Design of 3D-Printed Bone Tissue Engineering Scaffolds with Pore Architecture based on Triply Period Minimal Surfaces

OSTEO ENGINEERING LAB
Department of Plastic Surgery | OSU

THE OHIO STATE UNIVERSITY
WEXNER MEDICAL CENTER

Authors: Archie K. Tram[1], Jason Walker[2], David Dean[1,2]
Institutions: [1]*Department of Biomedical Engineering, The Ohio State University, Columbus, OH;* [2]*Department of Plastic Surgery, The Ohio State University, Columbus, OH*

Introduction

Background:

Porous scaffolds show promise to enhance osteogenesis due to increased nutrient and waste transport. Additionally, computer design and 3D printing of scaffolds contribute to cell-scaffold system development and also increase repeatability of experiments.

Hypothesis:

We hypothesize that a complex scaffold design could be computationally generated and customized using MATLAB. A distance field method [1] and gyroid-type triply periodic minimal surface (TPMS) were used to generate porous and 3D printable scaffold models.

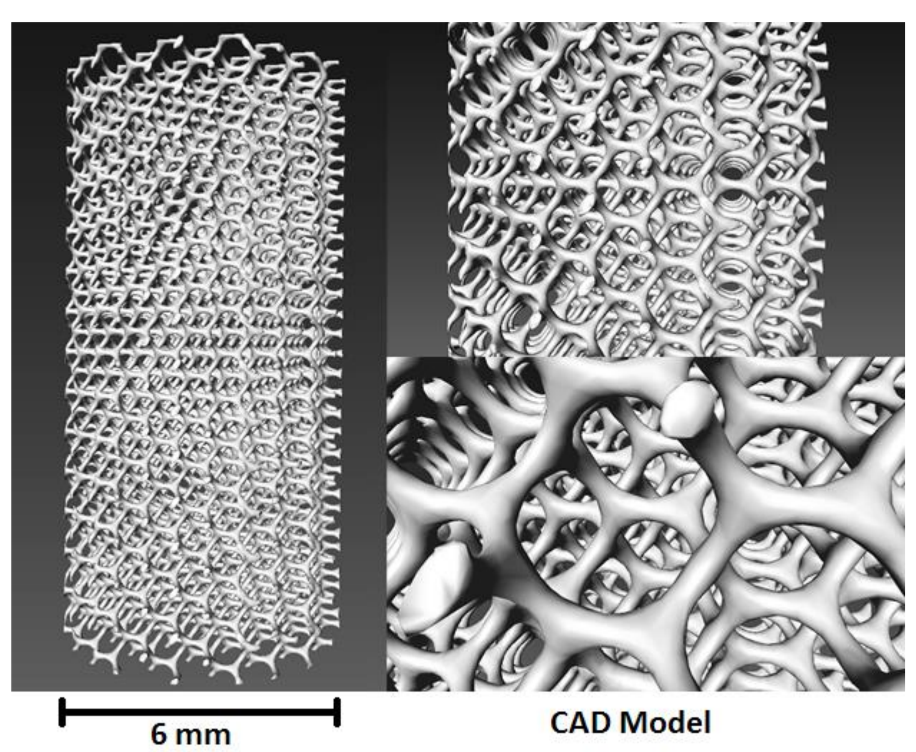
Objective:

Determine a method to control scaffolds with a wall thickness as thin as 125 microns and pore sizes from 300 to 800 microns during the generation process of the scaffold. Scaffold models were to be generated with porosities ranging from 80% to 97%. These scaffolds mimic the macrostructures from some living organisms [2] and might provide the ideal environment for wound healing and osteogenic development of stem cells.

Materials and methods:

Triply periodic minimal surfaces (TPMS)

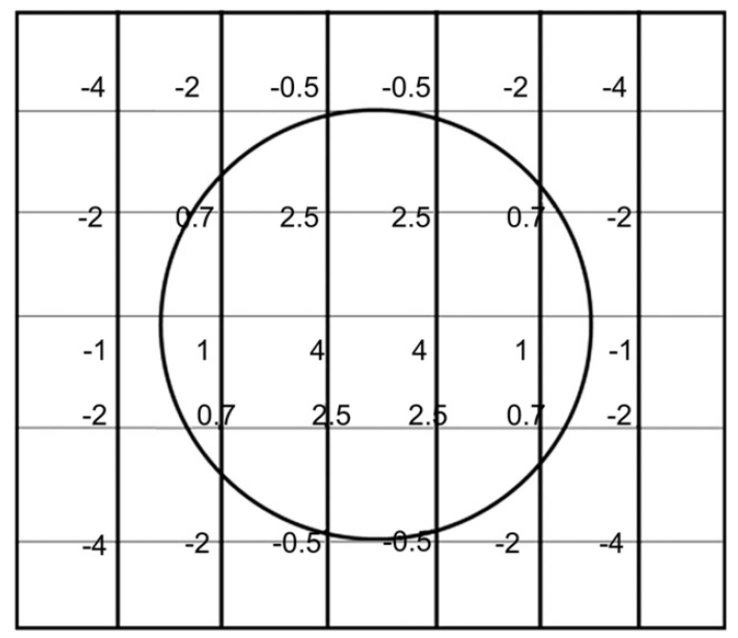
- A minimal surface is the surface with smallest possible area that meets some required boundary conditions, e.g. soap films or a sphere.
- TPMS are mathematically defined by trigonometric equations that can generate minimal surfaces infinitely in three dimensions. The Gyroid-type surface is used in this study:



$$\sin x \,.\, \cos y + \sin y \,.\, \cos z + \sin z \,.\, \cos x = 0$$

Signed Distance Field

- A signed distance field is a scalar field that expressed the distance from every point in space to the boundary of the surface.
- Distance fields of TPMS and Implant CT scan can be intersected to create implant models that have TPMS architecture [1].
- The algorithm was executed in MATLAB (Mathworks, Natick, MA).



From Dong J. Yoo [1]

Creating Porous Structure:

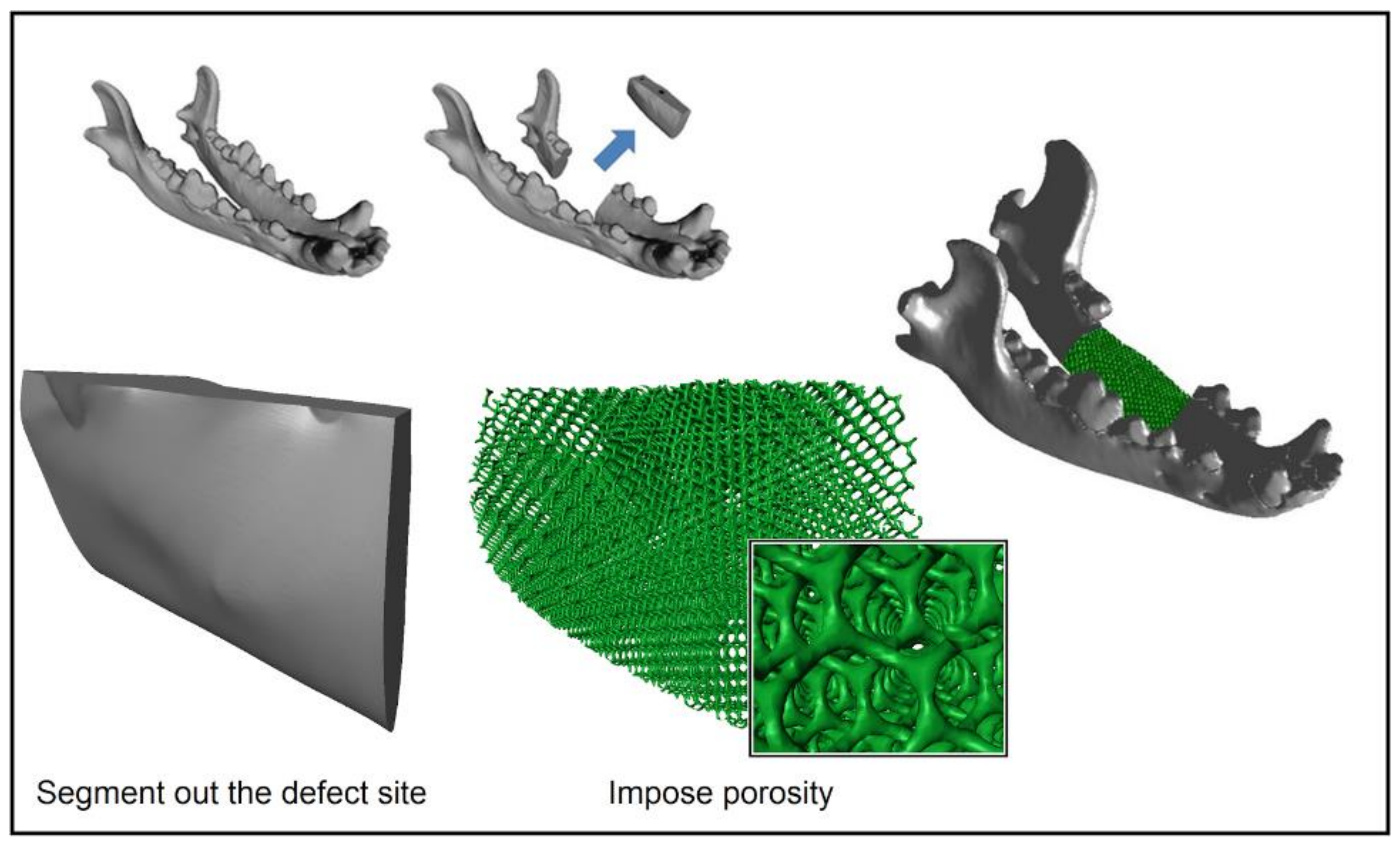
•A porous object can be generated using a Boolean expression:

$\varphi_{Object} \cup \varphi_G = \max(\varphi_{Object}, \varphi_G)$

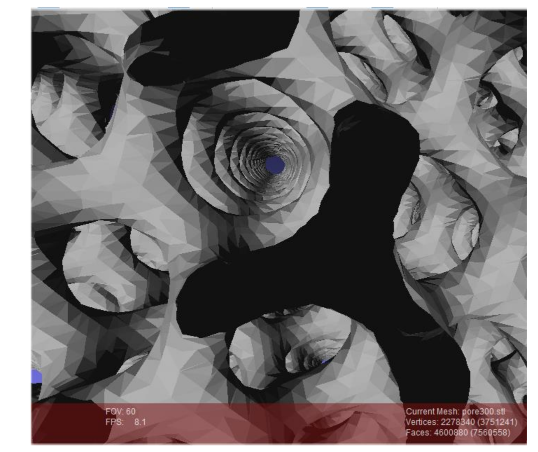
•Taking the maximum values of distance fields of object and gyroid surfaces gives the union of the two structures.

Results

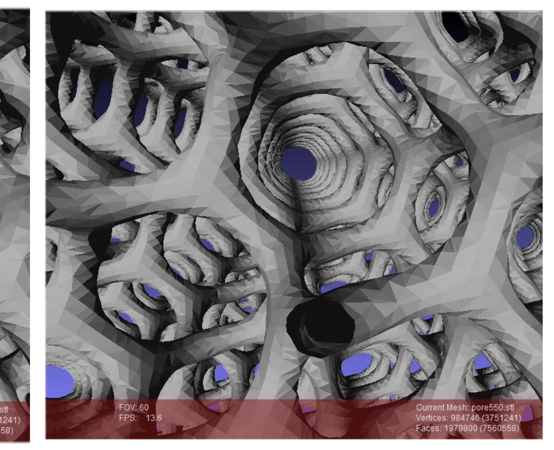
Work Flow to Create a Porous Implant



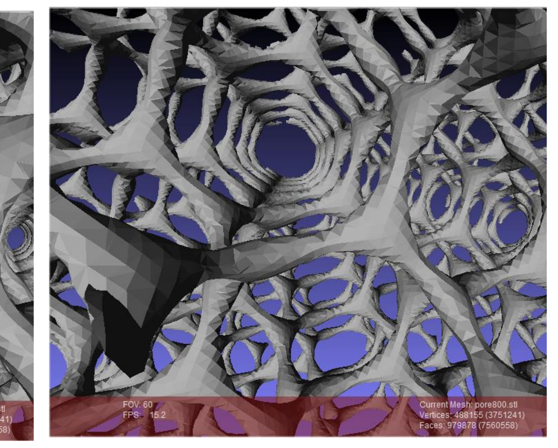
- The canine mandible is segmented from a skull CT scan using Amira Software (Mercury Computer Systems/3D Viz group, San Diego, CA)
- The defect site was cut and processed using MATLAB.
- TPMS was imposed onto the defect site model using MATLAB.
- The implant model is 3D printed and surgically placed in the defect site.



- Pore size: 300 microns
- Strut size: 125 microns
- Porosity: 80%

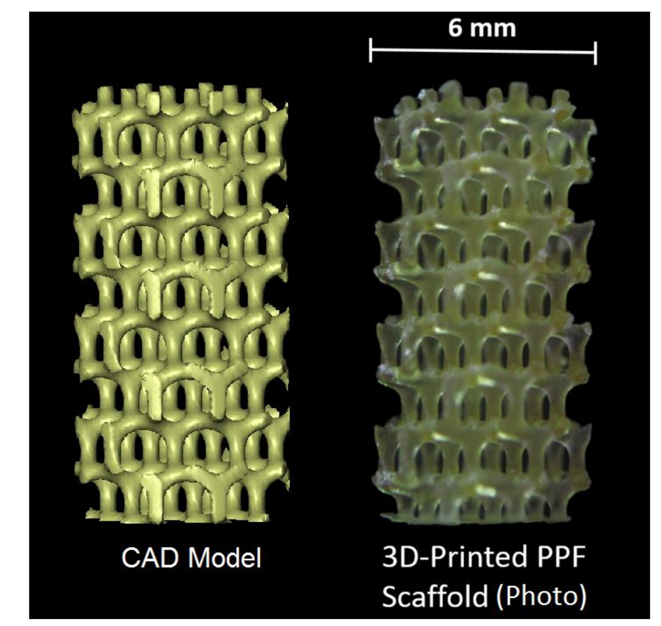


- Pore size: 550 microns
- Strut size: 125 microns
- Porosity: 92.4%



- Pore size: 800 microns
- Strut size: 125 microns
- Porosity: 96.6%

3D Printed Gyroid structure



Additive Manufacturing

The material used for 3D printing of our scaffolds is poly(propylene fumarate) (PPF). PPF is a photo-crosslinkable polymer, initiated by UV light. Some advantages of using PPF include its biocompatibility, biodegradability, and 3D-printability.

Conclusions

- Porous Implants that meet requirements for polymer resorption and enhance osteogenesis can be generated using MATLAB.
- In the future, perfusion of 3D printed scaffolds will be performed to optimize the pore geometry with respect to its biodegradable characteristics.
- This methodology sheds light on the complex design of bone tissue engineering and helps to improve our understanding of mathematics in living systems.

References

1. Yoo DJ. Porous scaffold design using the distance field and triply periodic minimal surface models. Biomaterials;32(2011):7741-7754
2. Michielsen K., Stavenga DG. Gyroid cuticular structures in butterfly wing scales: biological photonic crystals. Journal of The Royal Society Interface;5(2008):85-94

Acknowledgments

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