Calcium (Ti,Zr) hexaorthophosphate bioceramics for electrically stimulated biomedical implant devices: A position paper

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ABSTRACT

Osseointegration of biomedical implants as well as healing of broken bones are supported by novel bioceramic materials that, owing to their engineered ionic conductivity, in the presence of an electric field provide accumulation of negative electrical charges close to the interface between an implant and living bone tissue, thus stimulating the rate of bone growth. In this position paper, the structure as well as the chemical, electrical, and biomedical properties of Ca (Ti,Zr) hexaorthophosphates are reviewed. In addition, based on evaluation of the material’s properties, a conceptual configuration of a capacity-coupled bone growth stimulator will be presented. The advantage of the proposed novel device over already existing bone-growth stimulators is its provision of the intimate contact of a capacity-coupled electric field with the growing bone tissue as opposed to an externally applied inductively coupled electromagnetic field, which suffers substantial attenuation when transmitted through soft tissue covering the locus of bone growth. To achieve higher ionic conductivity in Ca (Ti,Zr) hexaorthophosphates, aliovalent doping with highly mobile Na or Li ions intercalated into the only partially occupied M1 sites appears to be a suitable route.

Keywords: Bioceramics, calcium hexaorthophosphate, plasma spraying, solubility, osseoconductivity, bone growth, bone growth stimulation, Biomaterials—Mineralogy Meets Medicine

INTRODUCTION

Worldwide, there is an increasing demand for load-bearing hip, knee, and dental endoprosthetic implants, for bone replacement parts in cranial, maxillar-mandibular, and spinal areas, for the ossicular chain of the inner ear, for periodontal pocket obliteration, percutaneous access devices, alveolar ridge and iliac crest augmentation, and osteosynthetic devices for bone healing (Heimann and Lehmann 2015). In 2011 in the United States, 204 total hip arthroplasties were performed per 100000 population (Dotinga 2015). With 284 cases per 100000 population, Germany’s figure was even higher (Wengler et al. 2014). In Australia, 83 hip arthroplasties per 100000 population were performed in 2004, increasing to 104 per 100000 population in 2014 (Bourlioufas 2016). This high and growing demand is the result of the wear and tear the joints providing the ambulatory kinematics suffer during a human lifetime, but is also caused by degenerative diseases such as osteoarthritis, rheumatoid arthritis, and osteoporosis, as well as damage caused by physical harm from external sources.

Arguably, total hip replacement (THR) is one of the most successful and safe surgical procedures today. It combines a sophisticated surgical technique and reliable pain reduction with few limitations during daily activities, in addition to acceptable longevity of the implant and a high success rate should a revision operation be required. State-of-the-art technology features implants with Ti6Al4V alloy shafts, plasma spray-coated with hydroxylapatite (Heimann 2006b) and equipped with an alumina femoral ball articulating against an acetabular cup solidly anchored in the hipbone. The acetabular cup consists of a commercially pure (cp)-titanium shell, lined with cross-linked (XLPE) or ultrahigh-density polyethylene (UHDPE) to assure a low coefficient of friction. Since the synovial fluid acting in healthy joints as a lubricant is absent in artificial joints, it is vital to select synthetic materials that can achieve the required low friction coefficient. Hence, acetabular cups with alumina inserts are increasingly used to articulate against an alumina ball. This tribological pair exhibits a particularly low coefficient of friction, resulting in linear wear rates of <5 μm/year (Heimann and Willmann 1998). Recently, femoral balls of alumina-zirconia composite ceramics reinforced with chromium oxide particles (Biolox delta, Kunts 2014) are employed and demonstrate linear wear rates <1 μm/year.

Currently, coating the metal stem of hip endoprosthetic implants by atmospheric plasma spraying (APS) of hydroxylapatite powder with particle diameters of tens to hundreds of micrometers is the most popular, and the only Food and Drug Administration (FDA)-approved, method to coat implant surfaces for clinical use (Heimann 2016). Unfortunately, thermal decomposition of incongruently melting hydroxylapatite in the extremely hot plasma jet, formation of amorphous calcium phosphate (ACP) deposits by quenching of superheated molten particles, enhanced dissolution of the coating in contact with biofluid in vivo, and adhesion failure at the coating-metal substrate interface are notorious limitations to this approach. To mitigate these problems, calcium (titanium, zirconium) orthophosphates may be good candidates, providing dense, well-adhering coatings...