary to understand the underlying mechanism driving the behaviour/response.
- Underlying mechanism: material and mechanical properties.
- Structure: cornea – main refracting component of the human eye
- Behaviour/Response: Goldmann Applanation Tonometry (GAT), a popular diagnostic method.
- GAT measures the indentation resistance of the cornea to estimate the IntraOcular Pressure (IOP), a risk indicator.

[1]Ateshian, G.A. And Friedman, M.H. 2009. *Integrative biomechanics: A paradigm for clinical applications of fundamental mechanics*, Journal of Biomechanics, 42(10): 1444-1451.

Introduction and Background







- Several experimental and numerical studies have been conducted to characterise corneal tissue.
- No consensus with regards to corneal material properties – large variation in proposed properties.
- Numerical studies agree that both geometric and material properties influence the IOP during GAT.
- Goldmann and Schmidt[2] designed GAT assuming material properties do not influence IOP estimation.
- Numerical studies contradict the initial design premise.

[2]Goldmann, H. and Schmidt, T. 1957. *Über Applanationstonometrie* (Applanation Tonometry), Opthalmologica, 134: 221-242. In Ritch, R and Caronia, R.M. 2002. Classic Papers in Glaucoma, Kugler Publications, pp. 155-162.

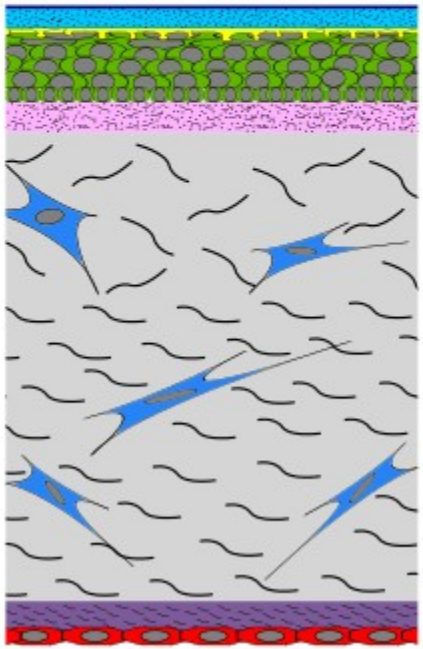
Study Objectives

1. Why is there such a large variation in proposed material properties from numerical studies?
2. Why does the numerical studies contradict the initial design premise of GAT?

Both questions can be answered by considering the effect of modelling assumptions on the corneal response during GAT.

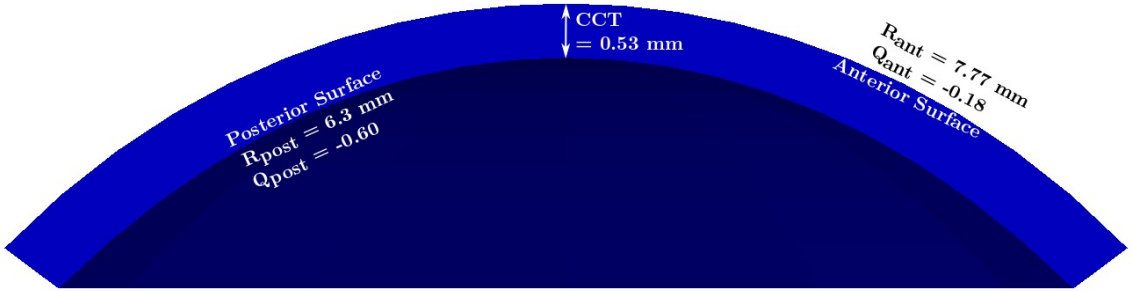
3 Modelling assumptions to investigate:
– Material model assumptions
– Boundary conditions
– Calibration data

Finite Element Model of a Human Cornea



Rotationally symmetric conicoid[3]:

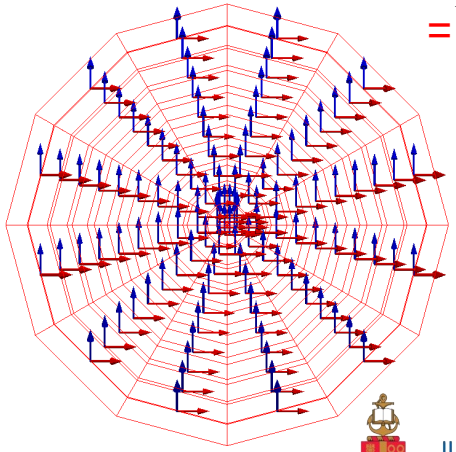
$$(X-X_o)^2+(Y-Y_o)^2+(1+Q)(Z-Z_o)^2-2R(Z-Z_o)=0$$

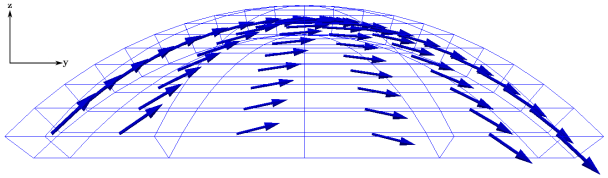


Fibre reinforced elastic material model[4]:

$$U=C_{10}(\bar{I}_1-3)+\frac{1}{D_1}(J-1)^2+\sum_{i=4,6}^{n}\frac{k_{1i}}{2k_{2i}}\left[e^{k_{2i}(\bar{I}_i-1)^2}-1\right]$$

= 0.4



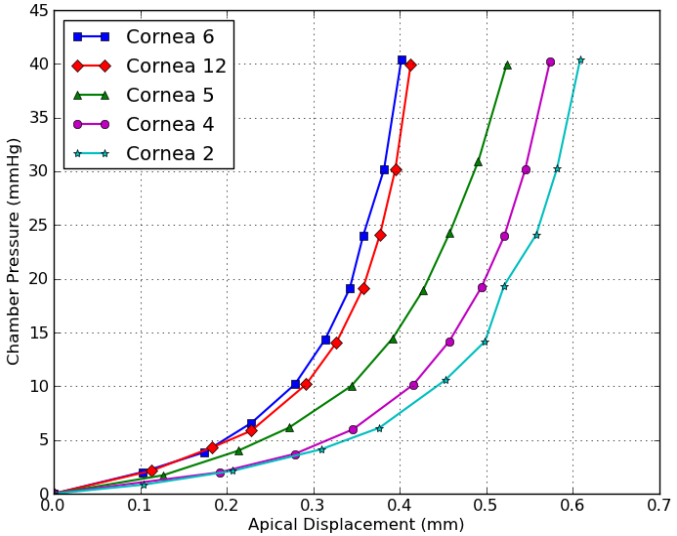


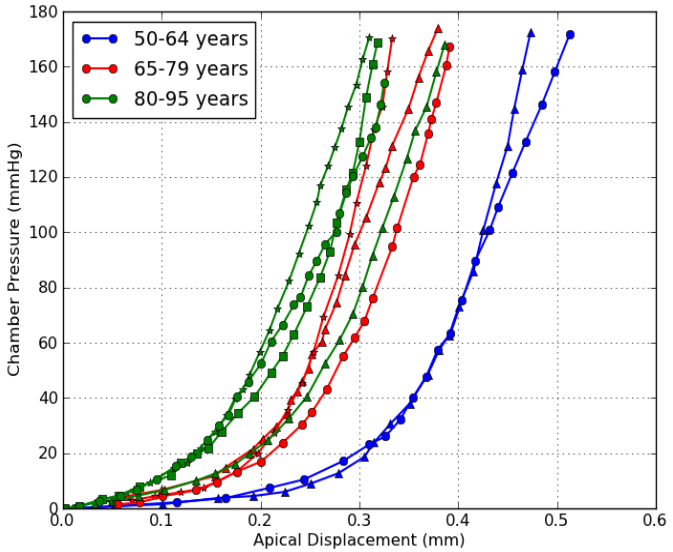
[3]Kiely, P, Smith, G. and Carney, L. 1982. *The mean shape of the human cornea*, Journal of Modern Optics, 29(8): 1027-1040.

[4]Holzapfel, G.A., Gasser, T.C. And Ogden, R.A.Y.W. 2000. *A new constitutive framework for arterial wall mechanics and a comparative study of material models*, Journal of Elasticity, 61(1): 1-48.

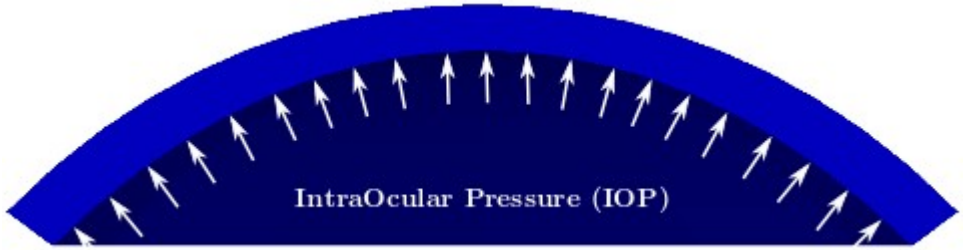
Calibration of Material Coefficients – Model Set Up

Experimental Inflation Data[5,6]:





Boundary Conditions:



Fixed Limbal Boundary

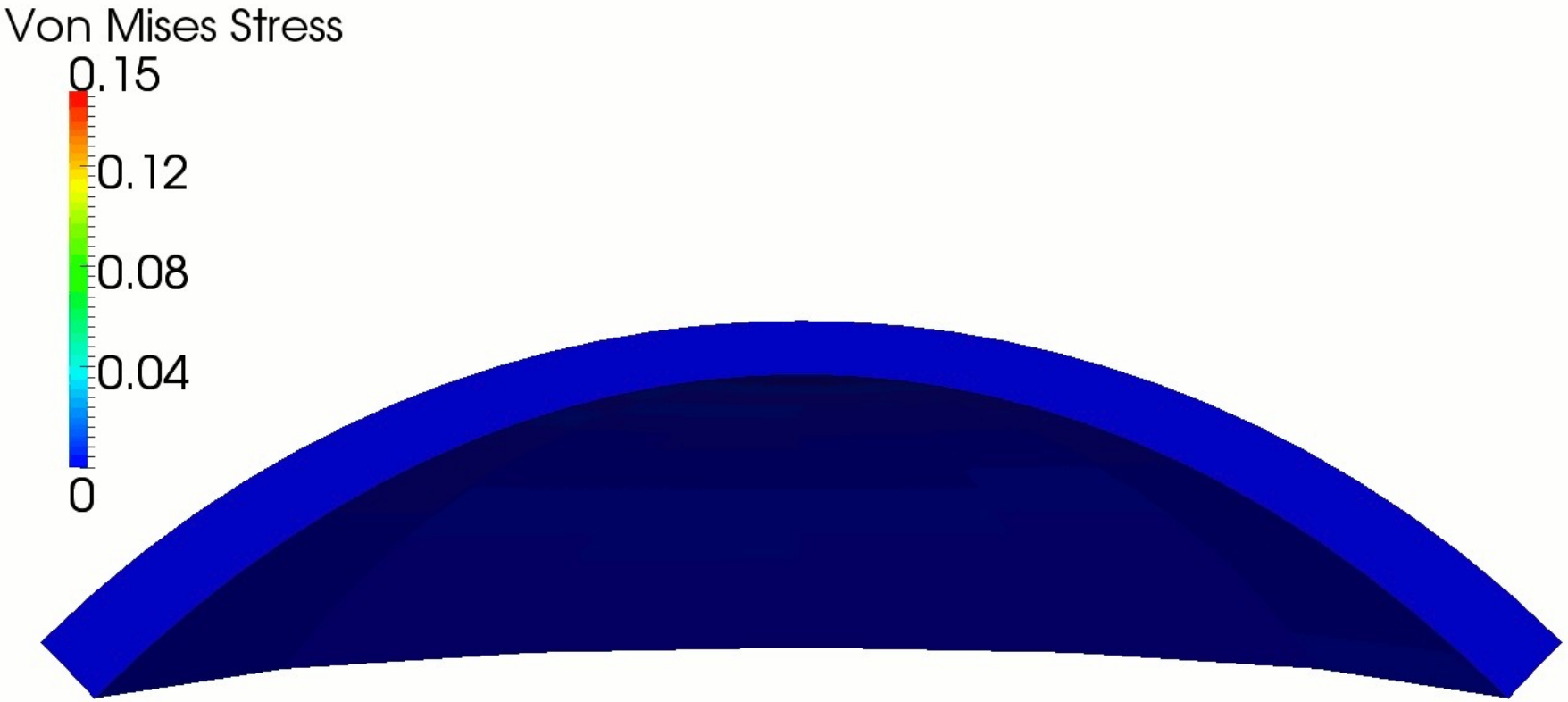
Loose Limbal Boundary

Nelder-Mead simplex method:

$$min\, F(\boldsymbol{X}) = RMSE = \sqrt{\frac{\sum_{i=1}^{n} (\exp_i - num_i)^2}{n}}$$

[5]Bryant, M.R. and McDonnel, P.J. 1996. *Constitutive laws for biomechanical modeling of refractive surgery*, Journal of Biomechanical Engineering, 118(4): 473-481.
[6]Elsheikh, A., Wang, D. and Pye, D. 2007. *Determination of the modulus of elasticity of the human cornea*, Journal of Refractive Surgery, 23(8): 808-818.

Calibration of Material Coefficients – Inflation Test



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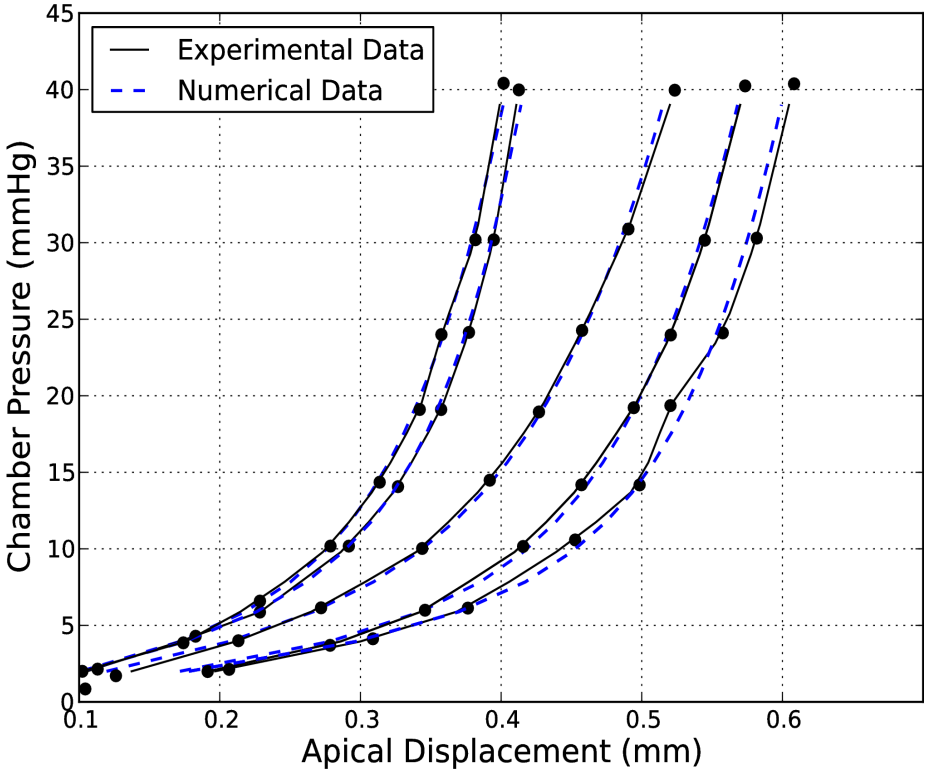
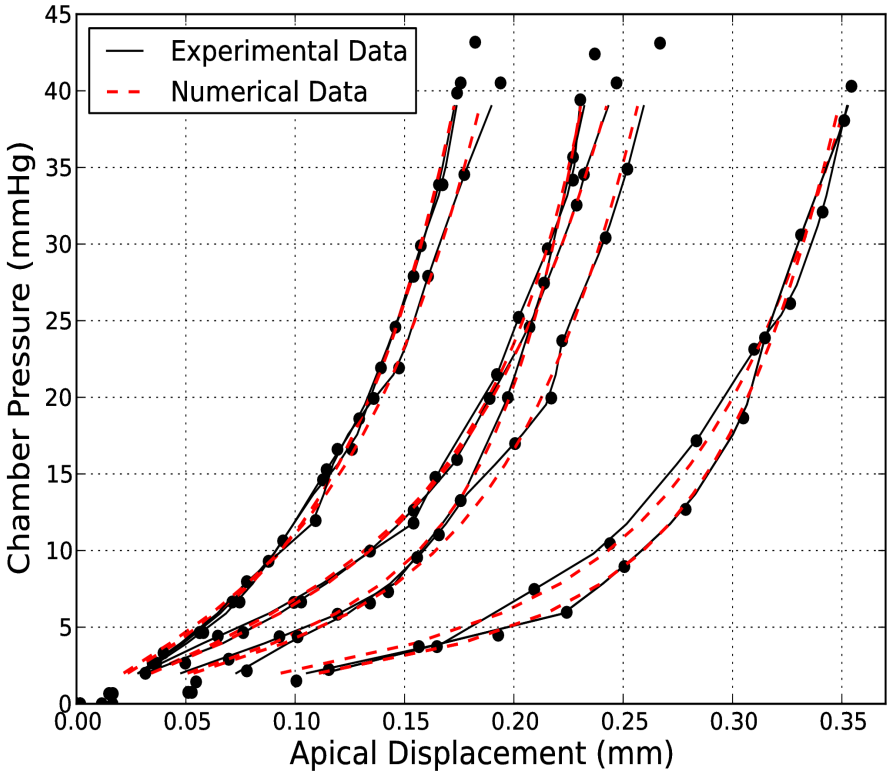
Calibration of Material Coefficients – Results

Case 1: 3 Coefficients (C_{10}, k_1, k_2)

Bryant Inflation Data



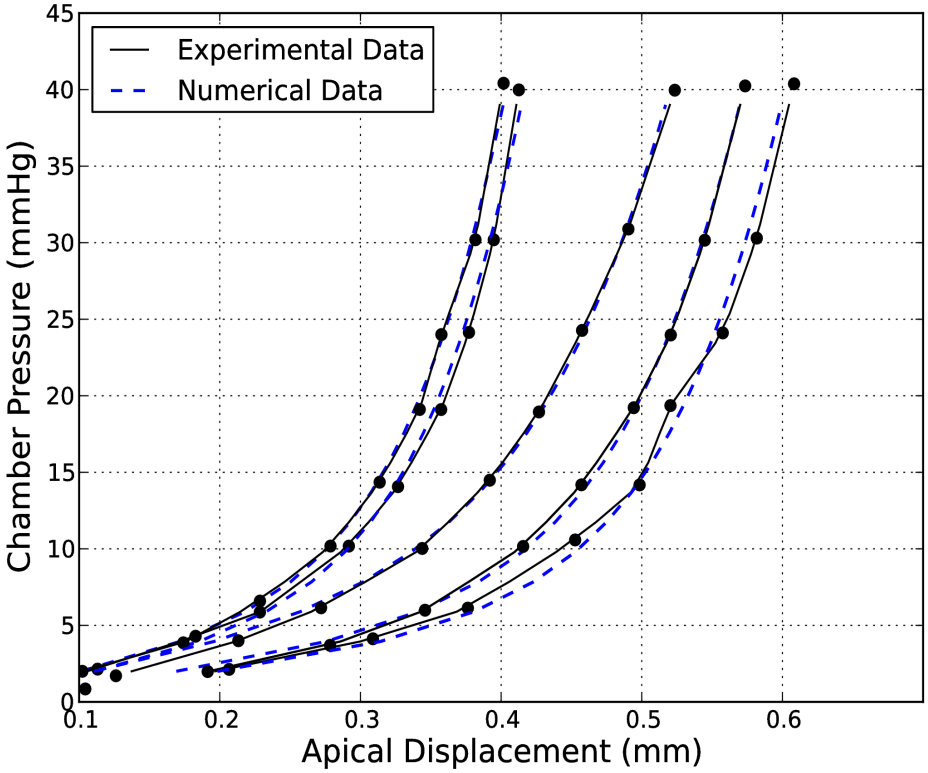
Elsheikh Inflation Data



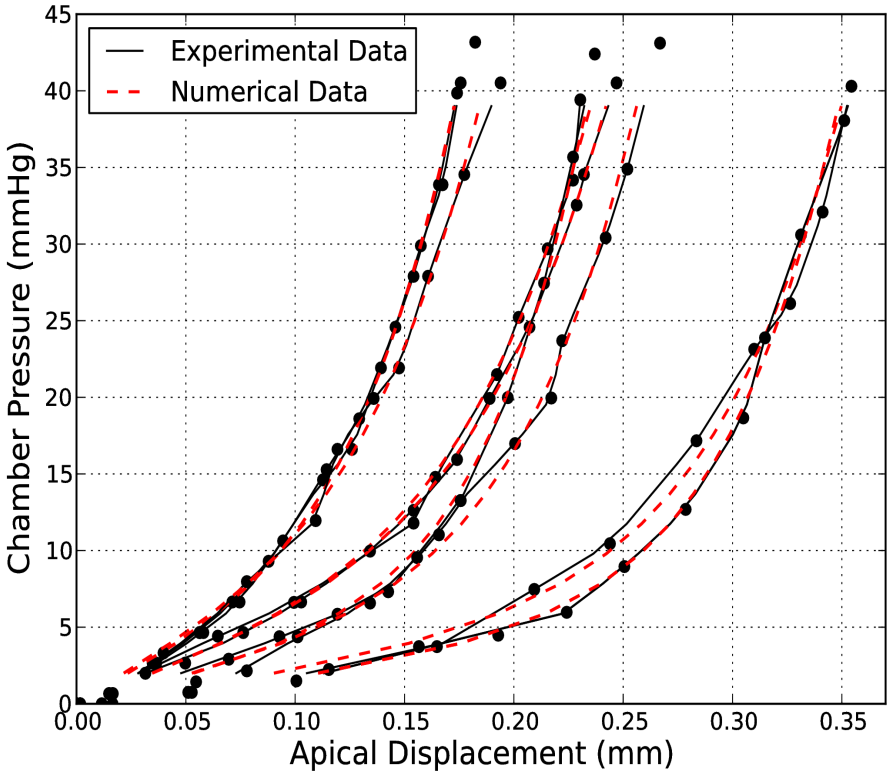
Calibration of Material Coefficients – Results

Case 2: 2 Coefficients (k_1, k_2)

Bryant Inflation Data

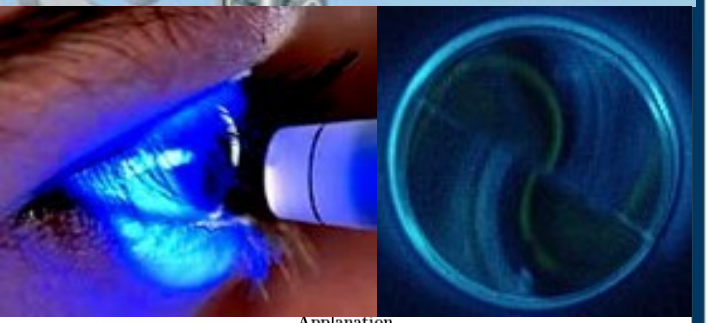


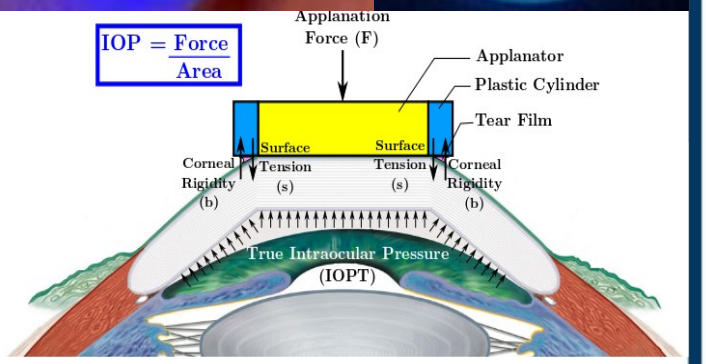
Elsheikh Inflation Data



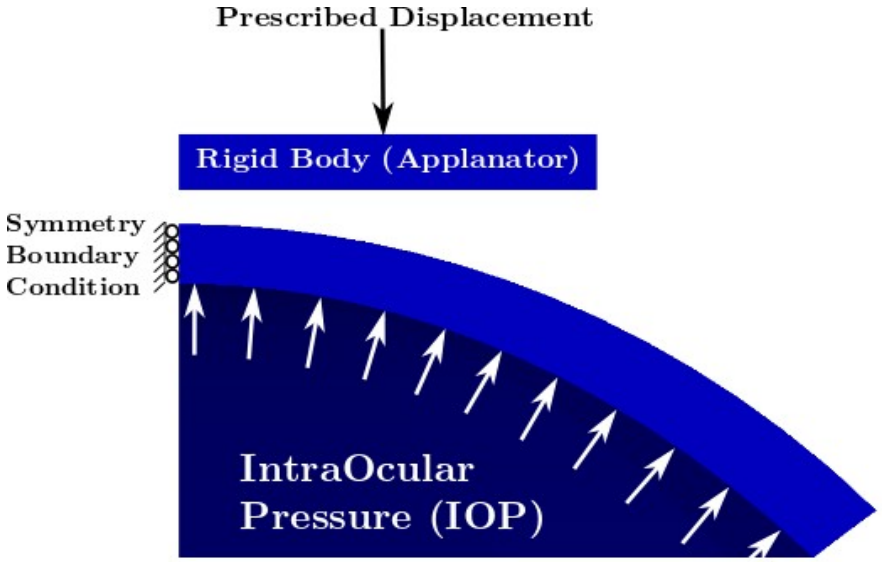
From sensitivity study: C_{10} = 0.004 MPa

Effects of Modelling Assumptions – Model Set Up

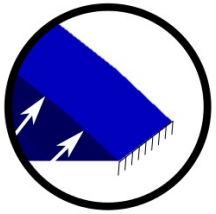




Boundary Conditions:



Fixed Limbal Boundary



Loose Limbal Boundary

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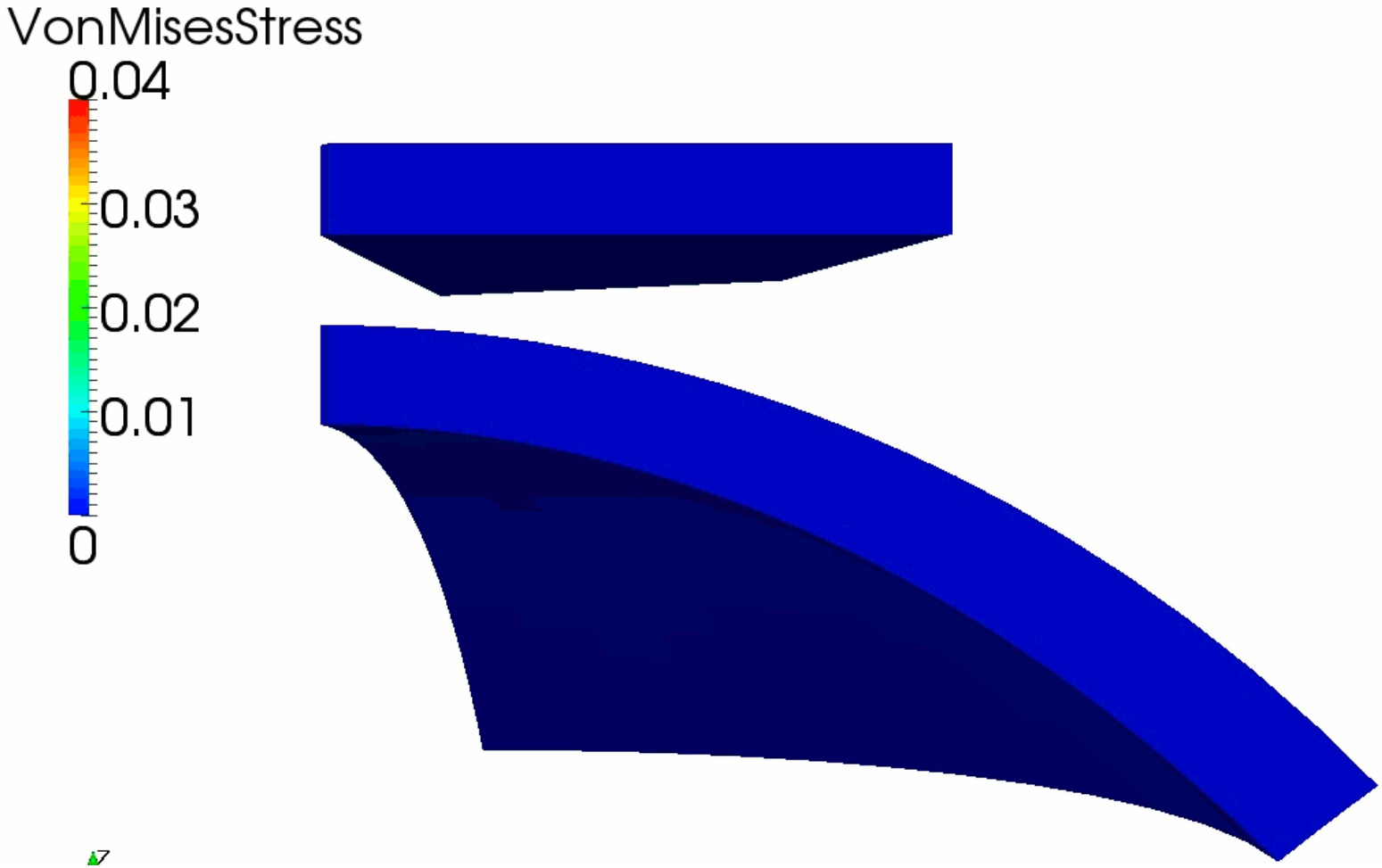
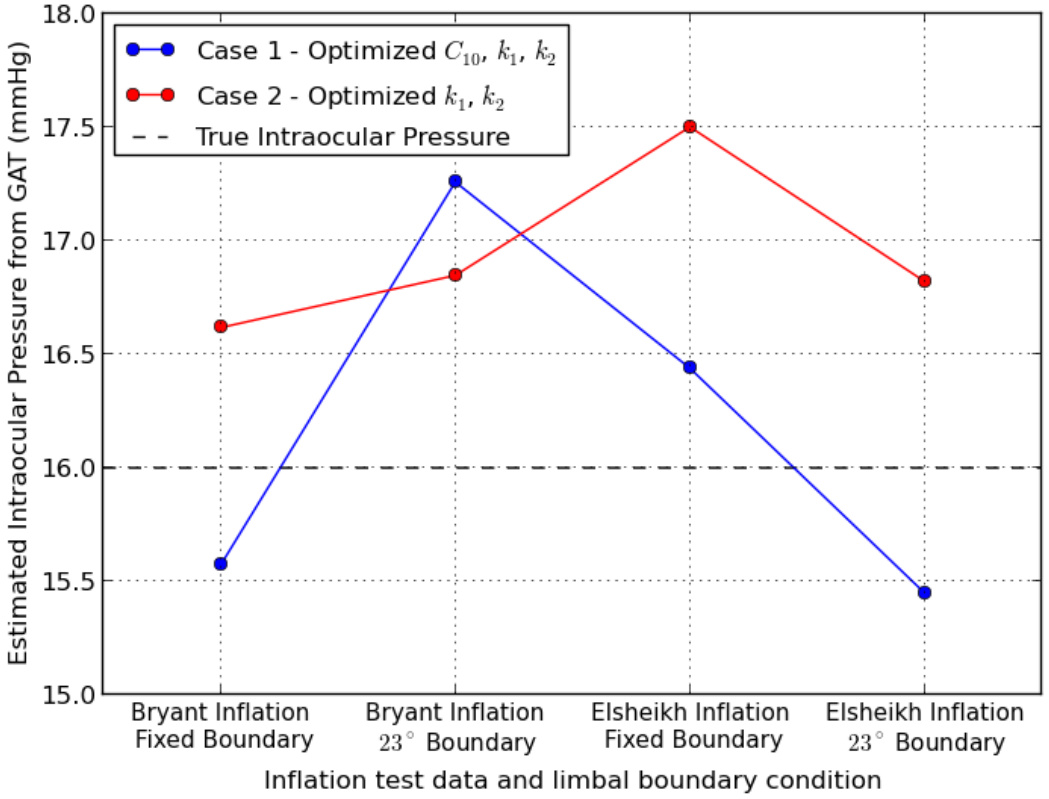
Effects of Modelling Assumptions – Goldmann Applanation Tonometry



Effects of Modelling Assumptions – Results

Boundary Conditions and Calibration Data



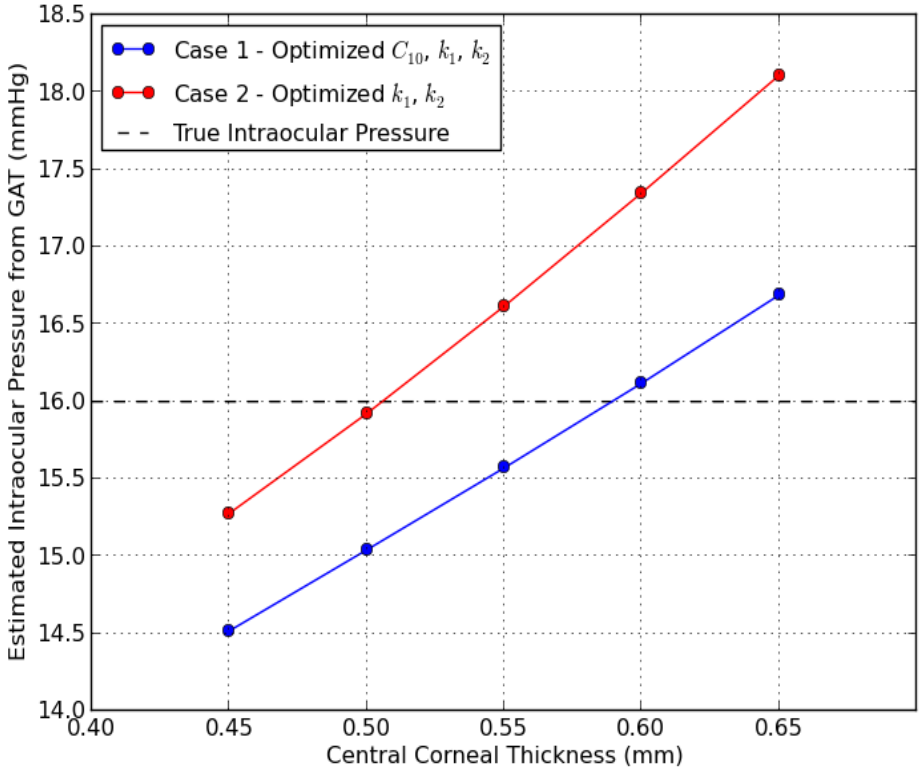
- Case 1: < 2 mmHg difference.
- Case 2: < 1 mmHg difference.

- Considered to either be significant or insignificant depending on the study.

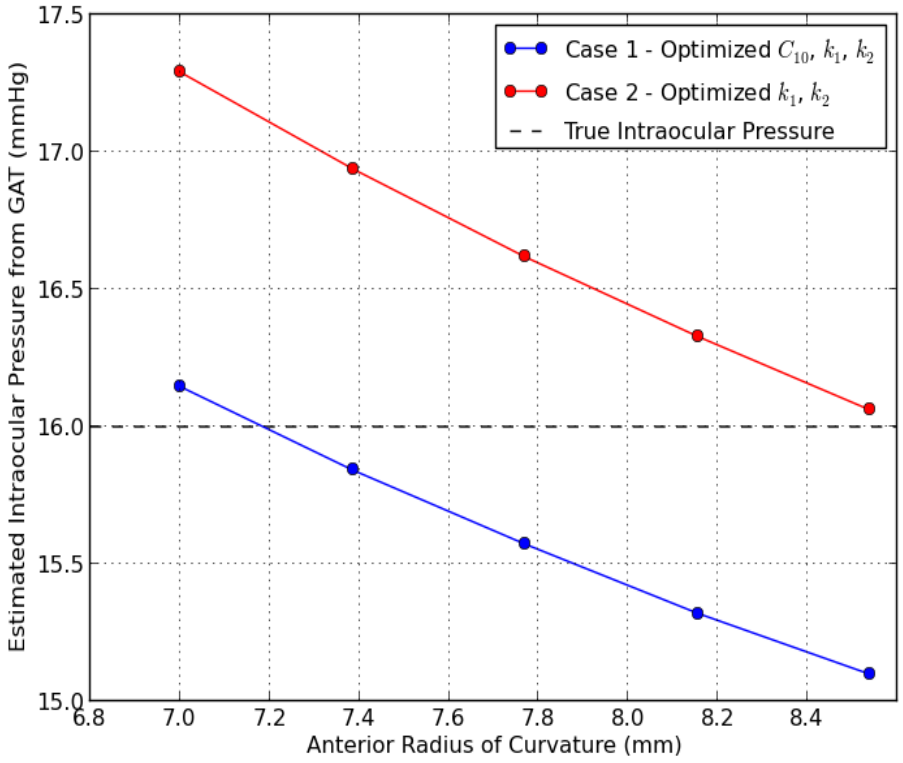
Effects of Modelling Assumptions – Results

Cornea Geometry

Central Corneal Thickness



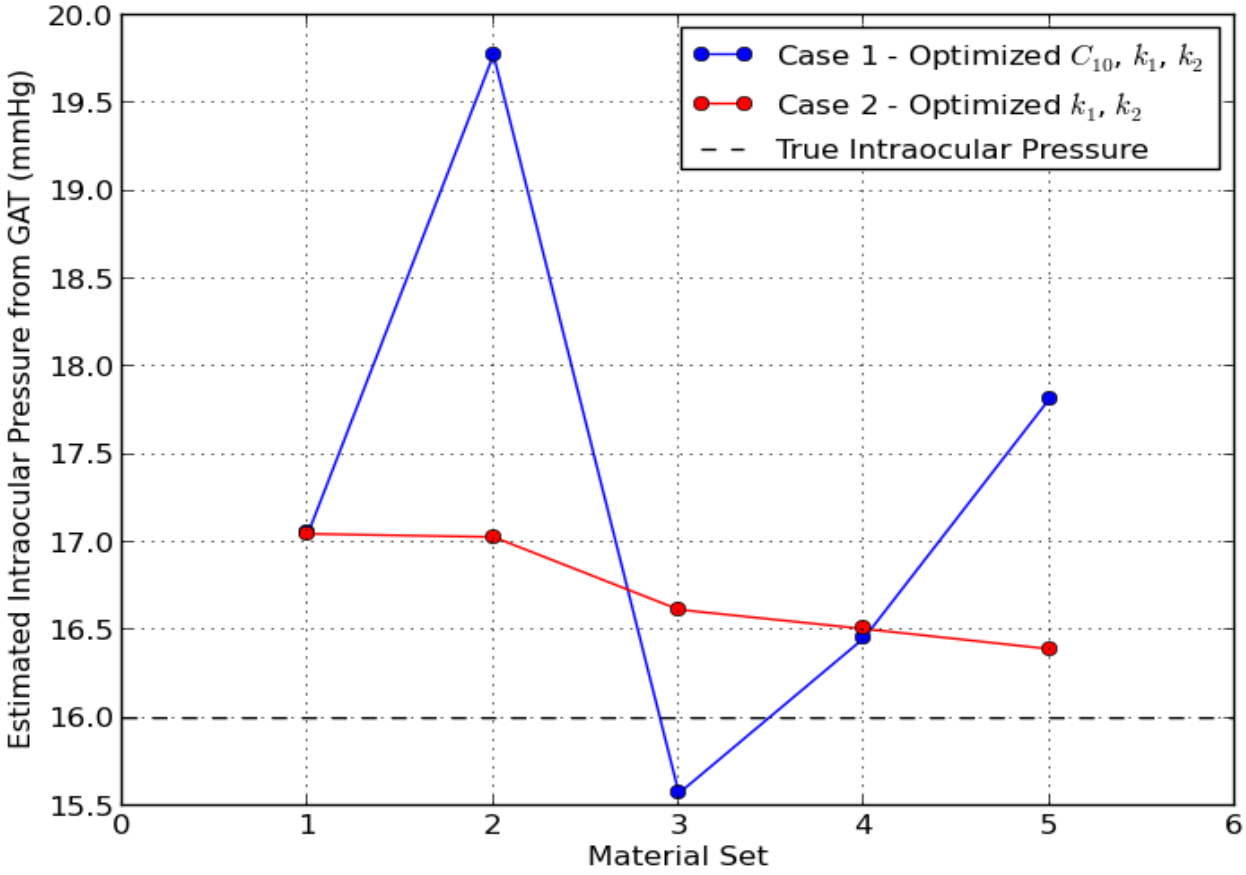
Radius of Curvature



- Thin, flat cornea underestimates IOP.
- Thick, steep cornea overestimates IOP.

Effects of Modelling Assumptions – Results

Material Coefficients



- Case 1: IOP erratic.
- Case 2: IOP constant.

Two contradictory conclusions:
1. GAT sensitive to material properties.
2. GAT is **not** sensitive to material properties.

Conclusions and Recommendations

Conclusions

- Inflation data not enough to uniquely quantify cornea material model.
- Take care when developing numerical models.

Recommendations

- Experimentalists should study cornea behaviour during applanation more in depth.
- Include additional experimental data – strip extensometry, bending tests, etc. - during calibration.

Acknowledgements

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THANK YOU