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Extension and Inflation in an Auxetic Stent

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Overview

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Problem Area

- Increasing number of patients with artery blockage annually – 700,000 only in US
  - Build-up of fatty material and other substances on the internal surface of the blood vessels
  - To restore blood supply one strategy is Angioplasty
  - The concept of remodeling the artery introduced in 1964, entered into mainstream of medicine 1977 and its advantages include:

Though benefits of artery remodeling

- ease of operation
- speed of recovery

But ….

- Nearly 70% of the lumen size lost due to arterial elastic recoil. and other early or delayed complications such as

Therefore…

- to mitigate elastic recoil of the artery
- to strengthen the artery wall
The concept of stent which is a tiny tube placed in an artery arose:

- to restore blood flow arose
- to mitigate elastic recoil of the artery
- to strengthen the artery wall

To date various types of blood vessel stents in clinical use:
- metal,
- polymeric,
- fabric
- drug-eluting.
However, the stents currently used are

- Sometimes inflexible
- Shortening in length on deployment due to geometrical pattern
- Early, delayed and potential life-threatening complications such as
  - long-term endothelial dysfunction,
  - Thrombosis
  - permanent physical irritation
  - mismatches in mechanical
  - surgical revascularization

Therefore, major current challenge

➢ To develop, design and manufacture such stents that are
  - Maximally compatible with living tissue
  - Biodegradable
  - Having ability to reduce blockage through drug delivery
  - Low stresses with artery wall
  - Minimise major threats of stenting to the patient – early and delayed complications
Studies and experiments demonstrated that auxetic materials

- Offer a huge potential in biomedical industry
- Several biological tissues possess negative Poisson’s ratio.
- Auxetic stents can help minimise the negative effects of current stent designs through:
  - tailored negative Poisson’s ratio
  - geometrical structure
  - deformation mechanism and
  - enhanced mechanical properties

Superior to conventional material
Therefore, the main focus is.....

→ To design an **auxetic** blood vessel stent of PTFE
→ To study mechanical characteristics
→ To wrap fabricated auxetic stent with nanofibers for drug delivery

This novel auxetic stents can help minimise the negative effects of current stent designs through its

→ enhanced mechanical properties tailored by internal auxetic microstructure and
→ unique deformation mechanism

Therefore, auxetic stent will be beneficial to improve early and delayed complications of stenting hence quality of life of patients.

**Current Objectives**

To discuss auxetic versus non-auxetic behaviour stent of polymer PTFE such as

• twisting moment,
• extension
• inflation.
Poisson’s ratio, $\nu = -\frac{\text{axial strain}}{\text{extension strain}}$

This behaviour doesn’t contradict theory of elasticity...

$-1 \leq \nu \leq 0.5$

**Auxetic**

An example of a cubic single crystal pyrite as having the **Poisson’s ratio of $-0.14$**, and he suggested that the effect may be caused by twinned crystals.


**Conventional**

Poisson's ratios of isotropic materials **can not only take** negative values, but can have a **range of negative values** twice that of positive ones.

Mechanism and structure

What gives rise to auxiticity.....

➢ The material’s geometrical structure

➢ The way the internal structure deforms when loaded
Stainless Steel 316 sample

Before stretching

After stretching
Polyurethane Foam Sample

Conventional Cylindrical Foam

Auxetic Cylindrical Foam

http://www.youtube.com/watch?v=PLDbSWSm5i8
History of auxetic material

- Accepted consequence of classical elasticity theory – A. E. H. Love (1927) in a cubic single crystal pyrite.
- The intentional development – Roderick Lakes (1987) with fabrication of Polyuratylene Foam
- This terminology was coined – Evans et al. (1991) with the fabrication of the microporous polyethylene with negative Poisson’s ratio.
- Since then, a wide range of materials have been produced covering the major classes of materials - polymers, composites, metals, and ceramics.

The most recent exciting research concentrating on
- Liquid crystalline polymer
- Auxetic nanostructures
Natural auxetic materials do exist.

To name a few-

- Single crystals of arsenic and cadmium
- $\alpha$-cristobalite, iron pyrites, many
- Cubic elemental metals and
- Several types of rocks

Some biological materials have been found to be auxetic in certain forms of skin-
- Cat skin, cow teat skin, salamander skin and
- Cancellous bone from human shins.

Arterial endothelium tissue due to pulsatile blood flow subjected to wall shear stresses and cyclic circumferential strain.
Mechanical properties of auxetic materials

Auxetic materials are harder to indent...

Synclastic behaviour...

Saddle shape  Conventional materials upon bending

Dome shaped surface of auxetic materials

Other Properties:
- Enhanced shear resistance
- Enhanced fracture toughness
- More crack resistance
Potential Applications

Applications in biomedical -

- Implants and Prostheses - Artificial intervertebral disks, annuloplasty prostheses, knee prosthetics and artificial blood vessels.
- The scaffolds with tailored auxetic cell geometry

- Applicable (but not limited) for drug delivery systems and **wound dressings**.

For Example: In response to a pulse of blood flowing through a blood vessel (a) decrease in wall thickness, (b) an auxetic arterial material will become thicker.
Auxetic dilator and stents

- **Auxetic dilator**
  Applying tension to the auxetic sheath causes it to expand laterally, which opens up the artery.

- **Artery**
- **Applied tension**
- **Auxetic PTFE flexible sheath**

- **Get a good grip with tumour tissue** by embedding inside the tissue compared to conventional stent.

- **large (expandable) diameter** due to deformation mechanism.

- **Behave like a balloon and** will dilate the artery by its novel expansion behaviour in both ways, transversely and longitudinally.
Artifical intervertebral disc with negative Poisson’s ratio

- allow the same range of motion that the natural intervertebral disc allows
- prevent interference with surrounding nerves

Suture/ muscles/ ligament anchor and fixing devices

Other areas of Applications

Applications in Aerospace
- Curved body parts, aircraft nose-cones, wing panel

Protection
- Blast protection curtains, crash helmet, projectile-resistant or bullet proof vest
As mentioned before in objectives...

- To design an **auxetic** blood vessel stent
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Material selection

- PTFE (Polytetrafluoroethylene) thin cylindrical tube

Why PTFE ..... 

- Highly anisotropic non-linear elastic material
- Biocompatible
- Outstanding physical, chemical, mechanical, and thermal properties
- Flexibility with a high tensile strength and resistance to fatigue
- Extremely hydrophobic
- Maintain material performance over time.
- Auxeticity
Microstructure of polymeric materials
Polytetrafluoroethylene – PTFE

- In the compressed state, the particles lie flat and closely packed.
- When ends are pulled, the disks tilt up, increasing the material’s bulk.
- PTFE expands because of its disk-shaped particles connected with strands.

Nodule–fibril microstructure of auxetic PTFE
A mathematical modeling is developed considering a cylindrical polymer tube as an auxetic stent in the context of non-linear elasticity.

The ends of auxetic cylindrical stent are subjected to tractions that supply:
• a net twisting moment $M$ and normal force, $N$

**Co-ordinates System**

Cylindrical polar co-ordinates as

• before deformation $X_1, X_2, X_3 = R, \Theta, Z$
• after deformation $x_1, x_2, x_3, = r, \theta, z$

$$r = r(R), \quad \theta = \Theta + \psi Z, \quad z = \lambda Z$$

where, $\lambda$ is the axial stretch ratio, $\psi$ is the angle of twist.
\[ W = C_1 \left[ (I_1 - 3) + \frac{1-2\nu}{\nu} \left( \frac{1}{I_3^{1-2\nu}} - 1 \right) + C_4^{4-1} (I_4 - 1)^2 \right] \] (1)

\[ W_1 = C_1, \ W_2 = 0, \ W_3 = -C_1 \frac{1}{I_3^{1-2\nu}}, \ W_4 = -2C_4 (I_4 - 1), \ W_5 = 0 \] (2)

The corresponding stress components are:

\[ J\sigma_{11} = 2C_1 r^2 - 2C_1 \frac{\nu}{I_3^{1-2\nu}} \] (3)

\[ J\sigma_{22} = 2C_1 \left( \frac{r^2}{R^2} + \psi^2 r^2 \right) + \psi^2 r^2 - 2C_1 \frac{\nu}{I_3^{1-2\nu}} + 4C_4 (I_4 - 1) \psi^2 r^2 \] (4)

\[ J\sigma_{33} = 2C_1 \lambda^2 - 2C_1 \frac{\nu}{I_3^{1-2\nu}} + 4C_4 (I_4 - 1) \lambda^2 \] (5)

\[ J\sigma_{23} = 2C_1 \lambda \psi r + 4C_4 (I_4 - 1) \lambda \psi r \] (6)

\[ J\sigma_{12} = 0, \ J\sigma_{13} = 0. \] (7)

where, \[ J = \frac{r \psi \lambda}{R}, I_3 = \frac{r^2 \psi^2 \lambda^2}{R^2}, I_4 = \lambda^2 + \psi^2 r^2 \] (7)
The equilibrium equation in terms of Cauchy stress is

\[ r \frac{d\sigma_{11}}{dr} + \sigma_{11} - \sigma_{22} = 0 \]  \hspace{1cm} (8)

\[ J(\sigma_{11} - \sigma_{22}) = 2C_1 \left( r^2 - \frac{r^2}{R^2} - \psi^2 r^2 \right) - 4C_4(\lambda^2 + \psi^2 r^2 - 1)\psi^2 r^2 \]  \hspace{1cm} (9)

Since for the purposes of illustration we consider an isotropic case to study auxetic and non-auxetic behaviour of materials and as cylinder is composed of Blatz-ko-compressible material, therefore, in this case we have

\[ W = \frac{\mu}{2} \left[ \left( \frac{I_2}{I_3} \right) + 2\sqrt{I_3 - 5} \right] \]  \hspace{1cm} (10)

where, \( I_2 = r^2 \left( \frac{r^2}{R^2} + \lambda^2 + \psi^2 r^2 \right) + \frac{\lambda^2 r^2}{R^2}, \quad I_3 = \left( \frac{r R \lambda}{R} \right)^2, \quad \mu = \frac{E}{2(1+\nu)}, \quad \nu \) and \( E \) are Poisson's ratio and Young's modulus respectively.
The expressions for resulting normal forces, twisting moment and inflation for the stent which is considered as a hollow cylinder with internal radius $a$ and external radius $b$ are:

\[ \sigma_{33} = \left( 1 - \frac{R(1+\psi^2 r^2)}{rr'\lambda^3} \right) \]  

(15)

\[ \sigma_{23} = \mu \frac{\psi r}{\lambda} \]  

(16)

\[ \sigma_{11} = \sigma_{22} = \sigma_{12} = \sigma_{13} = 0 \]  

(17)

The stress components along with the boundary condition $\sigma_{11}(b) = 0$, are obtained as:

\[ N = \pi \mu \int_a^b \sigma_{33} r \, dr \]

\[ M = \pi \mu \int_a^b \sigma_{32} \lambda^3 \, dr \]

\[ P = \frac{\mu}{a^2} \int_a^b \sigma_{33} r \, dr \]
Results

Pressure-radius curves auxetic stent
Pressure-radius curves non-auxetic stent
Comparison of auxetic versus non-auxetic behaviour
Pressure- radius curves of stents
Axial force – radius curves auxetic stent
Axial force – radius curves non-auxetic stent
Comparison of axial force – radius curves of an auxetic versus non-auxetic stent
Twisting moment – radius curves in an auxetic stent
Twisting moment – radius curves non-auxetic
Comparison of twisting moment – radius curves of auxetic versus non-auxetic stent
Conclusion

- The pressure, normal forces and twisting moment required to maintain increased radius is almost half compared to non auxetic stent.

- Under the effect of auxeticity the stent will display:
  - Increased circumferential stiffness with expansion and decreased flexural stiffness with compression
  - Reduction in foreshortening of stent on deployment because of its auxeticity
  - Reduced detachment of auxetic stent from the vessel wall
  - Initially having a small diameter could be beneficial in deployment of the stent

- As our further objective is wrapping auxetic stent with nanofibers therefore:
  - Due to flow of blood, the polymeric nano fibres will work as a delivery medium for drug. Micropores will open to release the drug with the stretch of auxetic stent and similarly when the stent will relax, the fibres micropores will close to cease drug delivery.
Summary

This novel auxetic stents can help minimise the negative effects of current stent designs through its

- enhanced mechanical properties tailored by internal auxetic microstructure and
- unique deformation mechanism

Therefore, auxetic stent will be beneficial to improve early and delayed complications of stenting hence quality of life of patients.

As well as auxetic materials concerned……

- Negative Poisson’s ratio can be engineered at different scales. The tailoring of the Poisson’s ratio with improved mechanical properties opens the door to new applications.

- Research involving auxetic materials and applications is highly multidisciplinary is increasingly recognized as an integral component of smart and advanced materials technologies.
Publications


Thank You
Contact for further information

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