Fluid Mechanics Simulation and Degradation of Bone Tissue Engineering Scaffolds with Gyroid Architecture

Authors: Archie K. Tram[1], Cynthia Schwartz, M.S.[2], Jason Walker, Ph.D.[3], Samir Ghadiali, Ph.D.[1,4], David Dean Ph.D.[1,3]
Affiliations:
[1]Department of Biomedical Engineering, The Ohio State University, Columbus, OH
[2]College of Medicine, The Ohio State University, Columbus, OH
[3]Department of Plastic Surgery, The Ohio State University, Columbus, OH
[4]Department of Internal Medicine, The Ohio State University, Columbus, OH

THE OHIO STATE UNIVERSITY
WEXNER MEDICAL CENTER

Introduction

Significance:

- Bone tissue-engineering scaffolds are frameworks for bone grafts.
- Scaffolds are 3D printed using poly(propylene fumarate) (PPF), a photo-crosslinkable, biocompatible, and degradable polymer.
- The scaffold needs to degrade in a timely manner *in vivo*.

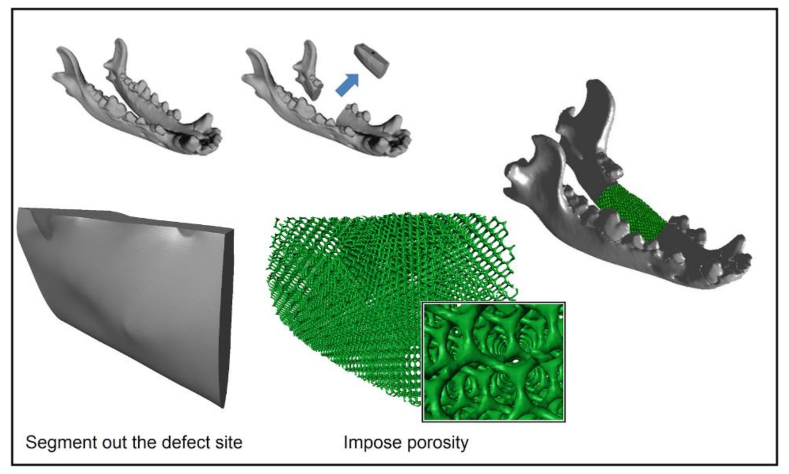

Figure 1: Work Flow to Create a Porous Implant

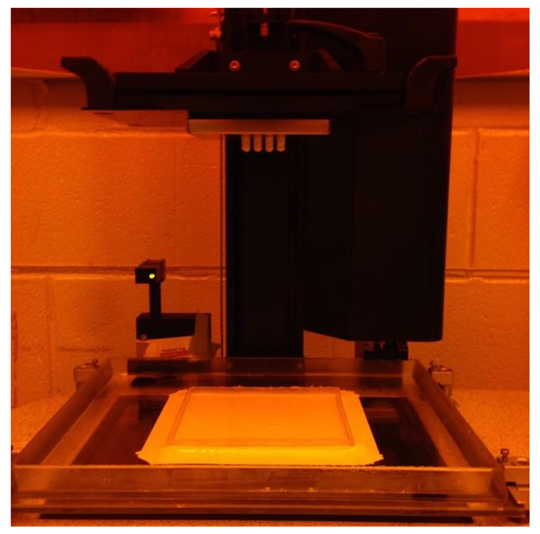

Figure 2: 3D printed scaffolds in Perfactory 3

Hypothesis:

- Scaffold degradation can be modeled *in vitro*.

Goals:

- Benchmark the degradation profile of resorbable, porous scaffolds with Schoen's Gyroid-type Triply Periodic Minimal Surface:
  - Begin with static condition.
  - Expand to model degradation in interstitial flow (dynamic condition).
    - To better understand the degradation in fluid flow, computer simulations were used to approximate the fluid mechanics (shear stress, particle trace, etc.) of the flow through the scaffold.

Materials and Methods

Additive Manufacturing of Scaffolds

- Scaffolds were 3D printed using EnvisionTEC Perfactory 3.
- "Green" scaffolds were washed using acetone, ethanol, and water before further crosslinking in an ultraviolet box.

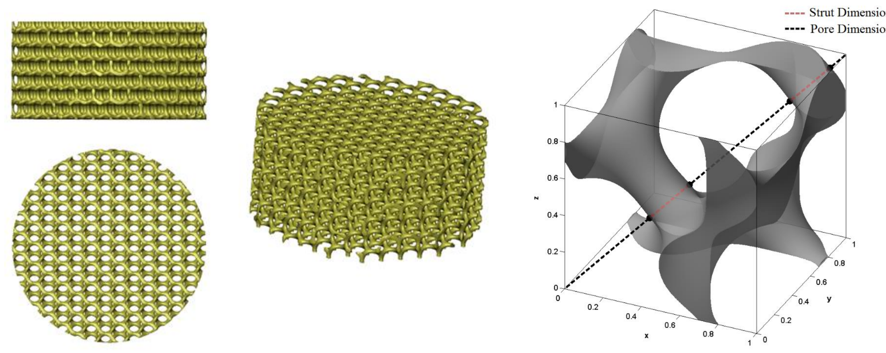

Figure 3: CAD Model of PPF Scaffold

Table 1: Scaffold Parameters

Parameter	Value
Height	5 mm
Diameter	10 mm
Strut Dimension	200 um
Pore Dimension	700 um
Molecular Weight	1500 Da

Experimental Degradation:

- Scaffolds were weighed and randomized to reduce differences between each group (20 scaffolds could be made per print; 4 groups of scaffolds were printed in total).
- Degradation rate was quantified using mass loss in the scaffolds, pH drop in media, and compression to failure data of the scaffolds.
- A pH 13 sodium hydroxide solution was used to accelerate the study.
  - PPF cross-linked polymer degrades by base-catalyzed ester hydrolysis.

Table 2: Experimental Design of Degradation Study

Condition:	Static	Dynamic
Time points	0, 2, 4, 6, 8, 10, 20, 30, and 40 days	0, 2, 4, 6, and 8 days
# of samples	5 per group	5 per group
Temperature	37 ºC	37 ºC
Set up	Individual test tubes	Individual bioreactors
Location	Hot water bath	Incubator

Flow Simulations

- The CAD model was generated in MATLAB (MathWorks, Natick, MA) and processed using AMIRA Software (FEI, Hillsboro, OR).
- Fluid mechanics simulations were conducted using ADINA Software (ADINA R & D, Inc., Watertown, MA).
  - Set up: scaffold inside a cylinder (which represents the bioreactor)
  - A small scaffold model (1 mm x 2 mm) was used as a preliminary model.

Table 3: Boundary Conditions of the CFD Model

	Boundary Conditions
Inlet	Flow velocity = 2.5 um/s
Outlet	Atmospheric pressure
Wall	No slip

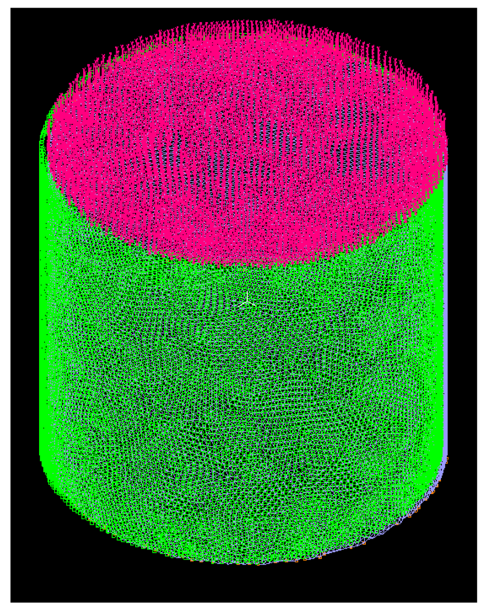

Figure 4: Boundary Conditions as seen in ADINA

- Mesh Convergence study: balance accuracy and computing resources (time, computing power, etc.)

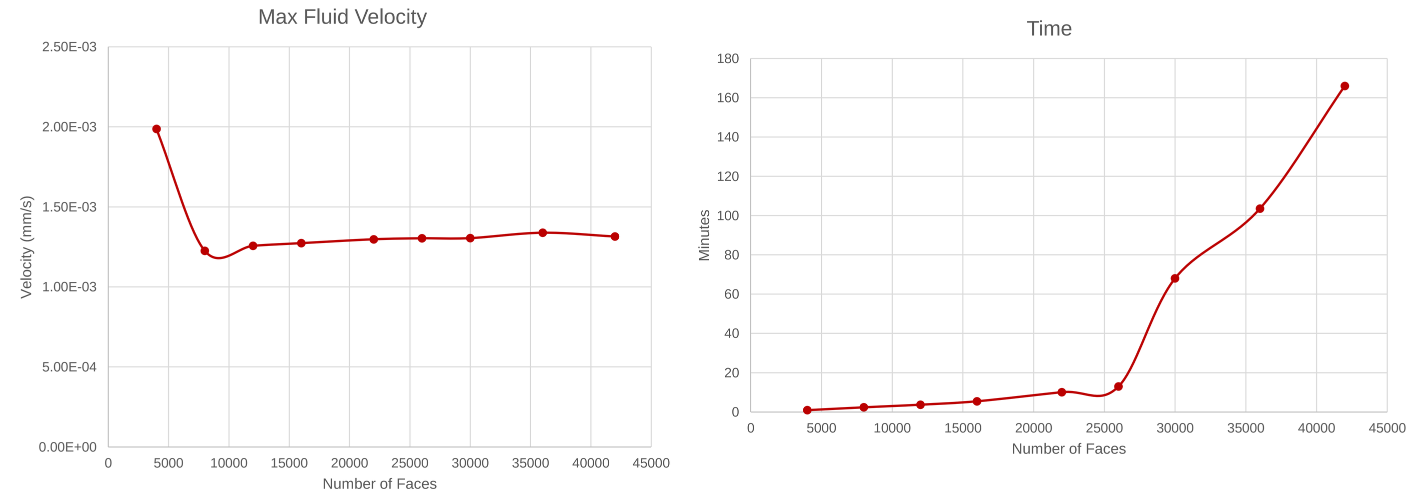

Figure 5: Mesh Convergence Study results

Results

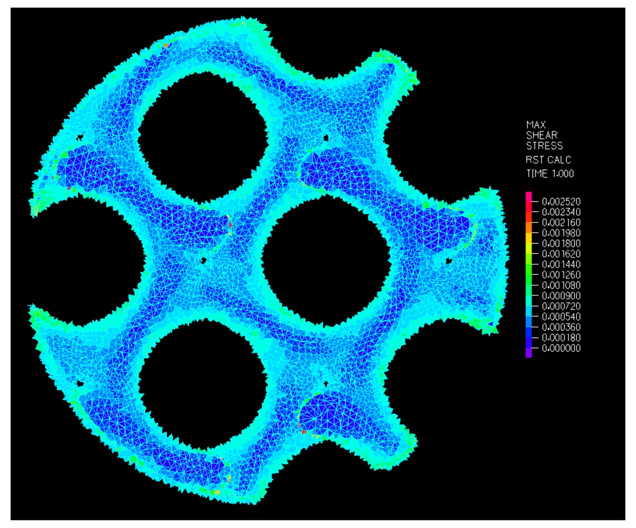

Figure 6: Shear Stress Result, Narrow Bioreactor

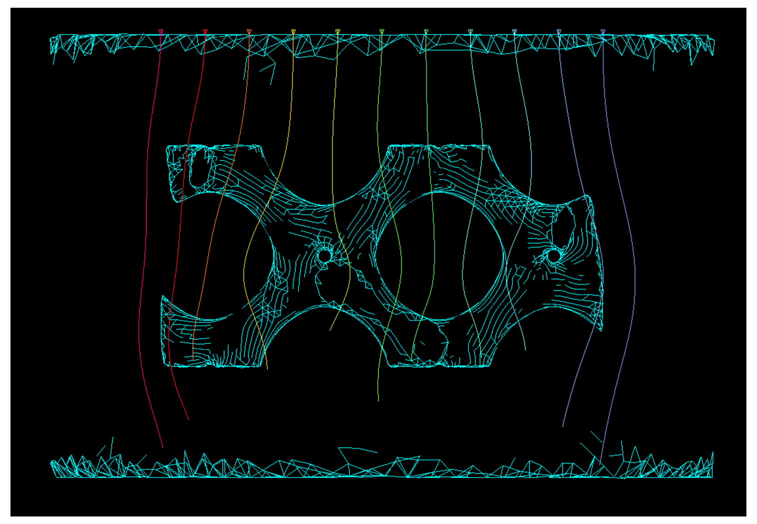

Figure 7: Particle Trace Plot, Narrow Bioreactor

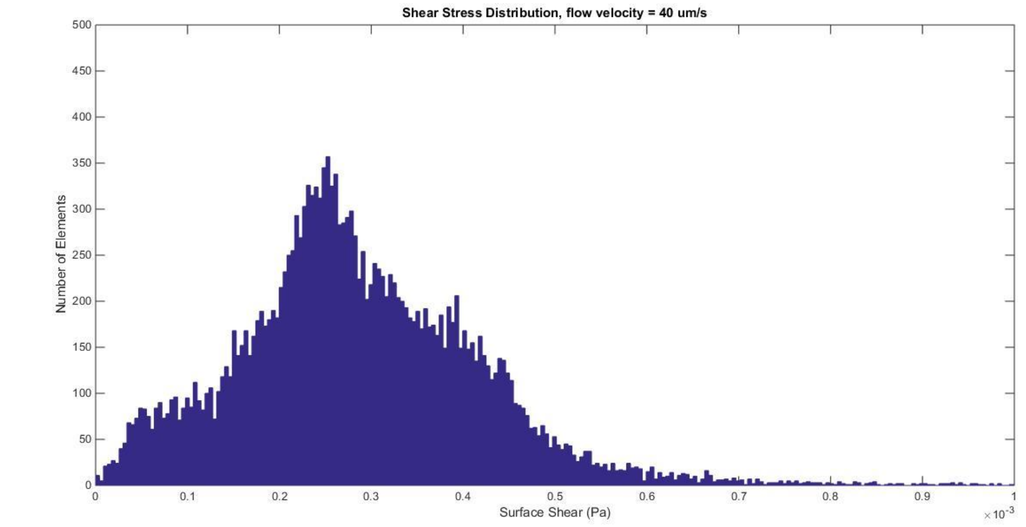

Figure 8: Stress Distribution, Small Scaffold Model

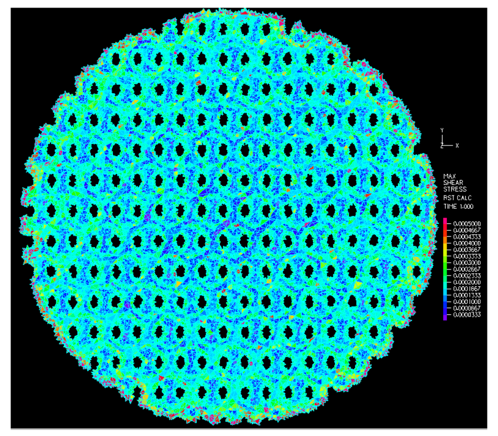

Figure 9: Shear Stress Result, Big Bioreactor

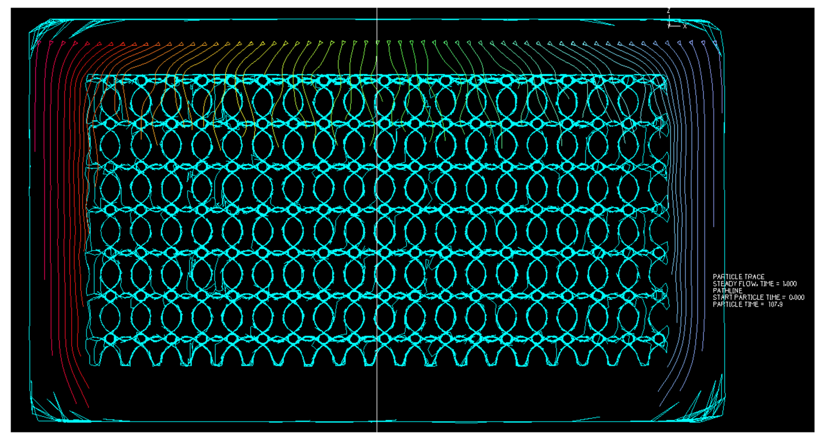

Figure 10: Particle Trace Plot, Big Bioreactor

Conclusions

- Experimental degradation study is still in progress.
- Computer simulation results suggest that fluid is going around the scaffold in the bioreactor system.
  - One possible solution is to use narrower bioreactors, so that the fluid is forced to go through the scaffold.

References

1. Maes F et al. Computational models for wall shear stress estimation in scaffolds: A comparative study of two complete geometries. J Biomech 2012; 45:1586-92.
2. Agrawal CM et al. Effects of fluid flow on the in vitro degradation kinetics of biodegradable scaffolds for tissue engineering. Biomaterials 2000; 21: 2443-52

Acknowledgments

This work was supported by the Army, Navy, NIH, Air Force, VA and Health Affairs to support the AFIRM II effort, under Award No. W81XWH-14-2-0004. The U.S. Army Medical Research Acquisition Activity, 820 Chandler Street, Fort Detrick MD 21702-5014 is the awarding and administering acquisition office. Opinions, interpretations, conclusions and recommendations are those of the author and are not necessarily endorsed by the Department of Defense.