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Anti-infective and osteointegration properties of silicon nitride, poly(ether ether ketone), and titanium implants

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ABSTRACT

Silicon nitride (Si_3N_4) is an industrial ceramic used in spinal fusion and maxillofacial reconstruction. Maximizing bone formation and minimizing bacterial infection are desirable attributes in orthopedic implants designed to adhere to living bone. This study has compared these attributes of Si_3N_4 implants with implants made from two other orthopedic biomaterials, i.e. poly(ether ether ketone) (PEEK) and titanium (Ti). Dense implants made of Si_3N_4, PEEK, or Ti were surgically implanted into matching rat calvarial defects. Bacterial infection was induced with an injection of 1×10^4 *Staphylococcus epidermidis*. Control animals received saline only. On 3, 7, and 14 days, and 3 months post-surgery four rats per time period and material were killed, and calvariae were examined to quantify new bone formation and the presence or absence of bacteria. Quantitative evaluation of osteointegration to adjacent bone was done by measuring the resistance to implant push-out ($n = 8$ rats each for Ti and PEEK, and $n = 16$ rats for Si_3N_4). Three months after surgery in the absence of bacterial injection new bone formation around Si_3N_4 was ~69%, compared with 24% and 36% for PEEK and Ti, respectively. In the presence of bacteria new bone formation for Si_3N_4, Ti, and PEEK was 41%, 26%, and 21%, respectively. Live bacteria were identified around PEEK (88%) and Ti (21%) implants, whereas none were present adjacent to Si_3N_4. Push-out strength testing demonstrated statistically superior bone growth onto Si_3N_4 compared with Ti and PEEK. Si_3N_4 bioceramic implants demonstrated superior new bone formation and resistance to bacterial infection compared with Ti and PEEK.

1. Introduction

Silicon nitride (Si_3N_4) is a synthetic non-oxide ceramic that is used in many industrial applications, and has been investigated or adapted as a biomedical material since 1989 [1–14]. The rationale for using Si_3N_4-based implants in skeletal reconstruction is based on its favorable combination of mechanical strength, microstructure, and cytotoxicity [11,12,15]. Polished and porous implants made of Si_3N_4 have shown encouraging outcomes in spine and maxillofacial surgery [11,13]. In contrast to the limited clinical experience with Si_3N_4, implants made of titanium (Ti) and its alloys have been used in skeletal reconstruction for many decades [16,17]. More recently, poly(ether ether ketone) (PEEK), a polymer with modest strength and a low modulus of elasticity compared with metal, has been investigated as an orthopedic biomaterial [18,19] and is commonly used in spine surgery [20].

Long-term, stable fixation of orthopedic implants to skeletal bone relies on direct in-growth of host bone into the textured implant surface. Implant failure and clinical symptoms of pain can follow if such bone in-growth does not occur. A serious problem that can complicate an otherwise well-fixed and properly functioning implant is bacterial infection, which can manifest itself immediately after surgery or even years later. Implant-related infections usually require extensive surgical debridement, implant extraction, and prolonged antibiotic treatment [21,22]. Implant surfaces can accumulate serum proteins that can promote bacterial adhesion and colonization [23]. Adherent bacteria such as *Staphylococcus epidermidis* are known to synthesize a complex surrounding biofilm layer that is impervious to host immune surveillance and systemic antibiotic therapy [23–25]. Therefore, resistance to bacterial infection would be a very desirable material property in orthopedic implants. To date, however, all implant materials are susceptible to bacterial seeding in vivo.

The purpose of this investigation was to test the potential antimicrobial properties and osteointegration capability of dense Si_3N_4 implants in an animal model. For comparison we used two common

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