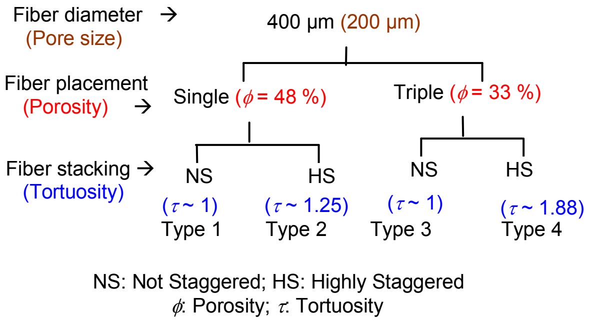
Effect of Scaffold Architecture on Diffusion of Oxygen in Tissue Engineering Constructs

Karande, TS[1,2], Mahadevan, J[1], Peppas, NA[1], Sun, W[3], Dean, DD[2,4], Agrawal, CM[1,2,4]
[1]The University of Texas at Austin, [2]The University of Texas Health Science Center at San Antonio,
[3]Drexel University, [4]The University of Texas at San Antonio

Statement of Purpose: Scaffold architecture plays an important role in the success of scaffold-based tissue engineering constructs. The important architectural parameters include pore size, porosity and permeability, which affect transport of nutrients, removal of waste as well as cell migration. The present study examined the effect of scaffold architecture on diffusion of oxygen within the construct using a mathematical model. The contributions of porosity and tortuosity to permeability and water retention within the scaffold are discussed.

Methods: Poly(ϵ-caprolactone) (PCL) scaffolds of height and diameter 1 cm were fabricated using a precision extrusion deposition system. Four different scaffold architectures (Types 1- 4) with the same pore size but different porosities and tortuosities, as shown in the chart, were evaluated for permeability and water retention:



Fiber diameter → 400 µm (200 µm)
(Pore size)

Fiber placement (Porosity) → Single (ϕ = 48 %) Triple (ϕ = 33 %)

Fiber stacking → (Tortuosity) NS HS NS HS

(τ ~ 1) Type 1 | (τ ~ 1.25) Type 2 | (τ ~ 1) Type 3 | (τ ~ 1.88) Type 4

NS: Not Staggered; HS: Highly Staggered
ϕ: Porosity; τ: Tortuosity

Scaffold permeability (K) was calculated using Darcy's Law by subjecting the samples to hydrostatic pressure:

$$K = Q.\mu.L/A.H$$

where, Q is volumetric flow rate (m^3/s), µ is viscosity of distilled water (cP), L is length of scaffold (m), A is cross-sectional area of scaffold (m^2), H is height of water level in reservoir over the level of scaffold in units of pressure (Pa).

The average time (T) spent by water within the scaffold, termed 'water retention time' was calculated as follows:

$$T = L/V$$

where, $V = q/\phi$ is the velocity of water within the pores, and $q = Q/A$ is volumetric flow per unit area (m/s).

A mass transfer equation was set up to model the 1D diffusion of oxygen into cylindrical scaffolds of different architectures, statically seeded with MG63 osteoblast-like cells, sealed from the sides as well as the bottom, resting in a well.

Mole Conservation (Volume Averaged):

$$\frac{\partial C_{O_2,m}}{\partial t} = D_{eff}\cdot\left(\frac{\partial^2 C_{O_2,m}}{\partial y^2}\right) - kC_{O_2,m} \quad \text{where,} \quad D_{eff} = D_{O_2}\frac{\phi}{\tau}$$

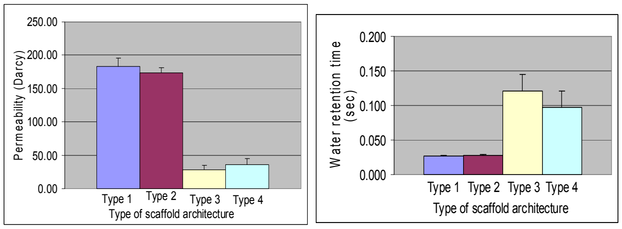
D_{O2} is diffusivity of oxygen in water at 37ºC, ϕ is scaffold porosity, τ is scaffold tortuosity and k is a rate constant that accounts for oxygen consumption rate. The above equation was solved analytically to obtain oxygen concentration profiles in the scaffold.

Boundary conditions: Initial Condition:

$$1)\ C_{O_2,m}\Big|_{y=L} = C_{O_2,S} \qquad 2)\ \frac{\partial C_{O_2,m}}{\partial y}\Big|_{y=0} = 0 \qquad C_{O_2,m}\Big|_{0<y<L} = 0$$

where, $C_{O2,m}$ is concentration of oxygen within medium in scaffold and $C_{O2,s}$ is concentration of oxygen in solution.

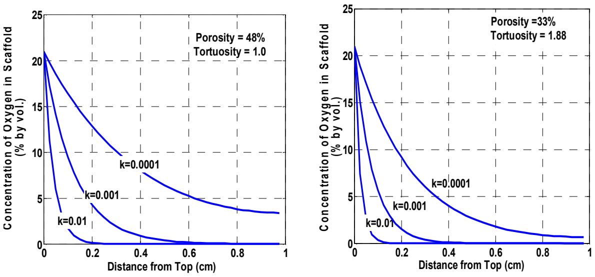
Results / Discussion:



(a) (b)

Fig. 1 (a) Permeabilities (Darcy) and (b) water retention times (seconds) for different scaffold architectures (Types 1 – 4)

Fig. 1 (a) shows that greater the porosity and lower the tortuosity, higher is the permeability of the scaffold for the specific values of architectural parameters considered. Also, permeability seems to be influenced much more by porosity than tortuosity. Fig. 1 (b) shows the inverse relationship between permeability and water retention i.e. as permeability increases, the time for water retention decreases and vice versa.



(a) (b)

Fig. 2 Concentration profiles of oxygen as a function of depth for different values of rate constant k (a) $\phi = 48\%, \tau \sim 1$; (b) $\phi = 33\%, \tau \sim 1.88$

Fig. 2(a) and (b) show that increasing the rate constant k by an order of magnitude decreases oxygen concentration due to higher rate of consumption by cells compared to diffusive rates. An increase in tortuosity causes the oxygen concentration to decrease due to decreased transport by diffusion. When porosity is decreased the oxygen concentrations fall even more steeply.

Conclusions: A simple mathematical model was developed to describe the process of diffusion of oxygen in cell-seeded scaffolds of varying porosity and tortuosity. Actual oxygen measurements will be performed to validate the proposed diffusion model. The model predicted that diffusion of oxygen in the scaffold interior was greatly reduced at lower porosity and higher tortuosity. Porosity and tortuosity had a similar effect on permeability, leading us to conclude that a scaffold architecture with greater permeability supported better oxygen diffusion into the scaffold interior for the specific values of architectural parameters considered.