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
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)

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**Blood**  
- Fluid

**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?
**NeoHookean**

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

**Hookean**

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


\[ \lambda \equiv \frac{r}{r_o} \]
Cavitation in Bulk

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

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

Syringe Induced Cavitation

\[ P = P_s + P_E \]

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

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

b)  

\[
\begin{align*}
P/E & \approx 5 + \frac{2\gamma}{6\gamma_s} \\
\lambda & \quad \text{ vs. } \gamma/\gamma_s
\end{align*}
\]
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

(a) Graph showing pressure (P) in kPa over time.

(b) Graph showing a parameter λ over time.

(c) Four images at different times:
   - 31.797 s
   - 32.000 s
   - 32.172 s
   - 32.531 s
Syringe Radius = 2.5 μm
Dependence on Syringe Radius

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

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

\[ E_{air} = 2.4 \text{ kPa} \]

\[ \gamma_{air/gel} = 0.072 \text{ J/m}^2 \]
Inner radius = 127 μm
Cavitation with Water

Graph showing the pressure (P) in kPa over time (s) for air and water.

Images showing cavitation at different times: $t_c - 0.1\ s$ and $t_c$.

Dimensions: $r = 203\ \mu m$, $r = 2.5\ \mu m$. 

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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 ($\phi$).

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

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

- \( E_{\text{cavitation}}: 1400 \text{ Pa} \)
- \( E_{\text{contact mech}}: 1500 \text{ Pa} \)

\[ P_c \neq E + \frac{2 \gamma}{r_s} \]
Size Dependence

Cavitation

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

Fracture

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

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

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

$G_c \approx (NU) \left( \frac{\text{chains}}{\text{area}} \right)$


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


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

Cavitation to Fracture Transition

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

**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 *in vitro* Vitreous

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

• 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

Consistent with predictions that internal network tension contributes to stiffness


The Lens

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

![Diagram of the human eye and lens with labels for various parts including the vitreous gel, optic nerve, macula, fovea, iris, cornea, pupil, retina, lens bow, epithelium, lens cortex, and lens nucleus.](Image)

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.13
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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