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Prediction of Fluid Flow in Artificial Cancellous Bone

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Abstract – *The permeability of blood in artificial cancellous bone is affected by certain morphological aspects including pore diameter, pore size, porosity and bone surface area. In this study, computational fluid dynamics method has been used to study the fluid flow through cancellous structure. The result of the present work shows that geometries with the same porosity and overall volume can have different permeability due to the differences in bone surface area. The hexahedron geometry has the highest permeability under stimulated blood flow conditions, whereas the cylindrical geometry has the lowest. Linear relationship has been found between permeability and the two physical properties, bone surface area and pore size.*

Keywords: Cancellous bone, Permeability, Porosity, ANSYS Fluent

1.0 INTRODUCTION

In recent years, there is a major health concern because of huge bone loss by musculoskeletal condition and osteoporosis due to the aging population [1-3]. In orthopaedic practice, autografts and allografts have been used in bone repair. However, these practices come with certain problems. For example, allografts carry several disadvantages which include risk infections, low quantity and low osteogenicity, whereas autografts have limitation due to insufficient supply, additional surgical procedure, and postsurgical pain associated with the donor site.

As an alternative to autografts and allografts, bone tissue engineering has developed the artificial cancellous bone. The whole idea in the development of artificial cancellous bone is to create a synthetic or partially synthetic scaffold for artificial cancellous bone that is able to support the implementation of progenitor bone cells or other biological components with the purpose of stimulating new bone growth [4].

Artificial cancellous bone must have the properties and characteristics similar to natural cancellous bone to ensure the bone can provide mechanical support and at the same time promote tissue regeneration.

The fluid passes through cancellous bone are an important characteristic for the successful development of the bone substitute as it determines the capability of the idealised structure to pass nutrients through the bone. Higher value of permeability would allow good supply of nutrients at the expense of the strength of the overall structure due to high porosity value. It is

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crucial to achieve the optimum performance of artificial cancellous bone by the right balance between permeability and mechanical strength [5].

In bone regeneration, permeability is an important parameter because it is believed that higher values of permeability will improve bone ingrowth [6], whereas inadequate values of permeability may induce the formation of cartilaginous tissue instead of bone [7-8].

In the design of scaffold, porosity determines the mechanical stimulus and consequently bone formation. Increasing value of porosity causes higher macroscopic mechanical stimulus, which induced higher rate of bone formation [9].

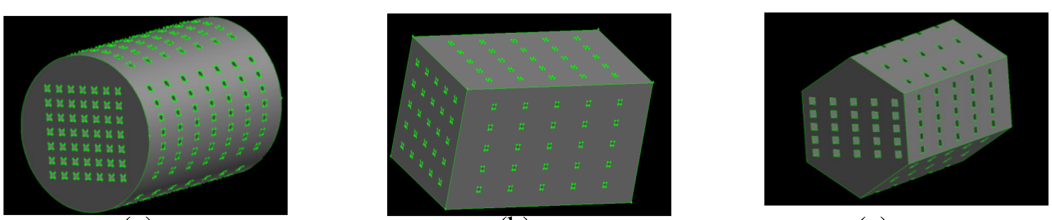
In terms of bone regeneration, bigger pore size favors direct osteogenesis, since they allow vascularization and high oxygenation, while smaller pores result in osteochondral ossification [10]. Smaller pore size with the same value of porosity slows down the cell migration process and the permeability, which consequently lowers the rate of the bone regeneration process, whereas larger pore size of the same porosity induces a lower specific surface, which has a negative effect on new tissue formation [9]. As a result, bone regeneration increased slightly.

2.0 GEOMETRY MODELING

A three-dimensional model was constructed by using Gambit as shown in Figure 1. The basic dimensional measurement for all the models used were 10 mm in diameter and a height of 15 mm. This was the common dimension used in the experimental study. Porosity (ε) can be calculated by the following formula [2, 5, 11]:

$$\varepsilon = \frac{V_0 - V}{V_0} \tag{1}$$

where V_0 is the total volume of a single cell.



(a) (b) (c)

Figure 1: Three models for artificial cancellous bone: (a) Cylindrical, (b) hexahedron, and (c) hexagon

The basic arrangement of the cancellous bone in the simulation was based on the experimental setup that studies the fluid flow in the cancellous bone. The cancellous bone geometry was placed in the centre of a slightly larger cylinder and a fluid represent blood was allowed to pass through the cylinder. For each simulation, the velocity and pressure values along the centerline of the cylinder were taken. The permeability of the cancellous bone was calculated using Darcy's law.

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The calculation of permeability can be obtained by using Darcy's law. Darcy's law describes the flow of fluid through the porous medium and in three-dimensional cases, it can be written as [5]:

$$\upsilon_D = \frac{Q}{A_s} = \left(\frac{kA}{\mu}\right)\frac{P_u - P_d}{L_s} \tag{2}$$

where Q is the volumetric flow rate (m^3/s), A_s is the cross-sectional area of the specimen (m^2), P_u is the upstream pressure (Pa), P_d is the downstream pressure (Pa), L_s is the length of the specimen (m), μ is the fluid viscosity and k is the intrinsic permeability of the specimen (m^2).

Using Darcy's law to calculate the permeability offers some important advantages than using Stokes approach. Darcy's law is easier to solve than the Stokes' flow equation and easy to implement if the objective optimized the unit cell topology in order to obtain the maximum performance [3]. The solution obtained using the homogenization of Darcy's law is similar with the solution from the homogenization of Stokes flow, if it is affected by a parameter that depends on pore size [12]. Therefore, the use of Darcy's law to calculate permeability for this research is a reliable approach.

2.1 Flow structure simulation

All the models were meshed in Gambit. Tet/hybrid was used due to the complexity of the design, and the hybrid meshing gave the greatest flexibility. Element of Tgrid was used which consisted of entirely triangular elements.

The meshed geometry was then exported to FLUENT. For the simulation, pressure-based approach was used as this method was derived from the continuity and the momentum equations in such a way that the velocity field, corrected by the pressure, satisfied the continuity equation. Boundary conditions for the present simulation is shown in Figure 2.

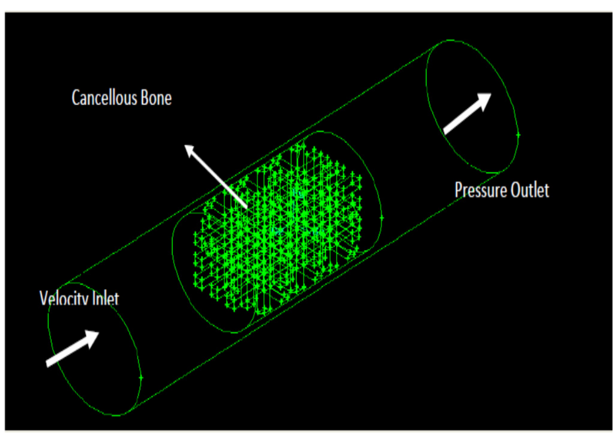


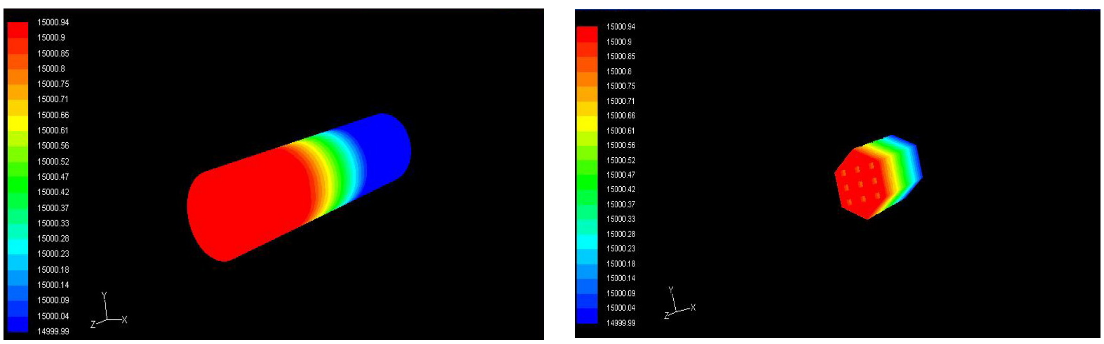
Figure 2: Boundary condition for the simulation

For permeability analysis, the geometries were assigned with isotropic properties. The operating pressure was set to 15 kPa, with the temperature of normal human at 37 °C, and dynamic viscosity of 0.005 Pa.s. The simulation was performed under static pressure with constant volumetric flow rate of 100 mL/h.

3.0 RESULTS AND DISCUSSION

For the case involving bone surface area, cylindrical models were used where the models were constructed into sub-models with different surface areas and the porosity and the overall volume were fixed, whereas for the case of cancellous bone geometry, three different geometries were used to construct the artificial cancellous bones namely hexahedron, cylindrical and hexagon.

Figure 3(a) and Figure 3(b) show the contour plot of pressure distribution outside and inside the bone with hexagon-shaped cancellous bone. The magnitudes of the pressure distribution along the centerline of the cancellous bone were extracted to calculate permeability.



(a) (b)

Figure 3: Pressure distributions in the bone: (a) Pressure distribution through the bone; (b) pressure distribution inside the cancellous bone

The bone showed a slight increase in pressure as the simulated blood entered the specimen and decreased as the blood flow through the bone. The permeability for all the models ranged from 6.3 x 10-9m2 to 4.48 x 10-9m2 for the cylindrical models, 7.31 x 10-8m2 to 7.08 x 10-8m2 for hexahedron models and 2.29 x 10-8m2 to 2.02 x 10-8m2 for hexagon models.

The pressure decreased as the simulated blood entered into the artificial cancellous bone because the velocity dropped as it flowed through the pores. This phenomenon happened when there would be drag experience on the velocity field which caused the velocity to decrease. Based on the continuity equation, velocity would be constant when the area did not change. Therefore, with the decrease in velocity, pressure energy was converted into kinetic energy to maintain the velocity.

3.1 Bone Surface Area

Figure 4 and Figure 5 illustrate the effect of bone surface area and bone geometry on the blood permeability respectively. The permeability of cancellous bone decreased as the bone surface area increased, and the complexity of cancellous bone increased. The significance level of the correlation of the line plot was 0.766 for the bone surface area and 0.758 for the bone geometry.

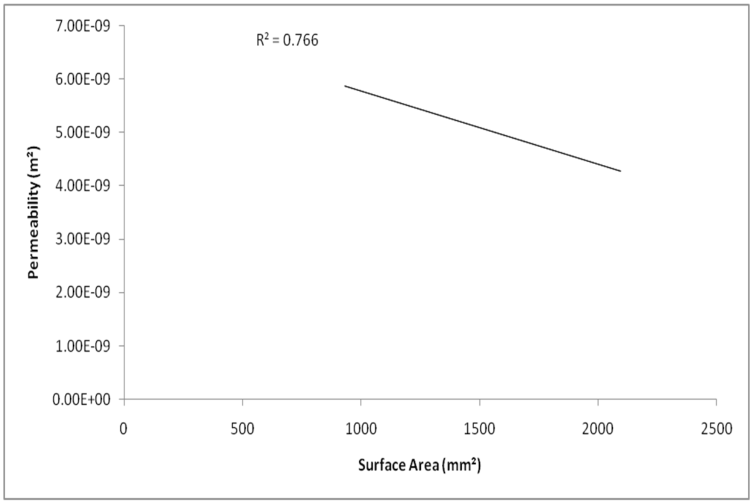


Figure 4: Line plot of permeability vs. bone surface area of idealized bone models

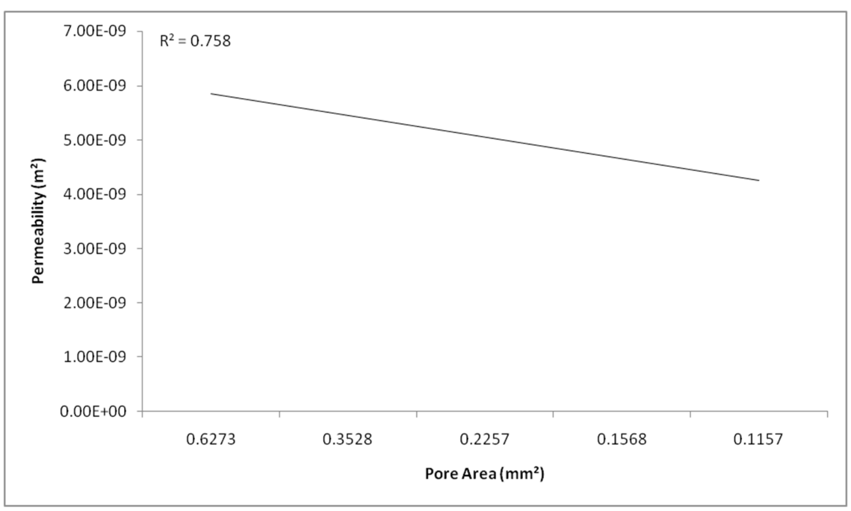


Figure 5: Line plot of permeability vs. pore area of idealized bone models

Based on the simulation, the structure with higher surface area had lower permeability than the one with the lower surface area. The reason to this phenomenon could be explained using Darcy's law where it was used to calculate the value of permeability. Since this law explained the permeability based on two physical factors namely viscosity and pressure drop, the graph of the line plot was affected by these two factors. However, as blood was the only working fluid for the models, the calculation of permeability was affected by the pressure drop.

Apart from that, at fixed porosity, the model with higher surface area had higher number of pores that contribute to complexity of geometry. Xu *et al.* [2] explained that fluid flow would experience drag due to the structural cross-sectional and roughness of the surface. This complexity of geometry would cause drag experience on the fluid flow, which contributed to pressure drop. Hence, with the decrease in velocity, pressure energy was converted into kinetic energy to maintain the velocity.

From the simulation, it was found that velocity and pressure drop were similar to the well-known velocity and pressure drop found in diffusers and nozzles. The velocity decreased as fluid entered the expanded passage and increased as it entered the restricted passage. This could be further explained by using the continuity equation where the velocity increase as the pore diameter decreased in order to maintain the constant flow rate. The increase in velocity would contribute to the increase of pressure drop. This could be explained as in the velocity, there were collisions between molecules as the fluid flowed. These collisions caused losses in the kinetic energy. With the increase in velocity, the collision between the molecules became greater, which contributed to more kinetic energy lost. Therefore, more pressure energy was converted into kinetic energy to compensate the losses and maintain the constant flow rate. The model with the highest pressure drop had the lowest permeability.

This finding is important because a structure with different geometry can still have the same porosity with a different total surface area. This research has purely analyzed fluid flow and assumed that there is no interaction with the bone structure. This is one of the limitations because under the real conditions, the bone will undergo deformation during the fluid flow.

Hexahedron cancellous bone had the simplest design compared to hexagon and cylindrical cancellous bones. This simple design leads to simplicity of structural cross- sectional that facilitates good fluid flow. According to Steinbuch [13], geometry with higher fluid flow has lower pressure drop. Since both hexagon and cylindrical models had more complex geometry, the value of permeability could be concluded based on the pore diameter as at fixed porosity, cylindrical model had smaller pore diameter size compared to hexagon model.

4.0 CONCLUSSION

In this paper, computational fluid dynamics method has been used to study the fluid flow through cancellous structure. Cancellous bone can have structure with the same value of porosity and overall volume but different surface area. However, this will affect the value of permeability as the value of permeability will vary with surface area. For the structure of same porosity, structure with bigger pore diameter is preferred as it will have the highest value of permeability.

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