CFD Projects
-Artificial Blood Vessels

Part 2-1,

Vascular Bypass Surgery

Vascular Bypass Surgery

Introduction

- Atherosclerosis is a leading cause of death around the world, a disease caused by the deposition of plaques in inner walls of arteries.
- In severe cases of atherosclerosis, invasive procedures such as vascul ar bypass surgery is required.
- To achieve higher patency in the procedure, it is important to control the wall shear stress produced by blood flow to be above a certain l evel, as it was previously discovered that low wall shear stress is signi ficantly correlated with atherosclerosis.
- Aim : to understand the correlation between anastomosis angle and wall shear stress distributions in a totally occluded vessel.

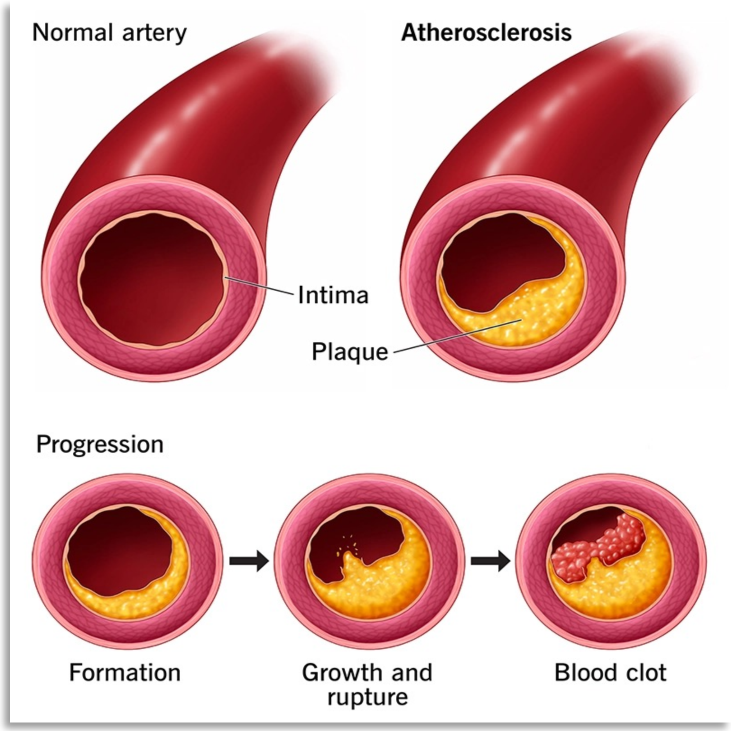


Figure 1. Development of Atherosclerosis
Image source : Cleveland Clinic

Vascular Bypass Surgery

Numerical Model

- Produced six simplified models of bypassed blood vessel to view the velocity distribution and the following wall shear stress according to anastomosis angle.
- The diameter of host vessel (D_h) was set to 4mm and the bypass graft thickness (D_g) was set to $0.9D_h$. (figure 1)
- The proximal host vessel length (l_p), distal host vessel length (l_d) and bypass length were all set to $10D_h$.
- The anastomosis angles (α) were set to 15°, 30°, 45°, 60°, 75°, and 90° respectively, for models A, B, C, D, E and F (figure 2).

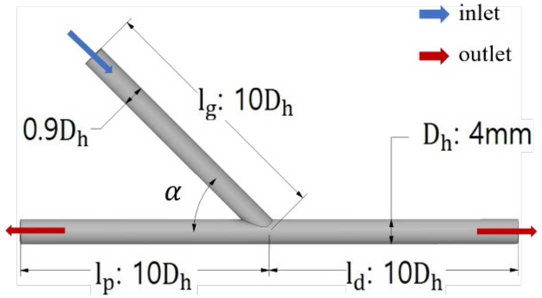


Figure 1. Common dimensions of simplified models.
Anastomosis angle (α) were used as only variable.

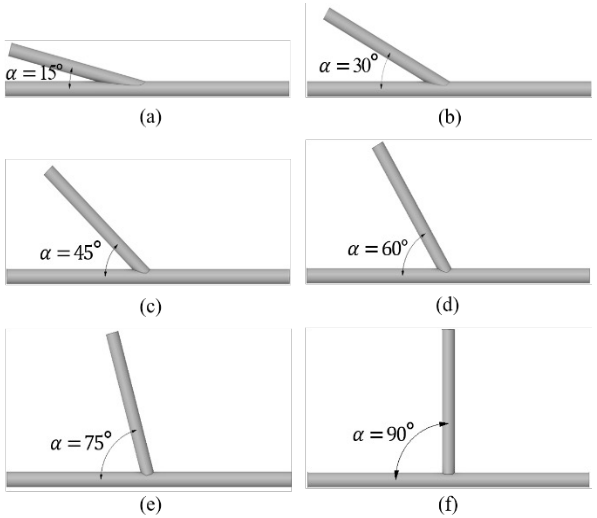


Figure 2. Anastomosis angles in model A~F
a) model A (α = 15°). b) model B (α = 30°). c) model C (α = 45°).
d) model D (α = 60°). e) model E (α = 75°). f) model F (α = 90°).

Vascular Bypass Surgery

Numerical Method

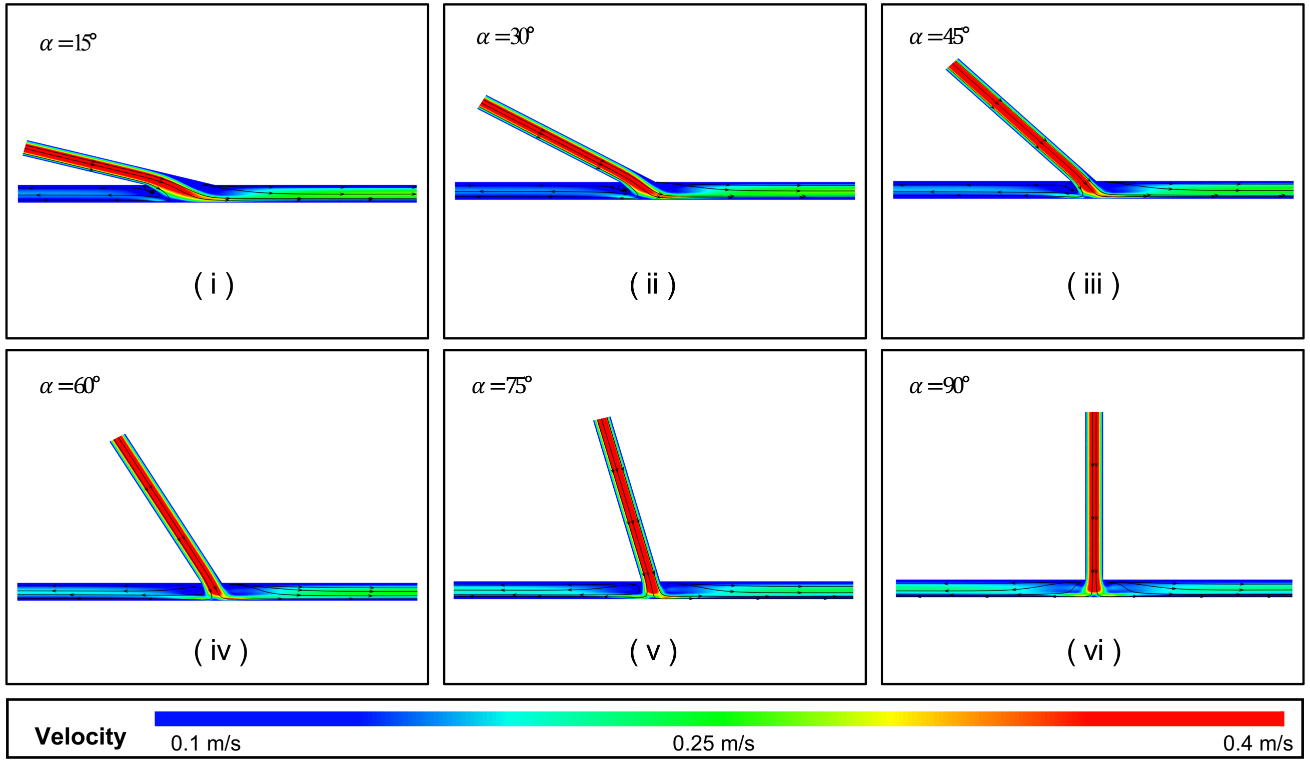
- Assumptions:
  - Blood flow was assumed to be laminar.
  - The effects of cardiac movements (i.e. contraction and relaxation) were neglected, the flow was assumed to be steady.
  - Blood was assumed to be incompressible Newtonian fluid.

- Numerical simulation:
  - Finite volume method was used to solve the governing equations: continuity equations and Navier-Stokes equations.
  - Inlet boundary conditions as fully-developed laminar flow with Reynolds number (Re) of 250.
  - Neumann outlet conditions, and pressure to be zero at both outlets.

Part 2-1

Vascular Bypass Surgery

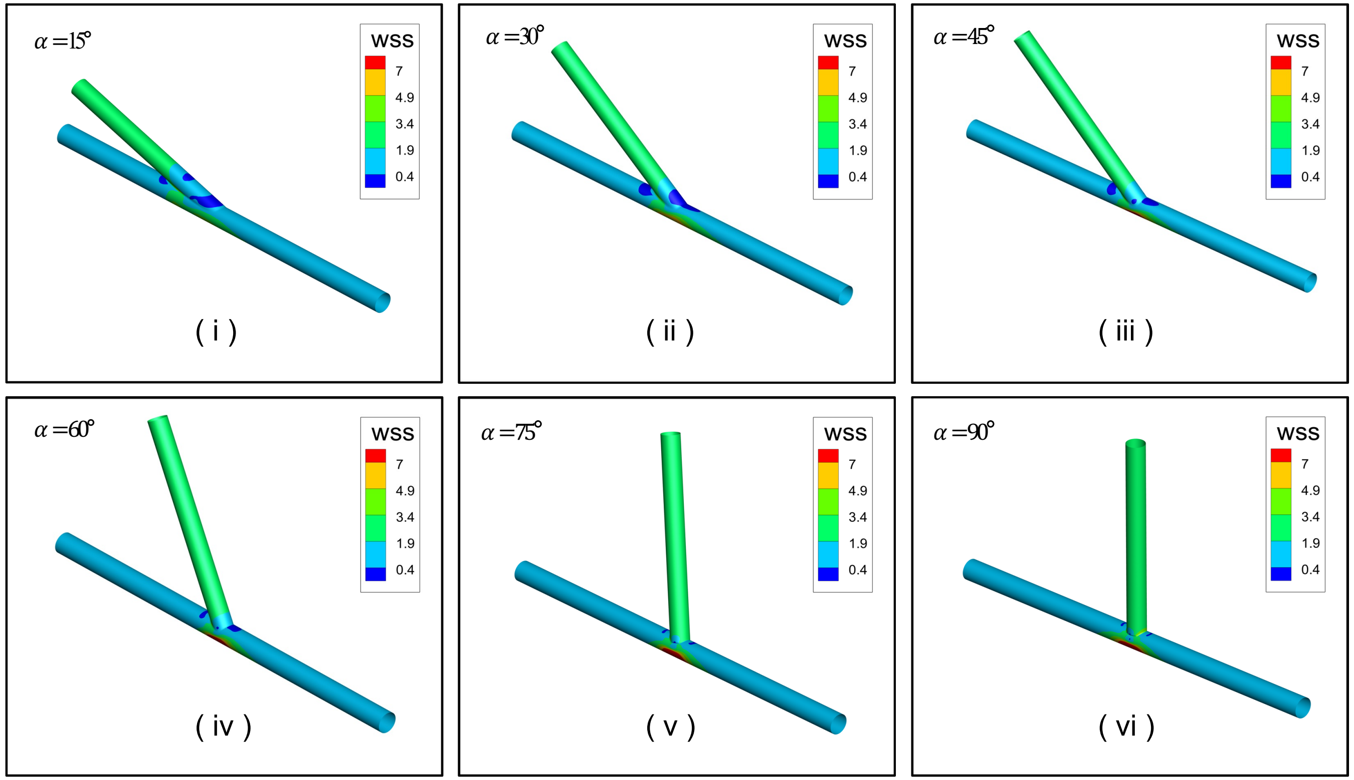
Result - Velocity Contour & Streamlines



- Flow with low velocity was observed in graft anastomosis in model i and ii (15° and 30°)
- Velocity in proximal area was faster in models with anastomosis angle above 45°.
- Anastomosis angle had no effect on high velocity flow (above 0.3m/s).
- Recirculating flow was formed in proximal anastomosis area in models with anastomosis angle below 45°.

Vascular Bypass Surgery

Result – Wall Shear Stress Contour

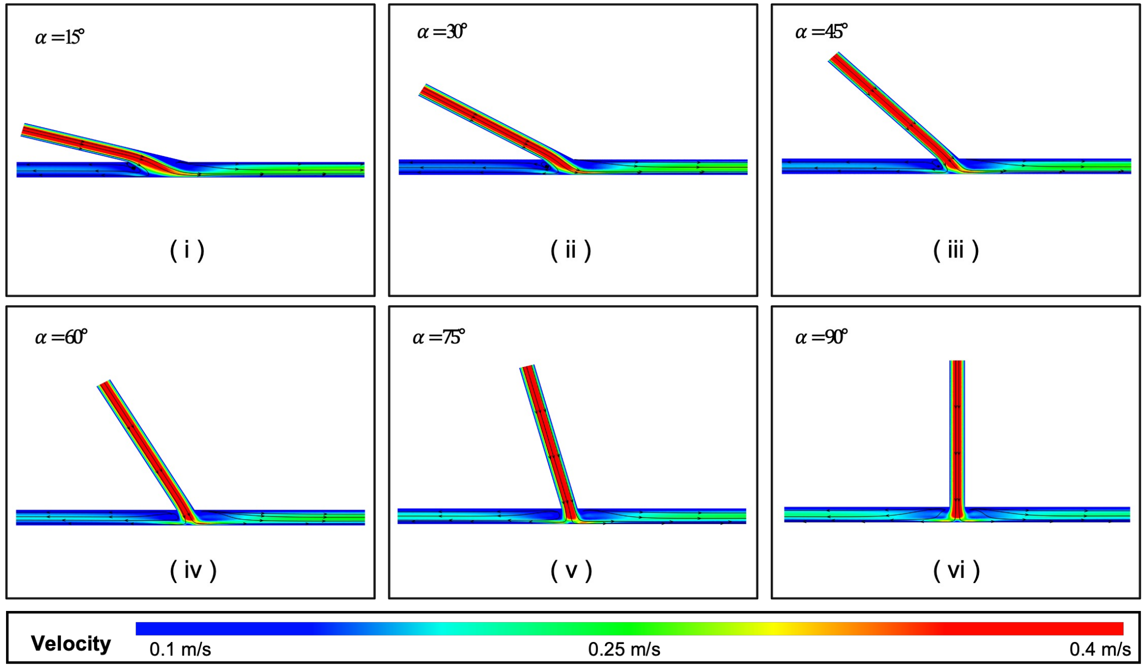


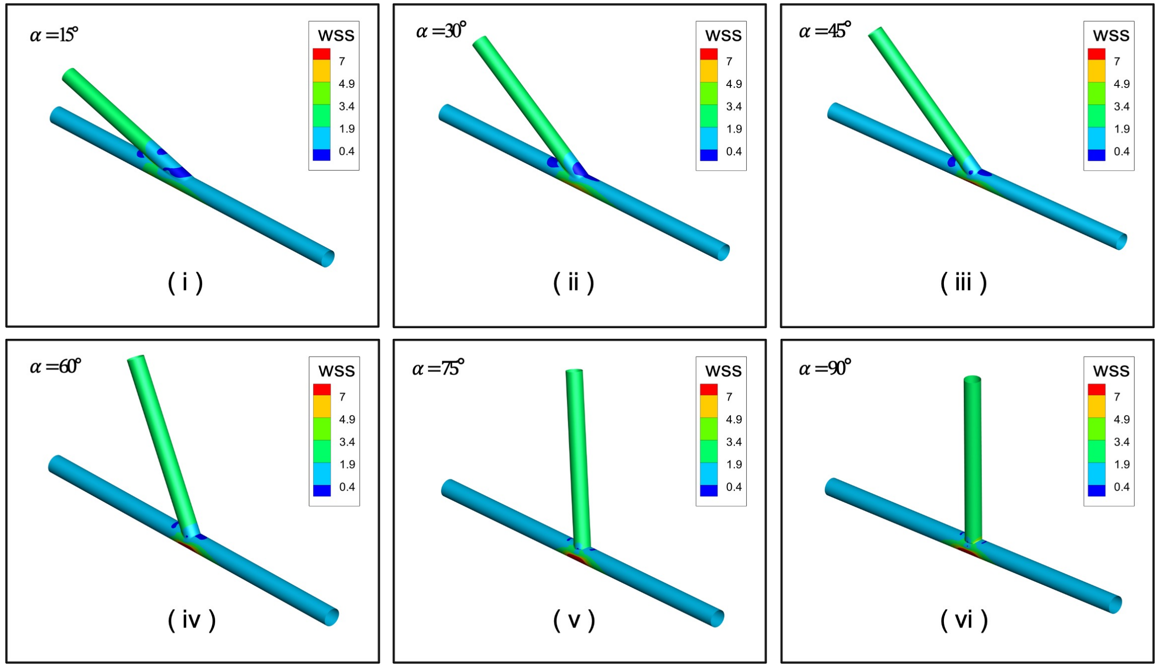
Result

- Low wall shear stress was concentrated near anastomosis in all models.
- The size of low wall shear stress region decreased as anastomosis angle increased.

Vascular Bypass Surgery

Conclusion





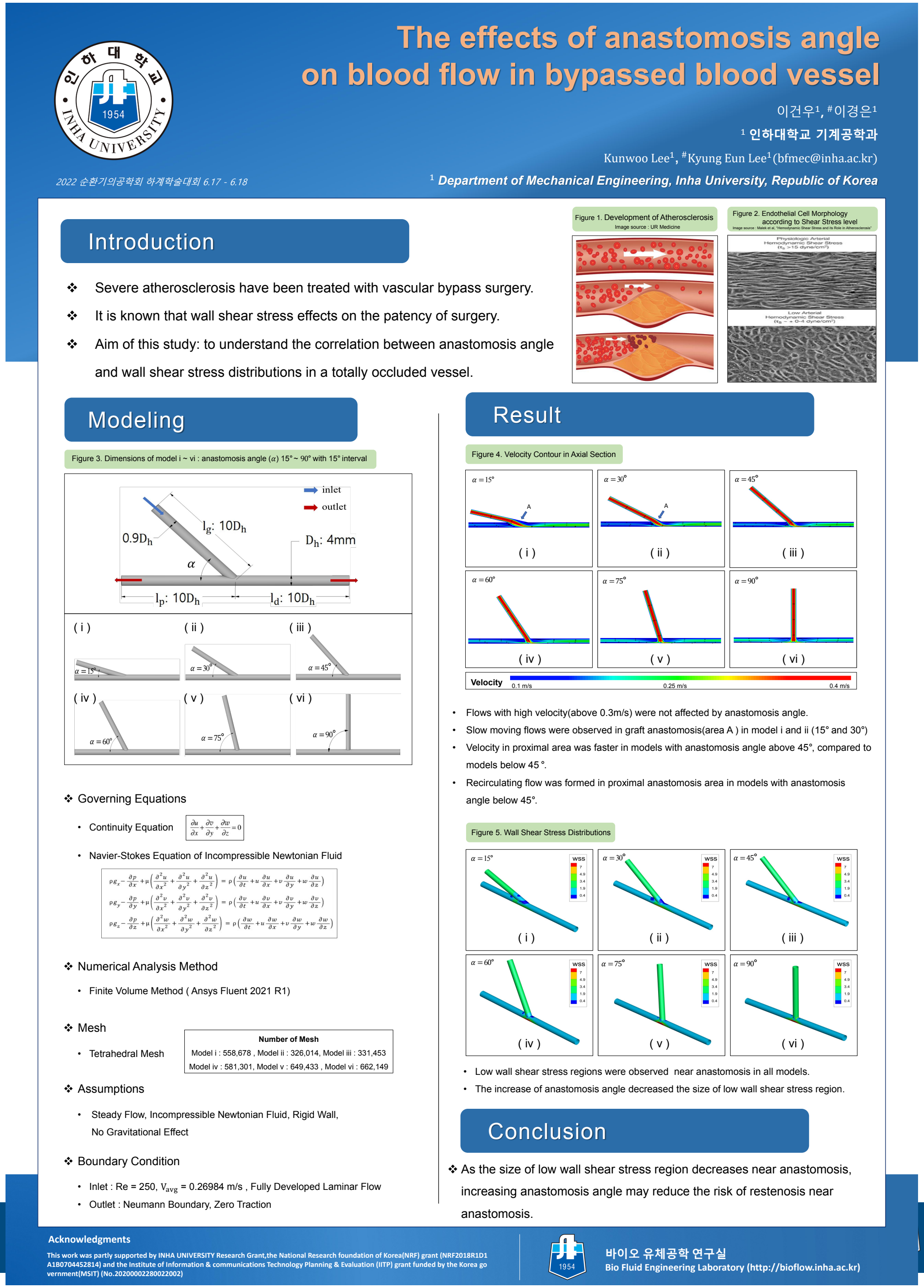
- As the size of low wall shear stress region decreases near anastomosis, increasing anastomosis angle may reduce the risk of restenosis near anastomosis.

Part 2-1

Vascular Bypass Surgery

*Poster for the project

Made poster of the project for the summer conference 2022 of Biomedical Engineering Society for Circulation



Part 2-2,

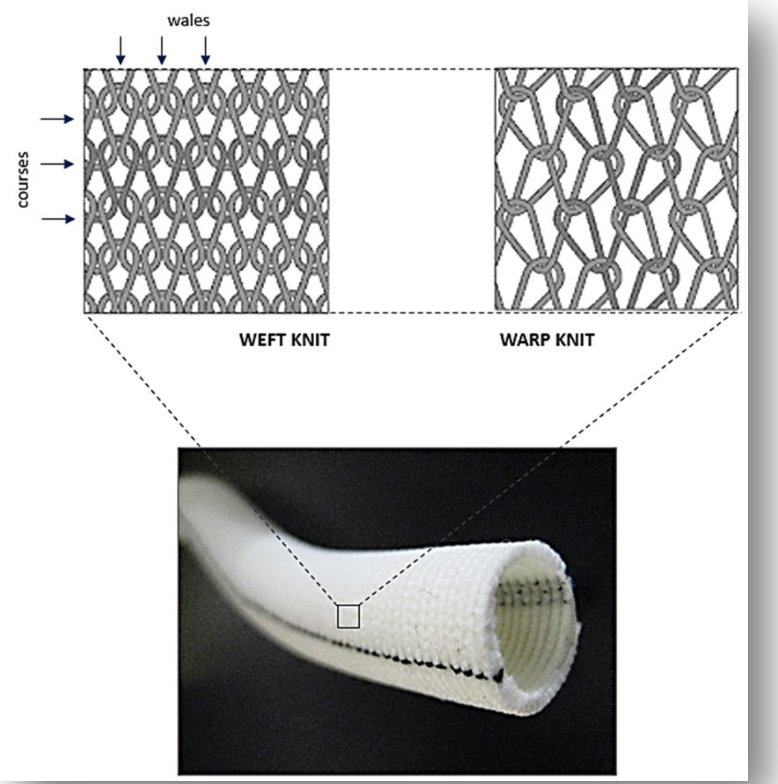
Artificial Blood Vessel w/ Pattern

Synthetic Non-Degradable Polymers

- Dacron, Teflon(ePTFE) or Polyurethane is used for synthetic non-degradable polymer artificial vessel.

- Healthy autologous vessel has limit in its supply, raising the need for polymer artificial vessel.

- Synthetic Non-degradable Polymers is widely used as it has advantage in the ease at changing mechanical properties.



↑ Example of Dacron artificial vessel.

Challenges of Non-Degradable Polymers

- Poor Patency Rates

  ex) Only 45% of standard ePTFE grafts are patent at 5 years as femoropopliteal bypass grafts

  ↔ 60-80% in autologous vein grafts. [1]

- Compliance Mismatch

  The compliance of polymer may be dozens of times bigger than soft tissues in our body, so leaving the compliance mismatch may cause problems in healing process or cause intimal hyperplasia. [2]

- Enhancing biocompatibility of synthetic material

  Low biocompatibility cause inflammatory responses. We can enhance biocompatibility via surface modification, coatings, chemical and protein modifications, endothelial cell seeding …

Advantages of Porous Synthetic Blood Vessel

1. Positive effect on biocompatibility
   - Endothelial cell has a shape with certain direction. Thus, having similar pattern in inner wall can have positive effect on endothelialization, increasing patency rate. [3]
   - Putting substances such as nitric oxide(NO), dopamine, heparin may help control inflammatory responses, inhibiting the formation of thrombus. [4]

2. Help solve compliance mismatch
   - Having porosity can help match human body's compliance.

Hemodynamic Factors and Patency

- Having porosity may have previously discussed pros, but flow disturbance due to porosity may cause side effects in hemodynamic aspects.

- Low wall shear stress may cause restenosis by intimal thickening

  In our body, blood vessels react to low shear stress by contraction, causing the blood velocity to temporally rise. Synthetic blood vessels can't react the same way, causing the endothelial cell in the area produce certain vasoactive substance, which leads to intimal thickening. [5]

- Recirculation may be formed.

Introduction

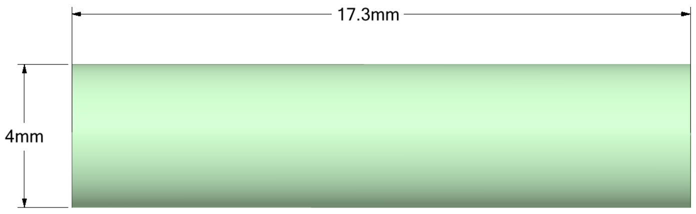
Aim of the Study

Model porous artificial blood vessel with a simplified model with pattern on the inner wall and investigate the effect of porosity on patency rate in the aspect of hemodynamics.

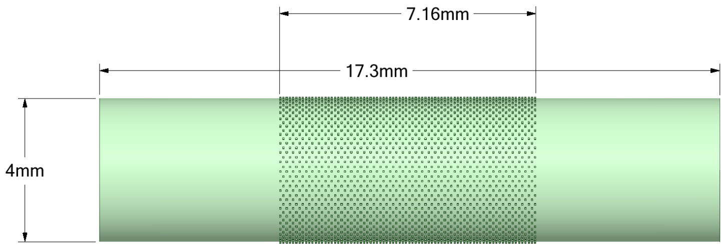
Modeling

Models

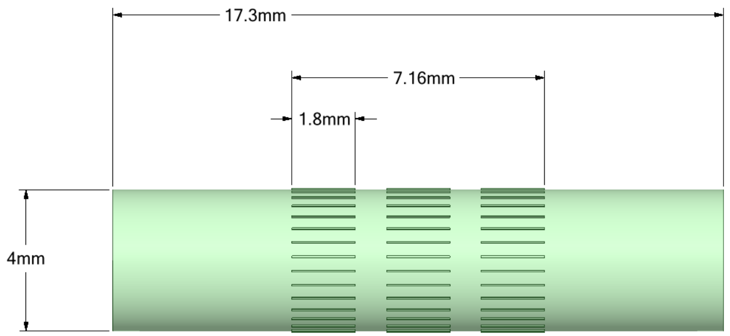
- Produced 3 models. Model I (No pattern), Model II (Cubic shaped pattern), ModelI III (Cuboid shaped pattern)
- The cube pattern of Model II has a side of 45 μm, and 47 pieces in the circumferential direction and 80 pieces in the axial direction are attached to the surface of a cylinder with a diameter of 4mm and a length of 7.16mm. For stability of analysis, cylinders were added to both ends forming a model with a total length of 17.3 mm.
- The cuboid pattern of Model III has the shape of the cube of Model II stretched 40 times in the axial direction. 31 cuboids are in the circumferential direction and 3 cuboids are in the axial direction, attached to the surface of a 7.16mm long cylinder. As in Model II, cylinders were added at both ends for stability.



↑ Model I



↑ Model II



↑ Model III

Modeling

Method

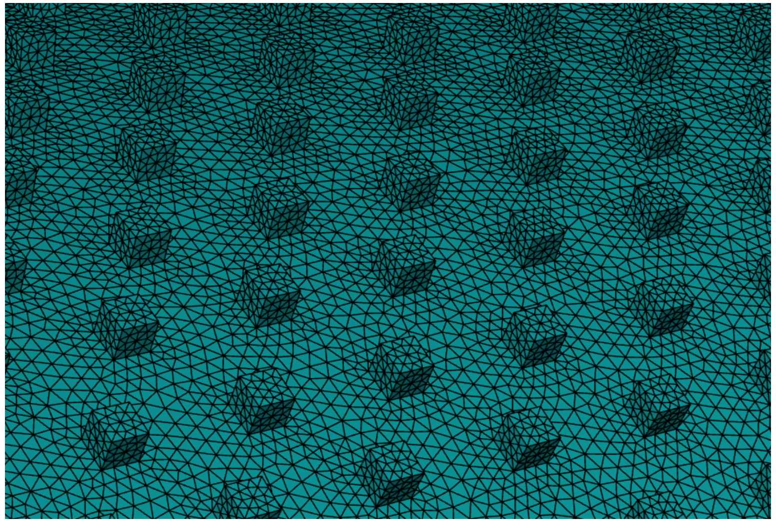
- Governing Equation : Continuity Eq. & Navier-Stokes Eq.
- Finite Volume Method (Fluent v.2021 R1)
- Tetrahedral Mesh

  Number of Mesh - Model I : 1,025,564 / Model II : 11,311,373 / Model III : 6,071,591
- Assumptions

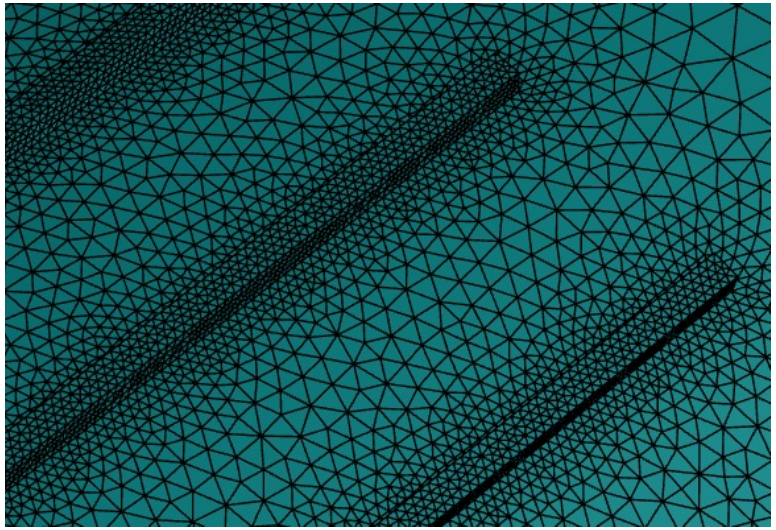
  Steady Flow, Incompressible Newtonian Fluid, Rigid Wall, No Gravitational Effect
- Boundary Condition

  Inlet : $\mathrm{Re} = 250$, $V_{avg} = 0.242857\ m/s$, Fully Developed Laminar Flow

  Outlet : Neumann Boundary



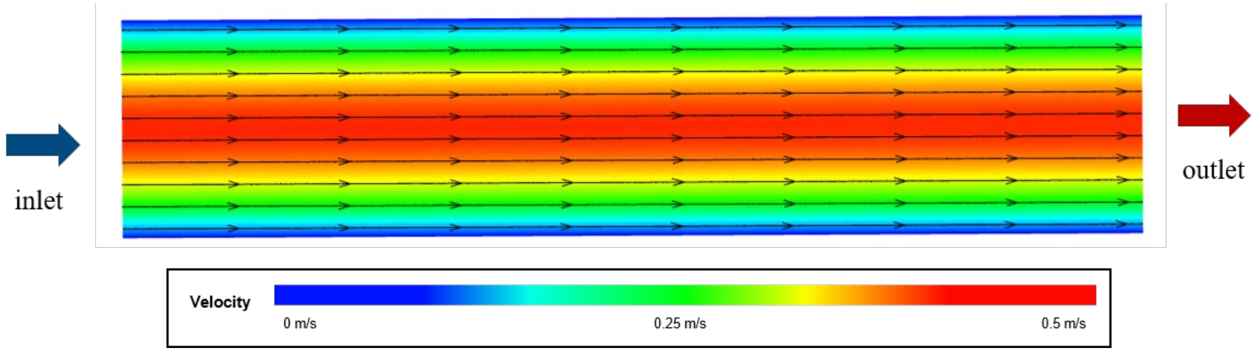
↑ Model II



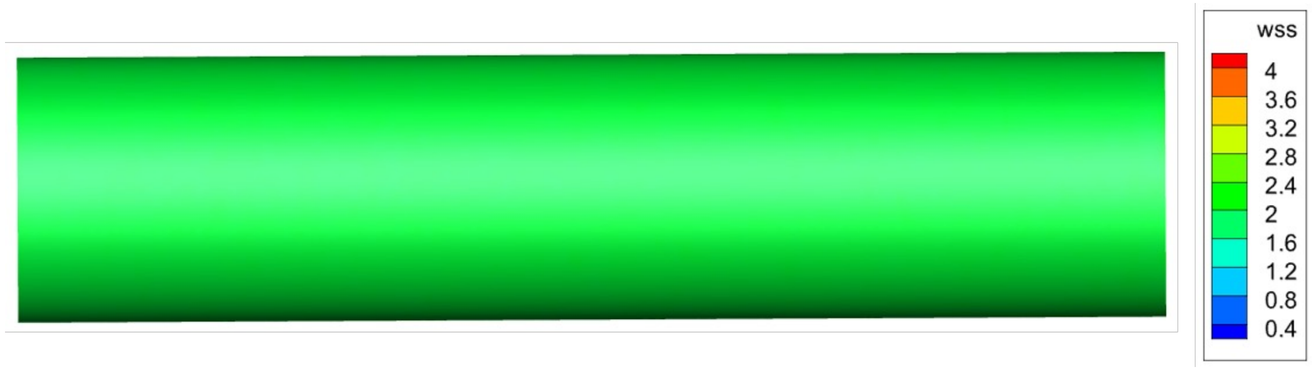
↑ Model III

Results – Model I

Streamline & Velocity



WSS Contour



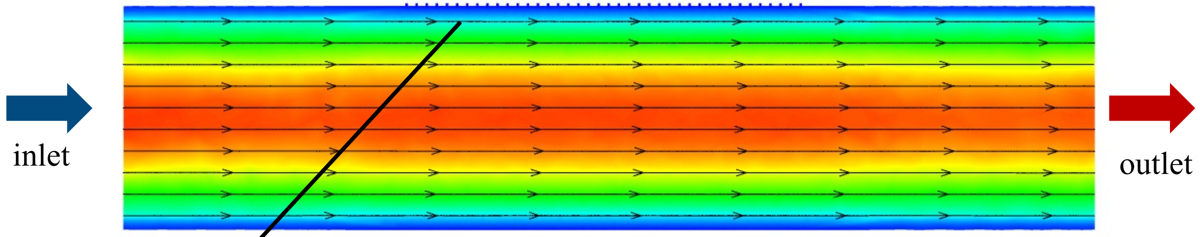
- The fully developed flow starting at the inlet is maintained, with linear streamline.

- The wall shear stress doesn't change either, staying at approximately at 2Pa.

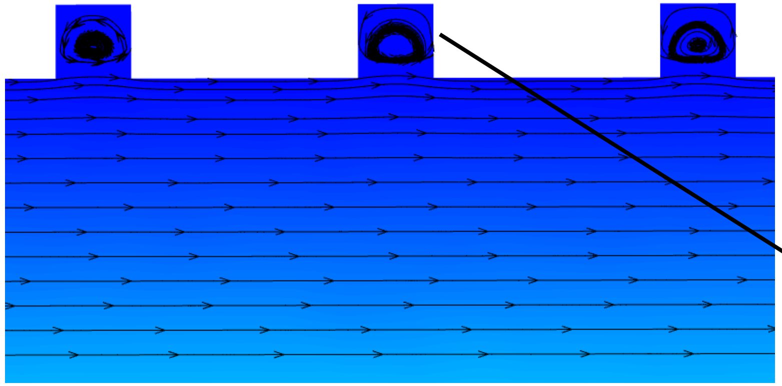
Part 2-2

Results – Model II

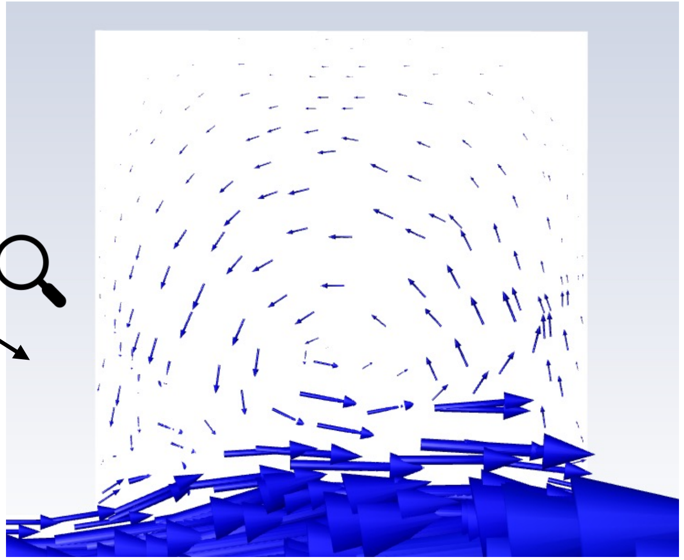
Streamline & Velocity



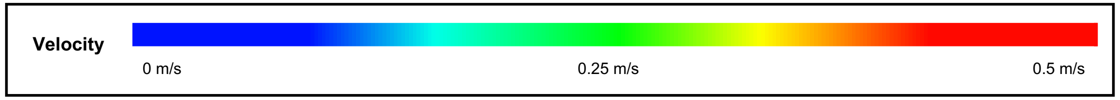
↑ figure 1 : Velocity & Streamline



↑ figure 2 : Velocity & Streamline near pattern



↑ figure 3 : velocity vector inside pattern

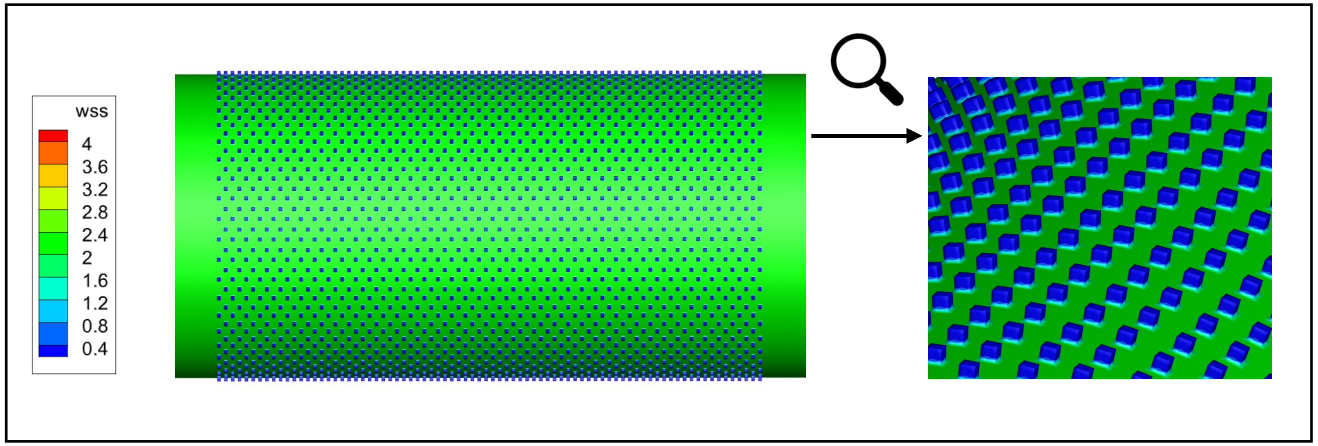


- In the aspect of mainstream, streamline and velocity was not affected. (figure 1)
- Streamline waves upwards near the pattern, and recirculation occurred inside the pattern. (figure 2)
- Looking at the velocity vector inside the pattern, we could confirm the recirculation. (figure 3)

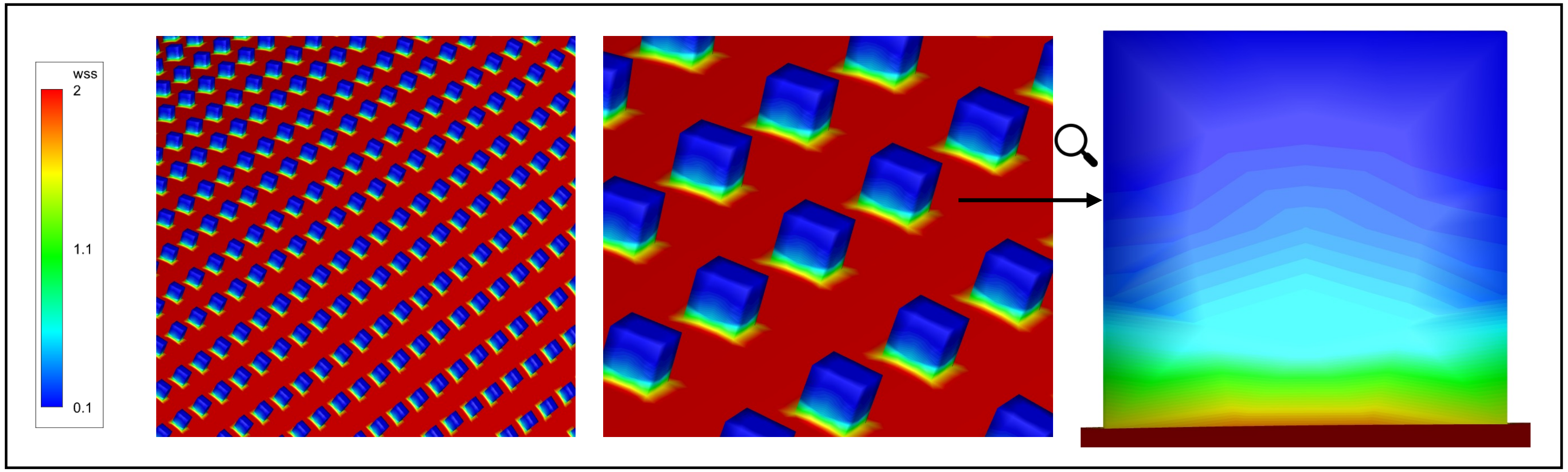
Part 2-2

Results – Model II

WSS Contour



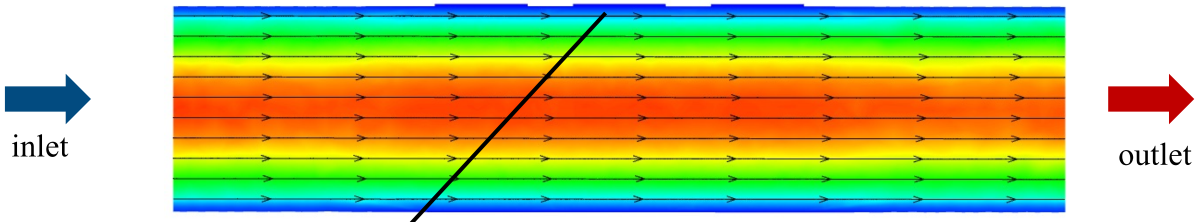
↑ figure 1 : WSS Contour (0.4 ~ 4Pa) / ↓ figure 2 : WSS Contour (0.1 ~ 2Pa)



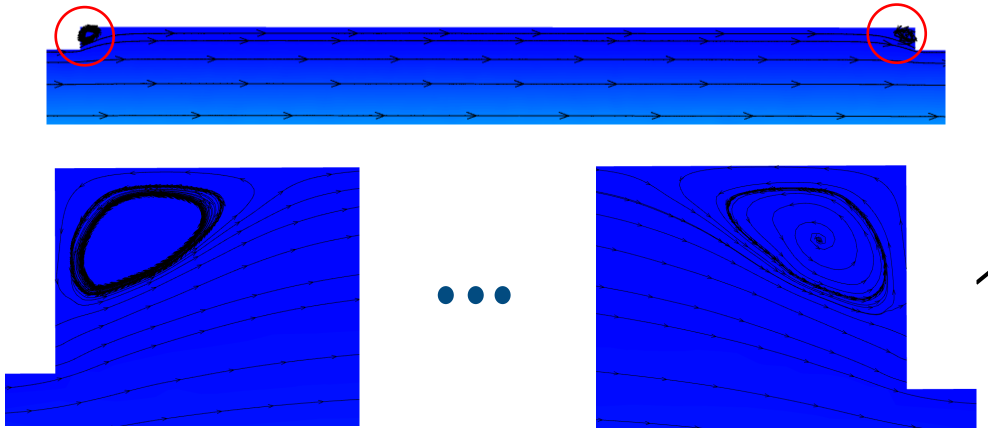
- Low wall shear stress was formed in the patterns. (figure 1)
- As it is the low wall shear stress we want to discuss, we changed the contour range to 0.1 ~ 2Pa and checked again.
- Increasing low wss was obsersved as it gets deeper inside the pattern. (figure 2)

Results – Model III

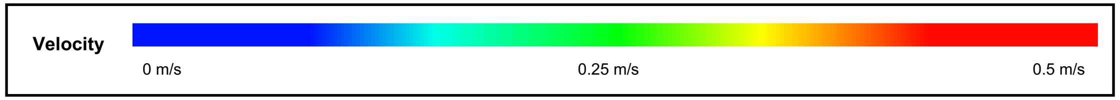
Streamline & Velocity



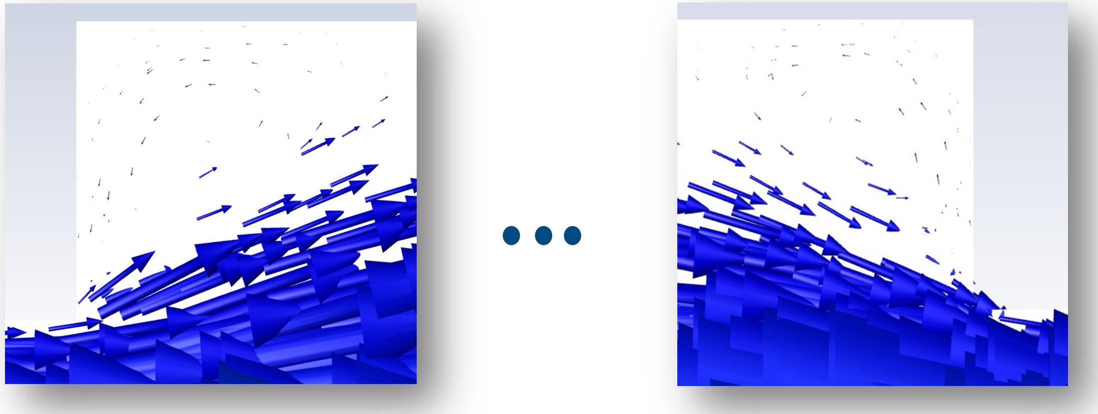
↑ figure 1 : Velocity & Streamline



↑ figure 2 : Velocity & Streamline near pattern and inside pattern



↓ figure 3 : velocity vector in the ends of the pattern

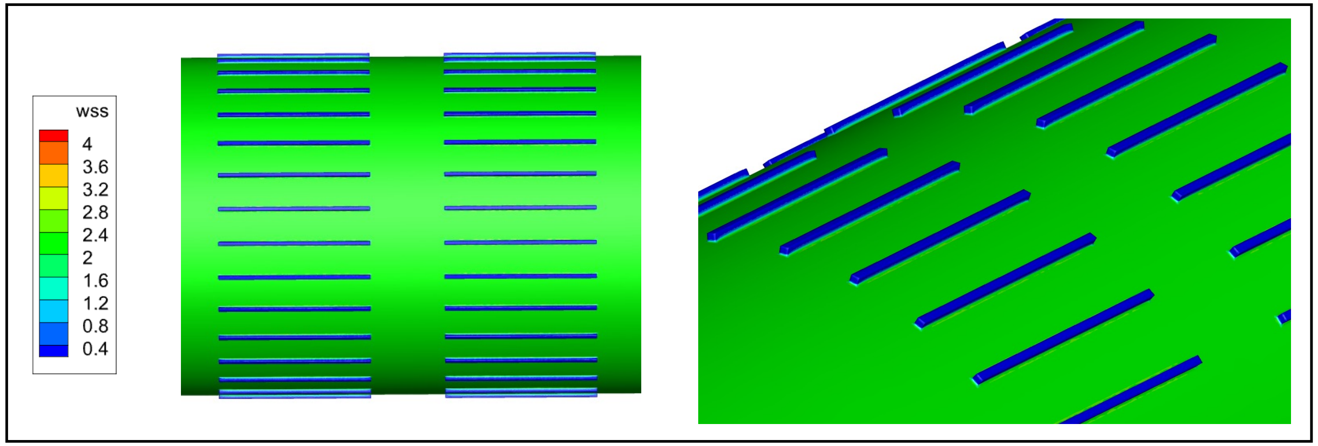


- In the aspect of mainstream, streamline and velocity was not affected. (figure 1)
- The streamline from mainstream goes through the middle part of the pattern, and recirculation is formed in the both ends of the pattern. (figure 2)
- Looking at the velocity vector inside the pattern, we could confirm the recirculation in both ends. (figure 3)

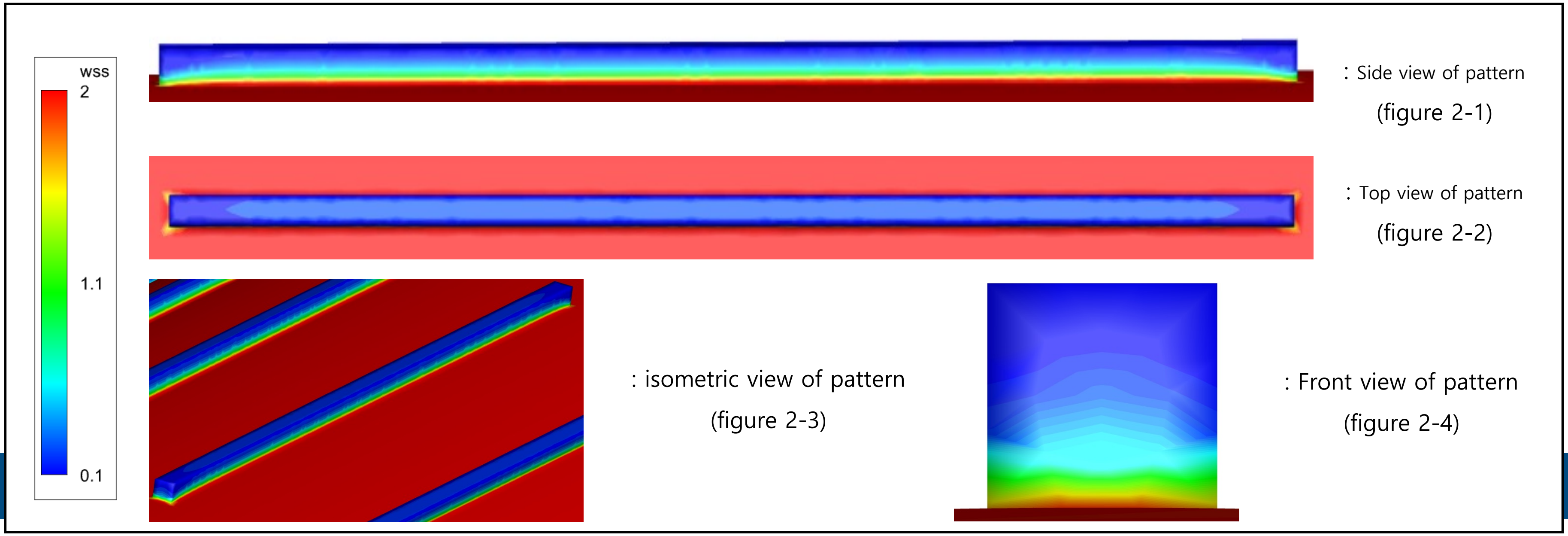
Part 2-2

Results – Model III

WSS Contour



↑ figure 1 : WSS Contour (0.4 ~ 4Pa) / ↓figure 2 : WSS Contour (0.1 ~ 2Pa)



- Low wall shear stress in formed in the patterns. (figure 1)
- Looking at the side view, the ends of pattern has thicker low wss region than midst of pattern. (figure 2-1)
- Looking at the top view, the wss of both ends has lower value than that of middle. (figure 2-2)
- Looking at the front view, there is lower wss in the deeper region of pattern. (figure 2-4)

Conclusion

Conclusion :

- Artificial blood vessels made from synthetic non-degradable polymers may have higher possibility of restenosis due to the recirculation and formation of low wall shear stress region caused by flow disturbance from pattern.

Reference

1) Johnson WC, Lee KK. A comparative evaluation of polytetrafluoroethylene, umbilical vein, and saphenous vein bypass grafts for femoral-popliteal above-knee revascularization: a prospective randomized Department of Veterans Affairs cooperative study. J Vasc Surg 2000;32(2):268–277. [PubMed: 10917986]

2) Trubel W, Schima H, Moritz A et al, Compliance mismatch and formation of distal anastomotic intimal hyperplasia in extremely stiffened and lumen-adapted venous grafts. Eur J Vasc Endovasc Surg 1995; 10:415-423.

3) J. Lu, M.P. Rao, N.C. MacDonald, D. Khang, T.J. Webster, Improved endothelial cell adhesion and proliferation on patterned titanium surfaces with rationally designed, micrometer to nanometer features, Acta Biomater. 4 (2008) 192– 201.

4) Reynolds MM, Hrabie JA, Oh BK, et al. Nitric oxide releasing polyurethanes with covalently linked diazeniumdiolated secondary amines. Biomacromolecules 2006;7(3):987–994. [PubMed: 16529441]

5) Kohler TR, Kirkman TR, Kraiss LW, Zierler BK, Clowes AW, Increased blood flow inhibits neointimal hyperplasia in endothelialized vascular grafts. Circ Res 1991; 69: 1557-1565.

Thanks to BFE lab

Link: BFE Lab Website

Thank You

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