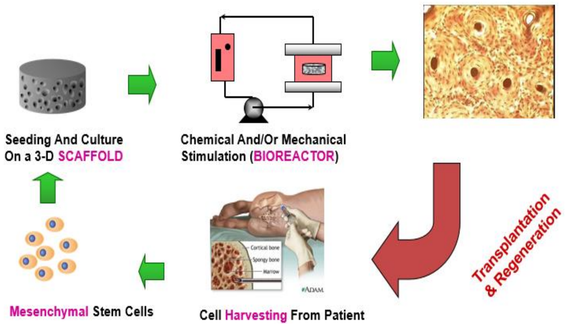
Numerical Accuracy Comparison of Two Boundary Conditions Commonly used to Approximate Shear Stress Distributions in Tissue Engineering Scaffolds Cultured under Flow Perfusion

Olufemi E. Kadri,[1] Cortes Williams III,[2] Vassilios Sikavitsas,[2] and Roman S. Voronov[1]

[1] Otto H. York Department of Chemical, Biological and Pharmaceutical Engineering, New Jersey Institute of Technology, Newark, NJ 07102, USA
[2] Stephenson School of Biomedical Engineering, The University of Oklahoma Norman, OK 73019, USA

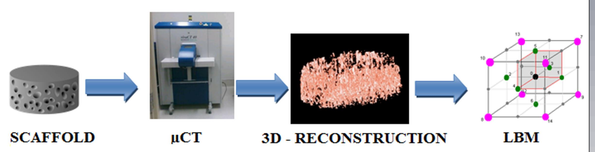
Abstract

Flow-induced shear stresses have been found to be a stimulatory factor in pre-osteoblastic cells seeded in 3D porous scaffolds and cultured under continuous flow perfusion. However, due to the complex internal structure of the scaffolds, whole scaffold calculations of the local shear forces are computationally-intensive. Instead, representative volume elements (RVEs), which are obtained by extracting smaller portions of the scaffold, are commonly used in literature without a numerical accuracy standard. Hence, the goal of this study is to examine how closely the whole scaffold simulations are approximated by the two types of boundary conditions used to enable the RVEs: "wall boundary condition" (WBC) and "periodic boundary condition" (PBC). To that end, Lattice-Boltzmann Method fluid dynamics simulations were used to model the surface shear stresses in 3D scaffold reconstructions, obtained from high resolution microcomputed tomography images. It was found that despite the RVEs being sufficiently larger than 6 times the scaffold pore size (which is the only accuracy guideline found in literature), the stresses were still significantly under-predicted by both types of boundary conditions: between 20 and 80% average error, depending on the scaffold's porosity. Moreover, it was found that the error grew with higher porosity. This is likely due to the small pores dominating the flow field, and thereby negating the effects of the unrealistic boundary conditions, when the scaffold porosity is small. Finally, it was found that the PBC was always more accurate and computationally efficient than the WBC. Therefore, it is the recommended type of RVE. Overall, this work provides a previously-unavailable guidance to researchers regarding the best choice of boundary conditions for RVE simulations.

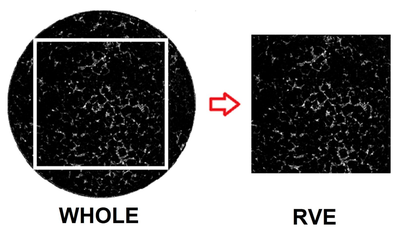


Schematic of the Tissue Engineering Approach

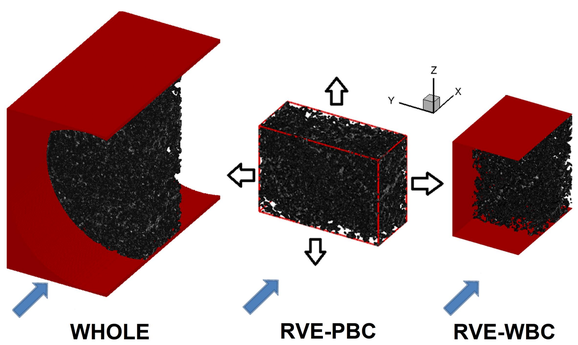
Methods



Computational methodology: The scaffolds were first manufactured, and then scanned using high-resolution micro-CT. Afterwards, their architecture was reconstructed virtually in 3D, and imported into the LBM fluid flow solver. Finally, the LBM simulation results were used to compute the shear stresses on the scaffold surfaces.



A 2D analogy of how an RVE simulation domain is cut out of a whole scaffold micro-CT image. Grayscale color is the X-ray radio-density of the scaffold material as imaged via micro-CT

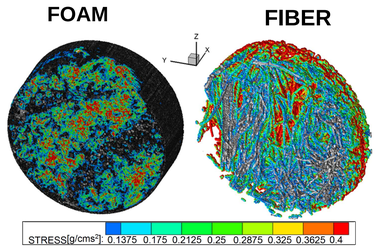


Simulation domain comparison between whole scaffold simulations and the RVEs. Cross-sectional views are shown for the whole simulation domain and RVE-WBC (right half is omitted for clarity). Wall and entrance length are shown in red. White arrows show the directions in which periodicity is applied for RVE-PBC. In all panes, the blue arrow is the flow direction; and the gray scale color is the X-ray radio-density of the scaffold material, as imaged via micro-CT.

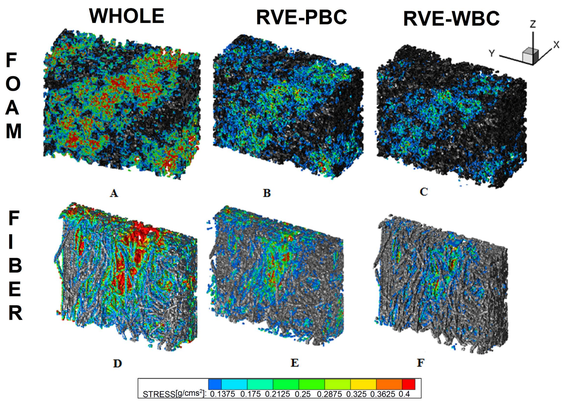
- Calculations were done for ten scaffolds at a flow rate of 0.15mL/min.
- For the accuracy comparisons, the error at every fluid surface node was calculated using:

$$\varepsilon_t = 100\% * \left| \frac{True\ (Whole\ Scaffold) Stress - Approximated\ (RVE)\ Stress}{True\ (Whole\ Scaffold)\ Stress} \right|$$

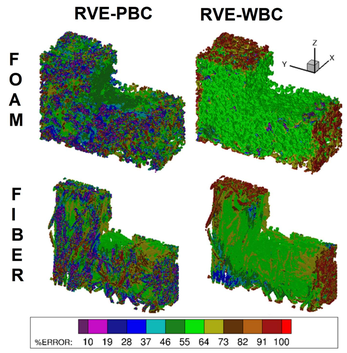
Results



3D reconstructions of the two scaffold types used in this study, with the surface stress maps (color) calculated from LBM overlaid on the micro-CT images (gray scale). The pipe surrounding the scaffold, and stress values below 0.1dynes/cm² are omitted for clarity. Sizes are 1.61mm x 5.1mm x 5.1mm and 1.10mm x 5.1mm x 5.1mm for salt-leached and nonwoven fiber scaffolds respectively.

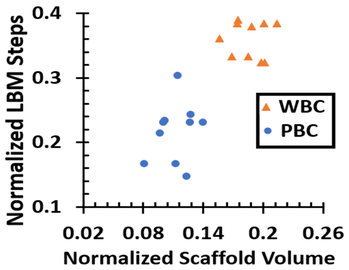


Surface *stress* maps overlays for the RVE-equivalents cutout from whole scaffold simulations and the two types of boundary conditions used for the RVEs. Colored portion represents calculated stresses while gray is the X-ray radio-density of the scaffold material as imaged via micro-CT. Dimensions are 1.61mm x 3.91mm x 2.81mm and 1.10mm x 3.79mm x 2.99mm for salt-leached and nonwoven fiber-mesh scaffolds, respectively.

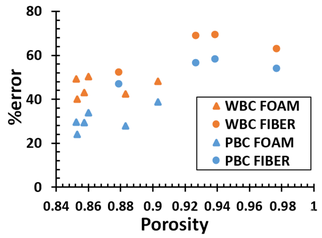


Surface *error* maps overlays for the two RVE types, relative to the whole scaffold simulation RVE equivalents. Top right quarter of each scaffold is removed in order to provide an internal view. Dimensions are 1.61mm x 3.91mm x 2.81mm and 1.10mm x 3.79mm x 2.99mm for salt-leached and nonwoven fiber-mesh scaffolds, respectively.

Results…



Total number of LBM steps required to reach convergence versus scaffold volume for RVE-PBC and RVE-WBC. The vertical and horizontal axes are normalized with respect to the whole scaffold values.



Average error in fluid-induced surface stress resulting from the RVE calculations plotted versus scaffold porosity and RVE boundary condition type. Orange color – WBC. Blue Color – PBC. Triangles – Salt Leached Foam. Circles – Nonwoven Fiber Mesh

Conclusions

- This work provides a previously-unavailable guidance to researchers, regarding the best choice of boundary conditions commonly used to estimate stimulatory stresses in tissue engineering scaffolds: Periodic (PBC) and Wall (WBC)
- The previously-uncharacterized PBC is, for the first time, shown to be superior to the WBC, due to being both more accurate and less computationally expensive.
- The stress estimation accuracy is also shown to depend on the scaffold porosity for both boundary condition types, which was previously unknown.

Future Work

- Perform study on scaffolds containing cells and neo-tissues.
- Study the effects of RVE cutouts and their boundary conditions on nutrient mass transport within the scaffolds.