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Mechanics of Living, Squishy Materials

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Mechanics of Living, Squishy Materials

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Amherst
DISCLOSURE

• I have no actual or potential conflict of interest in relation to this program or presentation.
BioInspired Materials Mechanics

BioInspired Adhesion and Friction Control

Snapping, Wrinkling, and Folding Polymers

Nanoparticle Stripes, Ribbons, and Ropes

Local Mechanics of Gels and Tissues
Tissue Mechanics

Challenge: Understand the development of mechanical properties in soft networks across multiple length scales.

Goal: Develop quantitative technique for synthetic and biological materials (in vitro and in vivo).

Objective: Make measurement at arbitrary locations and on biologically relevant length scales (10^{-7}-10^{-3} m)

Blood fluid | Brain | Muscle | Collagenous Bone
--- | --- | --- | ---
1 kPa | 10 kPa | 100 kPa

- Most knowledge from extracted tissue
- What can we learn from studying tissues in their native state?
Inflation


**Neo-Hookean**

\[ P = 2G \left( \frac{t_0}{r_0} \right) \left( \lambda^{-1} - \lambda^{-7} \right) \]

**Hookean**

\[ P = 12G \left( \frac{t_0}{r_0} \right) \left( \lambda^{-2} - \lambda^{-3} \right) \]

Cavitation in Bulk

\[ P = \frac{2\gamma}{r_0} \left( \frac{1}{\lambda} \right) + 2 \int \frac{\sigma d\lambda}{\lambda(1 - \lambda^3)} \]

\[ \frac{P}{G} = \frac{5}{2} - 2\left( \frac{1}{\lambda} \right) - \frac{1}{2} \left( \frac{1}{\lambda} \right)^4 + \frac{2\gamma}{Gr_0} \left( \frac{1}{\lambda} \right) \]

Syringe Induced Cavitation

\[ P = P_s + P_E \]

\[ P_s = \gamma \frac{dA}{dV} = \left( \frac{4\gamma}{r_s} \right) \frac{\left( \frac{\lambda^2 - 1}{\lambda^2} \right)^{1/2}}{\lambda^2} \]

\[ P_E = E \left( \frac{5}{6} - \frac{2}{3\lambda} - \frac{1}{6\lambda^4} \right) \]
Inner radius = 51 μm

Kundu and Crosby *Soft Matter* 2009
Zimberlin and Crosby *J. of Poly. sci. part B* 2009
Zimberlin et al. *Soft Matter* 2010
Crosby and McManus *Physics Today* 2011
Cui, McManus, Crosby. *Soft Matter*, under review
Representative Data
Syringe Radius = 2.5 μm
Dependence on Syringe Radius

\[ P_c \approx \frac{5}{6} E + \frac{2\gamma}{r_s} \]
Size Dependence

\[ P_c = \frac{5}{6} E + \frac{2\gamma}{r_s} \]

- \( E_{\text{air}} = 2.4 \text{ kPa} \)
- \( \gamma_{\text{air/gel}} = 0.072 \text{ J/m}^2 \)
Cavitation with Water

- Graph showing pressure (P) over time (s) with data points for air and water.
- Images showing cavitation at times $t_c$ and $t_c - 0.1$ s, with radii $r = 203 \mu m$ and $r = 2.5 \mu m$.
Surface Energy Effects

\[ P_c = \frac{5}{6} E + \frac{2\gamma}{r_s} \]

\[ E_{\text{air}} = 2.4 \text{ kPa} \]
\[ E_{\text{water}} = 1.8 \text{ kPa} \]
\[ \gamma_{\text{air/gel}} = 0.072 \text{ J/m}^2 \]
\[ \gamma_{\text{water/gel}} = 0.0072 \text{ J/m}^2 \]

**Zimberlin and Crosby, JPS: B, 2019, in press.**
Polyacrylamide (PAAm); monomer amount varied to obtain gels with different polymer volume fraction ($\phi$).

Reversibility

$\phi < 0.03$

$P_c \sim E + \frac{2\gamma}{r_s}$

$E_{\text{cavitation}}: 1400 \text{ Pa}$

$E_{\text{contact mech}}: 1500 \text{ Pa}$

$\phi > 0.03$

$P_c \neq E + \frac{2\gamma}{r_s}$

$2000 \mu m$

$3000 \mu m$
Size Dependence

Cavitation

\[ P_c \sim \frac{5}{6} E + \frac{2\gamma}{r_s} \]

Fracture

\[ P_c \propto \left( \frac{G_c E}{r_s} \right)^{1/2} \]
\[ E \approx \left( \frac{3kT}{b^3 N} \right) \phi \]

\[ N = f(\phi) \propto \phi^{-\frac{4}{3}} \]

\[ E \propto \left( \frac{3kT}{b^3} \right) \phi^{2.3} \]

**Kundu and Crosby, Soft Matter, 2009, 5, 3963-3968.**
\[ G_c \approx (NU) \left( \frac{\text{chains}}{\text{area}} \right) \]


\[
\frac{\text{chains}}{\text{area}} \propto \frac{\phi}{N^{1/2}b^2}
\]


\[
G_c \propto \frac{U}{b^2} \phi^{5/24}
\]

Cavitation to Fracture Transition

\[
\frac{P_c}{P_f} \propto 3 \left( \frac{kT}{U} \right)^{1/2} \left( \frac{r_s}{b} \right)^{1/2} \phi + 2 \left( \frac{\gamma b^2}{kT} \right) \left( \frac{kT}{U} \right)^{1/2} \left( \frac{b}{r_s} \right)^{1/2} \phi^{-1.3}
\]

The Vitreous Humor

- Weak gel that is 99.9% water and dissolved salts
- Held together by vitrosin fibers and hyaluronic acid
- Very fine network of fibrils D ~ 20-25 nm

M M Le Goff1 and P N Bishop, Eye (29 Feb 2008), doi: 10.1038/eye.2008.21, Review
Time Effect on *in vitro* Vitreous

- Modulus decrease with time of vitreous solution
- Attributed to hyaluronan loss in the exuded aqueous
Vitreous Cavitation

• Performed cavitation rheology on bovine eyes

• Two conditions:
  – Vitreous in eye
  – Vitreous removed

• Demonstrates ability to perform in vivo mechanical characterization

• Provides insight design of biological networks

**Sample**

<table>
<thead>
<tr>
<th>Sample</th>
<th>E (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR in Eye</td>
<td>600</td>
</tr>
<tr>
<td>CR extracted</td>
<td>99</td>
</tr>
<tr>
<td>Kornfield**</td>
<td>60</td>
</tr>
</tbody>
</table>

Consistent with predictions that internal network tension contributes to stiffness


The Lens

- **Chemical composition**
  - 35w% protein
  - 90w% are water-soluble proteins (crystallins), including $\alpha$, $\beta_h$, $\beta_l$, $\gamma$.

Fig. 3. Crystallin distribution in the bovine lens from centre (LHS) to outside. Single foetal (open symbols) and adult (solid symbols) lenses were divided into concentric layers by controlled dissolution and the $\alpha$-, $\beta$- and $\gamma$-crystallin content in each layer was determined using HPLC–GPC. The location of the layer in the lens was determined from its protein content, the total protein in the lens and the refractive index gradient.\textsuperscript{13}
Critical Pressure

Mapping Brain Tissue in vivo

In collaboration with Profs. Jennifer McManus and Sean Commins at NUI Maynooth, Ireland
Summary

- Biological systems provide many lessons, key points can be hidden
- Elastic instabilities offer advantages for material characterization
- Cavitation provides unique exploration of length scale and deformation properties of 3-D networks
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