Mechanics of Living, Squishy Materials

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Mechanics of Living, Squishy Materials

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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
**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**
  - 1 kPa
- **Brain**
  - 1 kPa
- **Muscle**
  - 10 kPa
- **Collagenous Bone**
  - 100 kPa

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

NeoHookean

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

Hookean

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

Cavitation in Bulk

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

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

Syringe Induced Cavitation

\[ P = P_s + P_E \]

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

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

\[ \frac{P_c}{E} \approx \frac{5}{6} + \frac{2\gamma}{Er_s} \]
Cavitation Rheology

Inner radius = 51 \mu m

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 $= 2.5 \, \mu m$
Dependence on Syringe Radius

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

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

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

Inner radius = 127 μm
Cavitation with Water

![Graph showing pressure (P) vs. time (s) for air and water with images of cavitation](image)

- Pressure in kPa:
  - Air
  - Water
- Time in seconds:
  - $t_c = 0.1\, s$
  - $t_c$
- Radii:
  - $r = 203\, \mu m$
  - $r = 2.5\, \mu m$
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 ($\phi$).

Deformation Transition

**Kundu and Crosby, Soft Matter, 2009, 5, 3963-3968.**
Reversibility

\[ \phi < 0.03 \]

\[ P_c \approx E + \frac{2\gamma}{r_s} \]

Ecavitation: 1400 Pa

Econtact mech: 1500 Pa

\[ \phi > 0.03 \]

\[ P_c \neq E + \frac{2\gamma}{r_s} \]
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: Volume Fraction Scaling

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

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

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

**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

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

**Kundu and Crosby, Soft Matter, 2009, 5, 3963-3968.**
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 $D \sim 20-25$ nm
Time Effect on \textit{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></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{15}
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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