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Research Paper

A new technique to improve the mechanical and biological performance of ultra high molecular weight polyethylene using a nylon coating

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ABSTRACT

A new patent pending technique is proposed in this study to improve the mechanical and biological performance of ultra high molecular weight polyethylene (UHMWPE), i.e., to uniformly coat nylon onto the UHMWPE fiber (Firouzi et al., 2012). Mechanical tests were performed on neat and new nylon coated UHMWPE fibers to examine the tensile strength and creep resistance of the samples at different temperatures. Cytotoxicity and osteolysis induced by wear debris of the materials were investigated using (MTT) assay, and RT-PCR for tumor necrosis factor alpha (TNFα) and interleukin 6 (IL-6) osteolysis markers. Mechanical test results showed substantial improvement in maximum creep time, maximum breaking force, and toughness values of Nylon 6,6 and Nylon 6,12 coated UHMWPE fibers between average 15% and 60% at 25, 50, and 70 °C. Furthermore, cytotoxicity studies have demonstrated significant improvement in cell viability using the nylon coated UHMWPE over the neat one (72.4% vs 54.8%) for 48 h and (80.7 vs 5%) for 72 h ($P<0.01$). Osteolysis test results have shown that the expression levels of TNFα and IL-6 markers induced by the neat UHMWPE fiber were significantly higher than those induced by the Nylon 6,6 coated UHMWPE (2.5 fold increase for TNFα at 48 h, and three fold increase for IL-6 at 72 h ($P<0.01$)). This study suggests that UHMWPE coated with nylon could be used as a novel material in clinical applications with lower cytotoxicity, less wear debris-induced osteolysis, and superior mechanical properties compared to neat UHMWPE.

Abbreviations: (CNTs), Carbon nanotubes; (DMEM), Dulbecco's Modified Eagle's Medium; (FBS), Fetal Bovine Serum; (HDPE), High density polyethylene; (HA), Hydroxyapatite; (IL-6), Interleukin 6; (MTT), Methylthiazol Tetrazolium; (MWCNTs), Multi wall carbon nanotubes; (PBS), Phosphate buffered saline; (THA), Total hip arthroplasty; (TNFα), Tumor necrosis factor alpha; (UHMWPE), Ultra high molecular weight polyethylene

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1. Introduction

Ultra high molecular weight polyethylene (UHMWPE) has been extensively used as a successful load bearing material in orthopedic applications due in part to its superior properties of biocompatibility, lightweight, good wear resistance, chemical stability, and lubricity which fit the biological and mechanical requirements for such applications. However, the properties of UHMWPE strongly depend on the synthesis and processing conditions which may alter the overall performance of the implanted device (Kurtz, 2009). Despite the relative high abrasion resistance of UHMWPE, wear and the induction of cytotoxicity due to leachable eluates from the material could limit the long term performance of total hip and knee replacement prostheses. The most common reasons for implant failure are osteolysis (a painful inflammatory reaction) due to wear debris and stress shielding induced by high-stiffness materials (Bougherara et al., 2007, 2010). Implants should have high strength and low stiffness to allow the underlying bone to carry a considerable amount of load, while having high wear resistance to prevent osteolysis at the joint (articulating components) and bone-implant interface (Bartel et al., 2006). Several studies have evaluated the wear resistance of this polymer and identified it as the primary cause for osteolysis and the subsequent aseptic loosening of the implant. In order to minimize the wear of UHMWPE, several solutions were introduced such as irradiation cross linking and composite technology. On the other hand, little improvement in wear resistance of UHMWPE was observed when reinforcement fillers such as glass or aramid fibers were used, however substantial improvement was achieved by extensive gamma radiation crosslinking and thermal processing (Kurtz, 2009). Deng and Shalaby (1997, 1998) demonstrated that the longitudinal tensile properties and creep resistance of continuous UHMWPE-fiber (Spectra 1000)/resin-(GUR 405 UHMWPE) homocomposites were improved compared with the control samples, although wear resistance was not improved and transverse mechanical properties were drastically degraded.

Xue et al. (2006) reported the improvement in wear resistance of high density polyethylene (HDPE)/UHMWPE composite reinforced with pre-treated multiwalled carbon nanotubes (MWCNTs). Chang et al. (2000) reported that the wear resistance of UHMWPE-fabric/resin-(GUR 4150HP) homocomposites were similar or worse than the control sample because of poor fiber–matrix adhesion. Xie et al. (2003) demonstrated that the wear resistance of UHMWPE filled with micron-sized quartz particles was improved using an organosiloxane coupling agent which increased the adhesion between the particles and the matrix. Poor adhesion of fiber-UHMWPE was also cited as a primary problem source which in turn caused inadequate consolidation and short term clinical failures in carbon fiber reinforced UHMWPE composites. Hofste et al. (1998) showed that pre-treatments (i.e., plasma irradiation and chemical etching with chromic acid) of aramid fiber could improve the fiber-UHMWPE interface and enhanced the mechanical (i.e., elastic modulus, yield stress, and stress at break) and tribological properties. Because of inconsistency of results and difficulties in manufacturing processes, self-reinforced UHMWPE composites have not been commercialized for orthopedic bearing applications. Cross linking of UHMWPE by gamma irradiation could enhance the wettability and wear resistance of UHMWPE, although it is associated with some important setbacks i.e., degradation of other mechanical properties (e.g., toughness) during the shelf ageing period and increasing the vulnerability of the polymer to oxidation due to generation of free radicals. Martínez-Morlanes et al. (2011) and Sreekanth et al. (2012) reported that the addition of carbon nanotubes (CNTs) to UHMWPE matrix was effective to compensate the negative effects of gamma irradiation after shelf aging period. In addition, Jia et al. (2005) introduced CNTs as a cytotoxic substance with characteristic features of necrosis and degeneration, although Haniu et al. (2012) reported that CNTs could also be biocompatible. Kang and Nho (2001) showed that the wear rate of UHMWPE was decreased after gamma irradiation. They proved that recrystallization of UHMWPE could be helpful to enhance polymer cross linking after gamma irradiation. In results, the tensile strength of irradiated recrystallized sample was continuously increased with the radiation dose. On the other hand, the elongation at break of the sample was reduced by increasing the radiation dose which was interpreted to be the result of increasing in crosslinking structure of polymer chains. In contrast, Lewis and Carroll (2001) showed that gamma irradiated GUR 1050 UHMWPE samples provided less tensile and compressive creep performance compared with the controls. Viscoelastic UHMWPE is inherently weak in creep and fatigue resistance when compared to the metal stem and cortical bone. Long term stability of body implants is dependent on creep characteristics of the components as well as wear resistance which maintains device dimensions. Mejia and Brierley (1995) showed that creep of UHMWPE implants under continuous stress (i.e., body weight) is important in orthopedic applications. Jacobs et al. (2000) showed that HDPE reinforced with UHMWPE fiber composites has lower creep but higher wear rate than UHMWPE which make them unsuitable for use as a tribal component for a total knee joint replacement. Penmetsa et al. (2006) suggested that the creep rate of polyethylene acetabular liner has an important effect on early penetration and wear rate due to smaller head-liner contact areas after total hip arthroplasty (THA), while it was found to have much less influence on the critical factor of long term volumetric wear rate. This finding was also confirmed by the study conducted by Hernigou et al. (2008) showing that creep has a significant influence on the penetration rate of the polyethylene femoral condyle implant. The rate of creep was found to dramatically increase if the implanted device was thin, misaligned, or if the patient was overweight. Pal et al. (2005) reported that a bioactive sprayed hydroxyapatite (HA) coating over alumina ceramic particulate reinforced UHMWPE composite could facilitate biological fixation between the prosthesis and the hard tissue. The integrity and long term stability of the composite were also claimed to be improved. Silva et al. (2010) coated titanium and titanium/HA on UHMWPE to stabilize bearing surfaces of the arthroplasty devices and to improve osteoblastic interfaces with bone.

Driven by the great interest in improving both the mechanical and biological performance of UHMWPE and