Design and Fabrication of Biomorphic Tissue Engineering Scaffolds using Trigonometric Templates

Srinivasan R, Lu L, Robb RA, and Yaszemski MJ.
Mayo Clinic College of Medicine, Rochester, MN, USA.

Statement of Purpose: Tissue engineering scaffold fabrication with computer-controlled solid freeform fabrication (SFF) offers precise control and reproducibility of matrix architecture. However, the status quo based on straight-edged, anti-biomorphic cubic lattices manacles the "*bench-to-bedside*" transition of tissue analogs. We introduce trigonometry-based unit cells to create biomorphic scaffolds with optimal stress/strain distribution and superior mechanical strength.

Methods: Single-valued trigonometric functions (Table 1) were used to describe the 50% porous Schwarz, Gyroid and IWP minimal surfaces[1]– curved, bicontinuous, non-intersecting, zero-mean curvature and hence biomorphic surfaces (Fig 1A-C). The trigonometric functions were solved using a level set formulation and the resultant unit templates were tessellated to form the respective scaffolds with pore-solid labyrinths (Fig 1D-F). A cubic partition based scaffold with identical porosity was also constructed. Multiple copies of the $5mm^3$ scaffolds and unit cells of the minimal surface and cubic partitions were fabricated with the PatternMaster rapid prototyping (RP) machine (Solidscape, Merrimack, NH). Mechanical characterization of the unit cells was performed with uniaxial compressive simulation on ABAQUS (HKS Inc, Plymouth, MI) and uniaxial compression on Dynamic Mechanical Analyzer (DMA: TA Inst., New castle, DE). The scaffolds were tested using DMA. The loading conditions and material properties were identical for all the configurations.

Results/Discussion: The results from ABAQUS simulation (Fig. 2) shows pronounced stress and strain concentrations on cubic unit cells but optimal stress distribution and significant strain reduction on Schwarz unit cells. Similar trend was observed for the Gyroid and IWP minimal surfaces. DMA testing (Fig. 3) validates the simulation and demonstrates significantly ($p < 0.02$) higher mechanical strength of TPMS based unit cells and scaffolds.

Conclusions: Though the natural manifestations of minimal surface forms have been observed in biology[2], and the computational framework to create such a geometry has been in place for decades, to the best of our knowledge, no attempt has been made so far to fabricate them using rapid prototyping devices let alone investigate their potential use as tissue surrogates. We have presented a trigonometric approach to physically realize and mechanically characterize these novel templates. This viable morphology, when replicated at macro (tissue) level may also have profound implications on cell migration and tissue growth and may provide an optimal biomorphic tissue analog.

Acknowledgements: This work was supported by Mayo Clinic and NIH (R01 AR45871 and R01 EB003060).

References:

1. Schwarz HA. *Gesammelte math. Abhandlungen*, 1890.
2. Landh T. *FEBS Lett.,* 369:13-13,1995.

Table1. Nodal trigonometric equations used to implicitly define the different minimal surface geometries.

Minimal Surface	**Nodal Equation** (Key: C(.) = Cos(.); S(.) = Sin(.)
Schwarz	$C(x) + C(y) + C(z) = 0$
Gyroid	$C(x)S(y) + C(y)S(z) + C(z)S(x) = 0$
IWP	$C(x)C(y) + C(y)C(z) + C(x)C(z) - C(x)C(y)C(z) = 0$

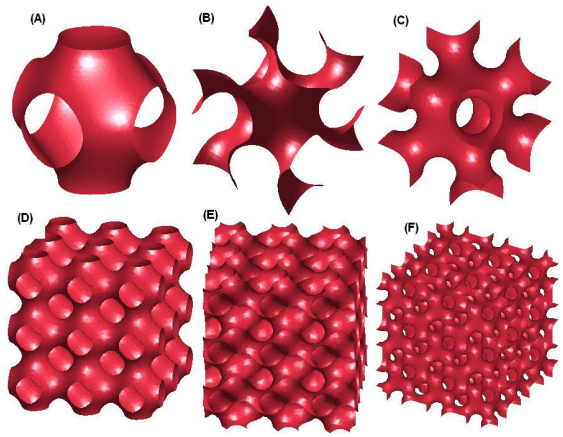

Figure 1. Unit cells and tessellations of Schwarz (A,D), Gyroid (B,E) and IWP (C,F) minimal surfaces**.**

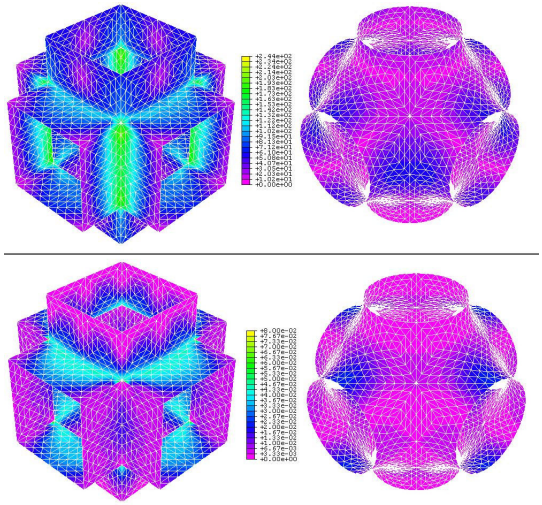

Figure 2. Von Mises Stress (top) and Principal Strain (bottom) map under bulk compression for cubic (left) and Schwarz (right) unit cells under identical loading conditions and material properties.

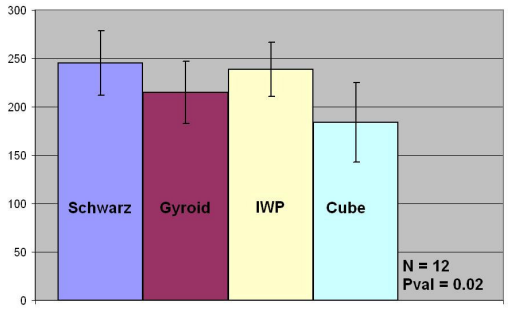

Figure 3. Linear modulus of minimal surface and cubic unit cells based on uniaxial compression on DMA under identical loading conditions (4 N/min. ramp force for 4.5 minutes)