A phenomenological model for the degradation of polymeric tissue engineering scaffolds

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Abstract

Biodegradable polymers have great number of applications in modern reconstructive medicine and orthopaedics. One of them is manufacturing of tissue engineering scaffolds, which are potential analogues of bone grafts. Bone scaffolds are commonly used to support reconstruction of tissue losses caused by injury or disease. The main goal of using the tissue engineered scaffolds is to maintain the mechanical function of injured tissue. Bone scaffolds are made as porous structures with interconnected pores. During the regenerative process implanted scaffold is subjected to degradation. Polymer matrix should be replaced by regenerated tissue. It is crucial to predict the degradation behaviour of biopolymer because of fact that its mechanical properties are function of its degradation properties. In the paper numerical model of aliphatic polyester degradation in aqueous medium are presented and adopted for prediction of degradation behaviour of bone scaffolds.

Keywords: bone scaffold, degradation, FEM, auto-catalytic effect

1. Introduction

One of the aims of the scaffold graft implantation is the preservation of tissue mechanical function. When the local bone loss occurs, mechanical integrity fails due to injury or degeneration. The scaffold should partially take over the mechanical function of impaired tissue temporarily [1]. Subsequently, the bone undergoes regeneration and remodeling of its macro- and microstructure. Simultaneously, the scaffold degrades in the *in vivo* environment and gradually loses its mechanical function. Finally, the scaffold is replaced by the newly formed bone. The mechanical function of the bone–scaffold system dynamically changes with time during the regeneration process. Then in designing of the optimal porous scaffold, the change in mechanical function should be considered. Hydrolytic degradation of aliphatic polyesters is characterized by strong auto-catalytic effect. The main consequence of this fact is that large size polymeric implants are degraded heterogeneously. In such a situation, the degradation of internal part is faster than at the implant surface [3]. Because of above mentioned fact the diameter of scaffold fibers is one of crucial parameters, which decide about scaffold usefulness. The rate of scaffold degradation has a great influence on decrease in its stiffness. The optimal scaffold should be characterized by suitable rate of stiffness loss. Complex geometry of tissue engineering scaffolds makes its stiffness loss hard to predict. The above problem could be solved by using the numerical model of polymer degradation presented in the paper.

2. Model of polyesters degradation

To simulate a degradation of aliphatic polyesters the numerical model described in details by Y. Wang [2] was adopted in the paper. The model takes into account two important phenomena, which take place during polymer degradation. The first of them is increasing of the number of carboxylic chain ends, which are known to autocatalyse the ester hydrolysis, whereas the second is that only monomers, which soluble in the surrounding aqueous medium can escape from the matrix. Soluble monomers, which are close to the implant surface can leach out before total degradation, whereas those, which are located deeply inside the scaffold domain remain entrapped and next become cause of autocatalytic effect [3][4]. Described above degradation process is modelled using a system of reaction-diffusion equations [2]:

$$\frac{dC_e}{dt} = -(k_1 C_e + k_2 C_e C_m^n), \tag{1}$$

$$\frac{dC_m}{dt} = k_1 C_e + k_2 C_e C_m^n + \underset{x_i}{div}\left\{ D_0[1+\alpha(1-\frac{C_m + C_e}{C_{e0}})] \times \underset{x_i}{grad}(C_m) \right\}, \tag{2}$$

where C_e is ester bounds concentration, C_{e0} is the initial ester bounds concetration, D_0 is the initial diffusion coefficient for monomers, C_m is monomers concentration. k_1 and k_2 are phenomenological reaction rate constants. The power n accounts for dissociation of the acidic end groups. α is a special parameter for computing the effective diffusivity of monomers. System of equations could be solved numerically by using finite element method (FEM).

3. Simulation of bone scaffold degeneration

The scaffold architecture and design used for this study is defined by the $0/90^o$ strut lay-down pattern [1]. Figure 1 shows the geometry of the scaffold of dimension $3.5 \times 3.5 \times 2$ mm^3. The scaffold consists of 6 layers with each layer consists of 4 struts, thus a total of 24 struts form the 3D scaffold. The numerical model of the scaffold was generated using ANSYS v.12 code. Algorithm for computing the system of equations (1) and (2) was developed using Ansys Parametric Design Language (APDL). Monomer concentration C_m at the scaffold

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surface was assumed to be zero (it means that each monomer, which is close to the surface is immediately taken away). The scaffold material is DLPLA (poly(DL-lactide)) [1]. In the simulation the following parameters were used:

$k_1 = 0.003/\text{week}$, $k_2 = 2\times10^{-3}\sqrt{\text{m}^3/\text{mol}}/\text{week}$, $n = 0.5$, $D_0 = 1.41\times10^{-14}\ \text{m}^2/\text{s}$, $C_{e0} = 1.73\times10^4\ \text{mol/m}^3$ [2]. FE model of the scaffold consisted of 165 000 elements (type SOLID70).

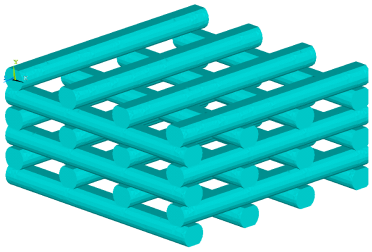

Figure 1: Geometry of scaffold

4. Results

Figure 2 shows diagrams of ester bounds and monomer concentrations averaged on scaffold domain. Scaffold molecular weight loss is a function of ester bounds concentration. It is worth to mention that monomer concentration C_m has its maximum at the first week of degradation. The ester bounds and monomer concentrations maps at 30th week of scaffold degradation are presented in Figures 3 and 4 respectively. It is characteristic that the lowest ester bound concentrations (and the highest monomer concentration) occurred in the middle part of scaffold fibres, which is in accordance to experimental results [3].

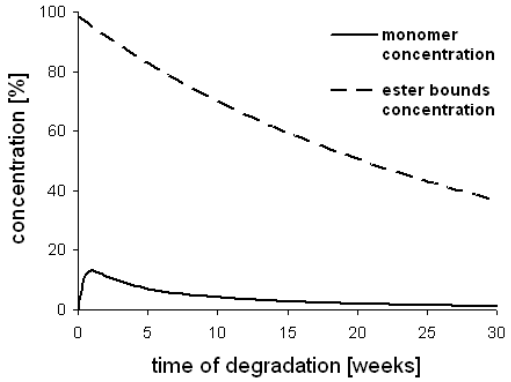

Figure 2: Diagrams of monomer concentration and ester bounds concentration (averaged on scaffold domain)

5. Conclusions

In this study, a phenomenological model of aliphatic polyesters degradation was applied to predict of degradation behaviour of tissue engineering scaffolds. The performed simulations enable for prediction of the time of scaffold degradation as well for evaluation of changes in molecular weight and mass of scaffold material. The ultimate goal of the future studies is to develop a simulation model for predicting changes in mechanical properties of the scaffold during its degradation. Summarizing, the design of scaffold which will be the best construct for the cells to regenerate bone and cartilage defects is a complex problem and require multitude in vitro and in vivo experiments. However combining experiments and numerical methods might results in more efficient way to find an optimal scaffold design for clinical application.

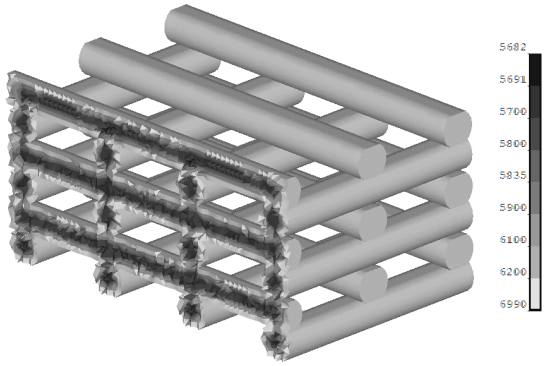

Figure 3: Map of ester bounds concetrations at the 30th week of degradation

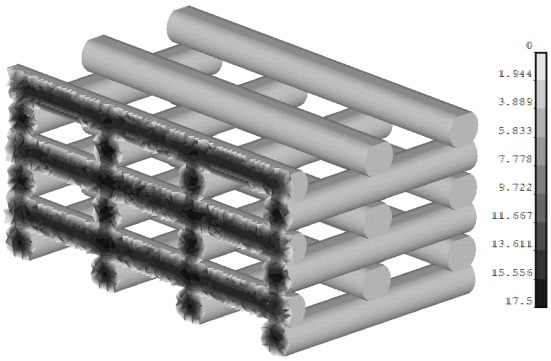

Figure 4: Map of monomer concetrations at the 30th week of degradation

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References

[1] Hutmacher, D.W., Scaffolds in tissue engineering of bone and cartilage, *Biomaterials*, 21, pp. 2529-2543, 2000.

[2] Wang, Y., Pan, J., Han, X., Sinka, C., Ding, L., A phenomenological model for the degradation of biodegradable polymers, *Biomaterials*, 29, pp. 3393-3401, 2008.

[3] Grizzi, I., Garreau, S.Li., Vert, M., Hydrolityc degradation of devices based on poly(DL-lactic acid) size-dependence, *Biomaterials*, 16, pp. 305-311, 1995.

[4] Göpferich, A., Mechanisms of polymer degradation and erosion, *Biomaterials*, 17, pp. 103-114, 1996.