5.1 biomembranes - motivation

The inner life of a cell, viel & lue, harvard [2006]

me239 mechanics of the cell

Tensegrity = tension + integrity

The term tensegrity was first coined by Buckminster Fuller to describe a structure in which continuous tension in its members forms the basis for structural integrity. Fuller most famously demonstrated the concept of tensegrity in architecture through the design of geodesic domes while his student, the artist Kenneth Snelson, applied the concept of tensegrity to creating sculptures that appear to defy gravity. Snelson's tensegrity sculptures are minimal in components and achieve their stability through dynamic distribution of tension and compression forces amongst their members to create internal balance. It was upon viewing Snelson's art that Donald Ingber became inspired by the sculpture's structural efficiency and dynamic force balance to adopt tensegrity as a paradigm upon which to analyze cell structure and mechanics. It has been 30 years since the premier appearance of the cellular tensegrity model, although the model is still largely under discussion, empirical evidence suggests that the model may explain a wide variety of phenomena ranging from tumor growth to cell motility.

4.4 tensegrity model for cells

Tensegrity = tension + integrity

Balanced interplay between tension and compression

4 trusses
6 trusses
8 trusses
12 trusses
6 trusses and 1 nucleus
3 trusses
4.4 tensegrity model for cells

prestress - analytically predicted

\[ P \approx \frac{1}{3} \frac{V_{\text{actin}}}{V_0} \sigma_{\text{actin}} \]
\[ V_{\text{actin}} = \frac{24A_{\text{actin}}l_0}{[5\sqrt{2}]/[3\sqrt{3}]l_0^3} = \frac{24A_{\text{actin}}}{1.3608l_0^2} \]
\[ \sigma_{\text{actin}} = \frac{F_0}{A_{\text{actin}}} \]
\[ P \approx \frac{1}{3} V_{\text{actin}} \sigma_{\text{actin}} = \frac{1}{3} \frac{24A_{\text{actin}}}{1.3608l_0^2} \frac{F_0}{A_{\text{actin}}} \]
\[ P \approx 5.85 \frac{F_0}{l_0^2} = E \]

prestress is of the same order as young’s modulus

prestress is of the same order as young’s modulus

\[ E_0 = \text{incremental modulus} \]
\[ F_0 = \text{resting force in actin filaments} \]
\[ L_0 = \text{length of microtubules} \]
\[ l_0 = \text{resting length of actin filaments} \]
\[ \varepsilon_0 = \text{strain in actin filaments} \]

\[ W_{\text{mac}} = W_{\text{mic}} \]
\[ W_{\text{mac}} = \frac{1}{2} E \varepsilon \]
\[ W_{\text{mic}} = \frac{1}{V_0} \int_{s_0}^{s_x} T \, dx \]
\[ E = 2\sqrt{3} \frac{T}{5\sqrt{2}l_0} \frac{T}{s_x - s_0} \]
\[ \text{small strain} \]
\[ E_0 = 5.85 \frac{F_0}{l_0^2} \]
\[ 1 + 4\varepsilon_0 \]

Wang, Naruse, Stamenovic, Fredberg, Milalovich, Tolic-Norrelykke, Polte, Mannix, Ingber [2001]
all cellular components are contained within a cell membrane which is extremely thin, approximately 4-5nm, and very flexible inside the cell membrane, most cells behave like a liquid as they consist of more than 50% of water. the cell membrane is semi-permeable allowing for a controlled exchange between intracellular and extracellular components and information.

mechanisms of transport through the membrane
• passive transport driven by gradients in concentration
• active transport that does require extra energy; it is regulated by ion channels, pumps, transporters, exchangers and receptors

5.1 biomembranes - motivation

• the cell wall

in most cells, the internal pressure is much higher than the surrounding pressure. the cell membrane thus has to be strong enough to prevent the explosion of the cell. plant cells and most bacteria have found an efficient solution to withstand the internal pressure: their cells have an external wall to reinforce their cell membrane and balance the pressure difference across it.

• the lipid bilayer

the barrier between the inner and outer cell is the cell membrane, a bilayer consisting of phospholipids of a characteristic structural arrangement. in aqueous solutions, these phospholipids essentially display two kinds of non-covalent interactions.

non-covalent interactions of phospholipids
• hydrophobic, water avoiding non-polar residues
• hydrophilic, water loving polar head groups

this behavior is similar to fatty acids or oil in water, where the hydrophilic polar heads tend to be oriented towards the water phase while the hydrophobic tails are oriented towards the oil phase.

Figure 5.16. Lipid bilayer of the cell membrane. Characteristic arrangement of phospholipid molecules with hydrophilic polar head group being oriented towards the aqueous phase while the hydrophobic tails are oriented towards the non-polar inside.
the lipid bilayer

Figure 5.1: Electron microscopy of the cell membrane stained with osmium tetroxide illustrating the polar head groups with a light 2nm space of hydrophobic tails sandwiched between them, adopted from [4].

5.1 biomembranes - motivation

the lipid bilayer

Figure 1.3. Cell membrane. Phospholipic bilayer with hydrophobic water-avoiding tails and hydrophilic water-loving heads.

Figure 1.5.1. Lipid bilayer of the cell membrane. Characteristic arrangement of phospholipid molecules with hydrophilic polar head group being oriented towards the aqueous phase while the hydrophobic tails are oriented towards the non-polar inside.

the inner life of a cell, viel & lue, harvard [2006]

Figure 1.5.2. The lipid bilayer of the cell membrane is by no means static and homogeneous. Lipids are a class of molecules stacking together to form the membrane which can be understood as a sea on which things are floating. The rafts floating on this sea are called lipid rafts.

the inner life of a cell, viel & lue, harvard [2006]

the cell membrane

Figure 1.3. Cell membrane. Phospholipic bilayer with hydrophobic water-avoiding tails and hydrophilic water-loving heads.
5.1.1 micropipette aspiration

**Figure 5.2:** During micropipette aspiration, a cell is aspirated into a thin glass tube. Knowing the applied suction pressure, we can determine the surface tension of the cell based on changes in cell geometry.

**Figure 5.3:** Experimental setup of micropipette aspiration. The applied suction pressure can be varied by adjusting the height of a fluid-filled reservoir. Cell deformation is measured optically.

**Figure 5.4:** The three stages during micropipette aspiration. The initial state with $L^{pro}/R^{pro} < 1$, left, the critical state with $L^{pro}/R^{pro} = 1$, middle, and the final state with $L^{pro}/R^{pro} > 1$, right.

**Figure 5.5:** Experimental observation of different stages during micropipette aspiration adopted from http://newton.ex.ac.uk/research/biomedical/membranes.

**5.1.1 micropipette aspiration**

- $n = \sigma h$ with $[n] = \text{[force / length]}$

**Figure 5.6:** Liquid drop model. The internal fluid pressure is balanced by a thin elastic shell. The membrane element of thickness $h$ is subjected to membrane stresses $\sigma$. Equivalently, the membrane can be represented as a thin sheet subjected to the surface tension $n$ which results from the integration of the membrane stress over the thickness as $n = \sigma h$. 
5.1.1 micropipette aspiration

Summary: Neutrophils behave as a liquid drop with a cortical surface tension of about 30 pN/μm and a viscosity of the order of 100 Pa·s. Chondrocytes and endothelial cells behave as solids with an elastic modulus of the order of 500 pN/μm = 0.5 kPa.

Finite element simulation of micropipette aspiration

Figure 5.10: Finite element simulation of micropipette aspiration of a chondrocyte modeled as an elastic solid. In contrast to analytical results, finite element simulations can account for large deformations, heterogeneous stress distributions, and a more realistic representation of the boundary conditions [21].