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Surface modification of bioactive glass nanoparticles and the mechanical and biological properties of poly(L-lactide) composites

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Abstract

Novel bioactive glass (BG) nanoparticles/poly(L-lactide) (PLLA) composites were prepared as promising bone-repairing materials. The BG nanoparticles (Si:P:Ca = 29:13:58 weight ratio) of about 40 nm diameter were prepared via the sol–gel method. In order to improve the phase compatibility between the polymer and the inorganic phase, PLLA ($M_n = 9700$ Da) was linked to the surface of the BG particles by diisocyanate. The grafting ratio of PLLA was in the vicinity of 20 wt.%. The grafting modification could improve the tensile strength, tensile modulus and impact energy of the composites by increasing the phase compatibility. When the filler loading reached around 4 wt.%, the tensile strength of the composite increased from 56.7 to 69.2 MPa for the pure PLLA, and the impact strength energy increased from 15.8 to 18.0 kJ m^{-2}. The morphology of the tensile fracture surface of the composite showed surface-grafted bioactive glass particles (g-BG) to be dispersed homogeneously in the PLLA matrix. An in vitro bioactivity test showed that, compared to pure PLLA scaffold, the BG/PLLA nanocomposite demonstrated a greater capability to induce the formation of an apatite layer on the scaffold surface. The results of marrow stromal cell culture revealed that the composites containing either BG or g-BG particles have much better biocompatibility compared to pure PLLA material.

Keywords: Polylactide; Bioactive glass; Nanoparticles; Composites; Mechanical properties

1. Introduction

In recent years, composites of biopolymers and bioactive inorganic materials have been developed as bone-repairing devices because of their bioactivity, biocompatibility and biodegradability [1–3]. They have been successfully used to deal with the abnormal hard tissues resulting from the intrusion in disease or accidental injuries [4,5].

Typical bioactive fillers include hydroxyapatite, β-tricalcium phosphate, bioactive glass, bioactive glass ceramics and calcium silicate [6–10]. Their morphology greatly influences the mechanical properties and bioactivity of the composites. Decreasing the filler size could improve the modulus of the composites, endowing the composites with much better processing and mechanical properties [11,12]. Furthermore, reducing the size of the granules would not only accelerate the formation of the bioactive hydroxyapatite layer but also provide more active sites for osteoblast attachment and tissue growth [13–15]. So combining nano-sized bioactive materials with biopolymer could produce materials with greater bioactivity and better mechanical properties. However, the nanoparticles would aggregate

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in the matrix because of their incompatibility with the biopolymer. The phase separation phenomenon resulting from this aggregation would then induce early failure at the interface and thus cause the mechanical properties of the composites to deteriorate [16,17]. So the surface modification of nano-sized bioactive ceramic particles by grafting organic molecules or polymers is necessary. The modification would make the particles disperse within the matrix more homogeneously. Furthermore, the molecules grafted onto the particles would interact with the matrix, thus the final mechanical properties could be greatly improved [18,19].

Bioactive glass (BG)/poly(L-lactide) (PLLA) composites have attract much interest because of their high osteoconductivity, osteoinductivity and biodegradability [20–26]. They combined bioactive behavior with mechanical strength and processability. This series of composites can potentially be applied in load-bearing situations. In order to yield composites with high bioactivity and strong mechanical properties, we prepared a PLLA composite containing BG nanoparticles. Moreover, in order to improve the interface compatibility between the particles and PLLA matrix, low-molecular-weight PLLA was coupled onto the surface of the particles by diisocyanate. The bioactivity and biocompatibility were evaluated in vitro. Fourier transform infrared (FTIR) spectroscopy, environmental scanning electron microscopy (ESEM), solid magic-angle-spinning nuclear magnetic resonance imaging (MAS NMR), and thermogravimetric analysis (TGA) were employed to characterize the BG nanoparticles and BG/PLLA composite.

2. Materials and methods

2.1. Chemical reagents

Ammonia (30%), $Ca(NO_3)_2 \cdot 4H_2O$, $(NH_4)H_2PO_4$, HNO_3 and tetraethoxyl orthosilicate (TEOS) were all of analytical grade and used as received. Hexane methyl diisocyanate (HMDI) was purchased from Aldrich.

Low-molecular-weigh PLLA ($M_n = 9700$ Da), used for grafting onto the surface of BG particles, was synthesized by the ring-opening polymerization of the L-lactide. Ethylene alcohol was used as the initiator to get the binary hydroxyl-ended PLLA macromolecules. PLLA 5051X (M_v: 65,000 g mol^{-1}, Cargill Company) was used to blend with BG particles to prepare the BG/PLLA composites.

2.2. Preparations of nanobioactive glass particles

BG nanoparticles were produced by the following procedures. First, 7.8 g of TEOS and 12.5 g of $Ca(NO_3)_2 \cdot 4H_2O$ were dissolved in a mixture of 120 ml of deionized water and 40 ml of ethanol, and stirred at room temperature for the hydrolysis of TEOS. The pH value of this solution was adjusted to 2 with HNO_3. Secondly, 1.98 g of $NH_4H_2PO_4$ was dissolved in 1500 ml of deionized water containing 15 g of PEG 10,000, and the pH of the solution was adjusted to 10 with ammonium water. Thirdly, when TEOS was completely hydrolyzed in about 4 h, the TEOS–$Ca(NO_3)_2$ solution was dropped into $NH_4H_2PO_4$ solution under vigorous stirring and the reaction mixture aged for 24 h at room temperature to obtain a white gel precipitate. Finally, CaO_2–SiO–P_2O_5 ternary BG nanoparticles were obtained by filtration, lyophilization and calcination of the precipitate.

2.3. Surface modification of the BG nanoparticles

The modification process was described as follows. PLLA was first reacted with a twice molar ratio of hexamethylene diisocyanate (HMDI) at 80 °C for 4 h under an Ar atmosphere. Toluene and dibutyltin dilaurate were used as the solvent and catalyst in this reaction, respectively. The isocyanate-ended PLLA–toluene solution was further reacted with the pre-dried BG particles at 80 °C for about 12 h. Then the surface-grafted BG particles were washed exhaustively with chloroform to remove the free PLLA. After centrifugation, the PLLA-grafted BG powder (g-BG) was dried under a vacuum at 50 °C to completely remove any residual chloroform and kept in a desiccator for characterization.

2.4. Preparation of the composites

A certain quantity of BG or g-BG was homogeneously suspended in chloroform with an ultrasonicator. PLLA was then dissolved in the suspension using a magnetic stirrer. After precipitation in ethanol and drying under a vacuum, BG/PLLA and g-BG/PLLA composites were obtained.

2.5. In vitro test

The g-BG/PLLA porous scaffolds were prepared via the salt-leaching technique as follows. A 4 g aliquot of PLLA was dissolved in 20 ml of chloroform containing a certain amount of g-BG particles. When the PLLA was fully dissolved, 36 g of NaCl crystals, 150–250 μm in size, were mixed into the g-BG/PLLA solution. After stirring for 6 h, the mixture was cast into a culture dish and dried in a fume hood overnight to completely remove any chloroform. The g-BG/PLLA scaffold was then soaked in warm water to dissolve the NaCl crystals away and vacuum dried at 50 °C. Pure PLLA scaffold was also prepared as control samples. In order to evaluate the bioactivity of the composite scaffold, an in vitro test was carried out in simulated body fluids (SBF) that were prepared according to the procedures described by Cüneyt [27,28]. After soaking in 100 ml SBF at 37 °C for different numbers of days, samples were removed from the SBF, carefully cleaned with distilled water and dried for the measurement of the surface morphology and element components.

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