A Numerical Investigation of Stresses, Printing Efficiency, Printability, and Cell Viability in Nozzle Printheads for 3D Extrusion Bioprinting

3D押し出しバイオプリンティングに関する流体せん断応力、印刷効率、印刷適性、細胞生存率に関する数値解析

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1. Introduction

- 3D extrusion bioprinting
    - Manufacturing tissues and organs.
- Printing with bioink
    - Extruding inks that contain living cells.
- Shear-thinning behavior
    - Viscosity decreases under shear rate.

Benefit	Drawback
Affordable and scalable	Limited printing resolution/speed
Ease of operation	High stresses inside the needle
Deposit high cell densities	Low cell viability (40–80%)[1]

Table 1. Benefits and drawbacks of 3D extrusion bioprinting.

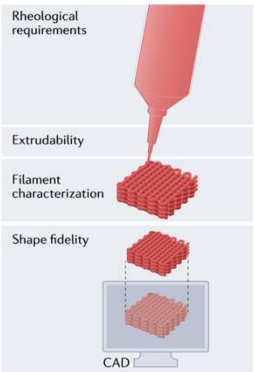

Figure 1. Assessment Criteria of 3D extrusion bioprinting. [1]
*CAD: computer-aided design.

3. Objectives

- Performing numerical simulation to assess stresses, efficiency/printability, and cell viability.
- Investigating needle geometries and bioink's rheological properties to increase cell viability.

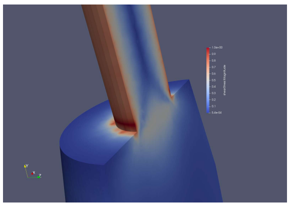

Figure 2. Numerical simulation carried out by OpenFOAM. Shear stress distribution (kPa).

4. Part I: Bioink Inside the Needle

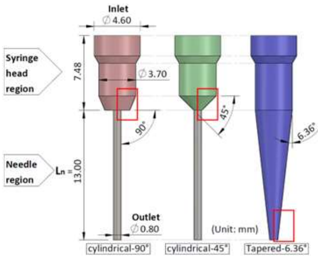

Figure 3. Needle dimension setup for assessment of bioink inside needles.

- Investigating 3 types of needles.
- Bioink acts as power-law fluid.
- Validating simulation results with analytical models.
- Visualizing shear stress distribution and cell viability zones.

$$\tau_{rz} = \eta(\frac{\mathrm{d}V_z}{\mathrm{d}r}) = K\dot{\gamma}^n$$

$$\eta = K\dot{\gamma}^{n-1}$$

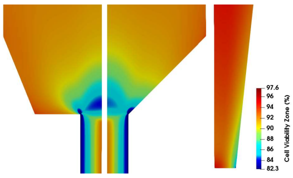

Figure 5. Comparative visualization of cell viability in three different needle types: 90° Cylindrical, 45° Cylindrical, and Tapered. The viability zones [2] illustrate the impact of needle design on cell stress and potential for bioprinting applications.

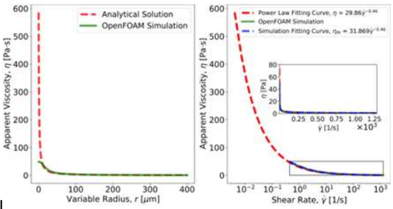

Figure 4. The relationship between shear rate and apparent viscosity (cylindrical needle). The simulation indicates that the apparent viscosity doesn't diverge due to the non-divergence of the shear rate at the center of the needle.

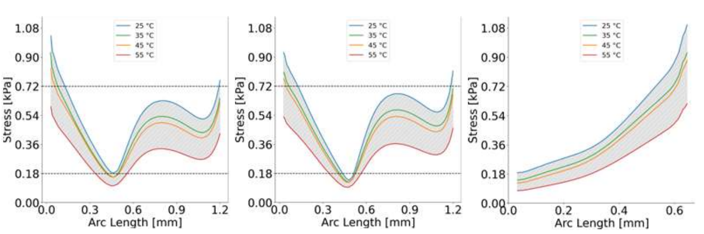

Figure 6. Shear stress dependencies on temperature for 90° Cylindrical, 45° Cylindrical, and Tapered needles. Temperature variations distinctly alter stress distributions, with the most significant impact observed under the 2.5% (w/v) condition.

2. Challenges

- Difficult to observe shear stress/cell viability experimentally.
- Testing thousands of different bioinks is repetitive and tedious.
- The need to optimize needle geometry, cell viability, printing efficiency, and printability.

5. Part II: Printed Bioink Strand

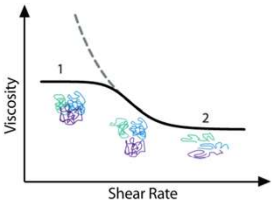

Figure 7. Visualization of rheological behavior driven by the disentanglement and elongation of polymer chains. [3]

- Solid line: non-Newtonian shear-thinning behavior.
- Dashed line: yield stress observed outside the needle.
- Yield stress needs to be considered for the printed strand.
- Bioink acts as Herschel-Bulkley fluid.

$$\tau = \boxed{\sigma_y} + K\dot{\gamma}^n$$

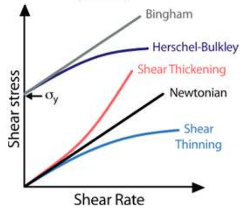

Figure 8. Classification of fluids with shear stress as a function of shear rate. [4]

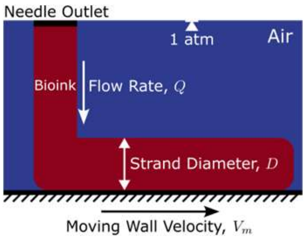

Figure 9. Simulation setup for the assessment of printability.

- Comparison between analytical models and simulation results.
- The Herschel–Bulkley fluid model provides an adequate estimate (81.1%) on the printed strand diameter.

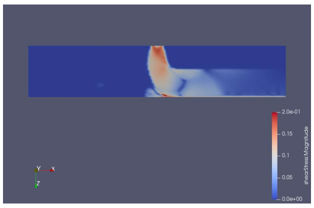

Figure 10. Assessment of shear stress (kPa) experienced by the printed strand at 25°C.

$$D = \sqrt{\frac{4Q}{\pi V_m}}$$

Strand diameter
Volumetric flow rate
Horizontal needle moving speed

6. Conclusion

- The 90° cylindrical needle provides a smaller maximum wall stress area, but a higher extensional stress region at the needle inlet region over its 45° counterpart.
- The tapered nozzle exhibits the least stress in terms of both magnitude and area.
- Visualizations of shear stress distribution, efficiency/printability, and cell viability zones are established.

7. Future Work

- Utilizing supervised learning regression to estimate cell viability zones; comparing them with experiments.
- Acquiring experimental data to train machine learning models.

8. References

[1] Y. S. Zhang et al., *Nature Reviews Methods Primers*, **1**(1), pp. 1–20, 2021
[2] Lemari ́e et al., *Bioprinting*, **21**(2021), e00119, 2021
[3] Cooke and Rosenzweig, *APL Bioengineering*, **5**(1), p. 011502, 2021
[4] Schwab et al., *Chemical Reviews*, **120**(19), pp. 11028–11055, 2020