Nanophase Ceramics : Boon for Osseointegration

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ABSTRACT

Traditional materials utilized for dental applications have been selected based on their mechanical properties and ability to remain inert in vivo; this selection process has provided materials that satisfy physiological loading conditions but do not duplicate the mechanical, chemical, and architectural properties of bone. The less than optimal surface properties of conventional materials have resulted in clinical complications that necessitate surgical removal of many such failed bone implants due to insufficient bonding to juxtaposed bone. Due to unique surface and mechanical properties, as well as the ability to simulate the three-dimensional architecture of physiological bone, one possible consideration for the next generation of orthopedic and dental implants with improved efficacy are nanophase materials.

Key words – *Nanophase, bioceramics, cytocompatibility*

INTRODUCTION

Implanting a dental implant can be a costly procedure and involves considerable patient discomfort. Both patient discomfort and cost can increase if surgical revision becomes necessary after implantation when a dental implant is rejected by host tissue, is insufficiently integrated into juxtaposed bone, and/or fails under physiological loading conditions. Careful design of implants with improved properties (such as biocompatibility, ability to enhance integration into surrounding bone, and mechanical properties similar to physiological bone) could increase biomaterial success rate and, therefore, decrease patient discomfort as well as surgical costs associated with device retrieval and implantation of another dental prostheses.

Conventional dental materials meet requirements for mechanical loads in the physiological range, but their less than optimal surface properties have resulted in clinical complications and necessitated surgical removal of many such failed dental implants.¹ In contrast, ceramics, which have exceptional biocompatibility and surface properties with bone cells and tissues but are brittle under loading, have experienced limited use in dental implant applications. Dental biomaterials of the future must promote swift deposition of new bone on the surface of implants and support bonding of juxtaposed bone (that is, osseointegrate) to stabilize prostheses in situ and thus minimize motion-induced damage to surrounding tissues.¹

One possible consideration for the next generation of orthopedic and dental implants with improved efficacy are nanophase materials. Nanophase materials are new material

formulations that possess grains composed of the same atoms, but the atoms are fewer (less than tens of thousands) and smaller (less than 100 nm in diameter) than in conventional materials (which contain several billions of atoms and grain sizes of micrometers to millimeters).² Control of the size of the constituent clusters and the manner in which these clusters are assembled in nanostructures has produced new materials with unique, custom-made mechanical, electrical, chemical, magnetic, and optical structures and properties.³

Materials Currently Used as Dental Implants

Metals (such as commercially pure titanium, titanium alloys, stainless steel, and Co-Cr alloys), ceramics (such as alumina, hydroxyapatite, and bioglass), and polymers (such as polymethyl methacrylate (PMMA) and ultrahigh-molecular-weight polyethylene) have been used as either single or multicomponent dental implants.⁴ To date, titanium and titanium alloys have been the dental material of choice due to their superior mechanical properties (such as low-weight-high-strength ratio), excellent resistance to corrosion, and ability to remain inert in vivo.⁵

These biomaterials possess exceptional biocompatibility with bone cells and tissues; mechanical properties (such as low ductility), however, have limited their wide use as dental implant materials.^{6,7} Once implanted into bone (usually as coatings for traditional orthopedic or dental implant metals), various bioceramics (such as hydroxyapatite, bioactive glass, and calcium phosphate) physiochemically bonded to bone and, in select cases, promoted new bone formation, leading to implant

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NOVEL SURFACE MODIFICATIONS OF DENTAL IMPLANTS

Several attempts have been made to increase the cytocompatibility of conventional materials for dental applications using in vitro cellular models. Anchorage-dependent cells (such as osteoblasts, fibroblasts and endothelial cells) must first adhere to a surface in order to perform normal, subsequent functions (such as spreading and proliferation). Although adhesion is a critical cell process, subsequent functions (such as the deposition of calcium-containing mineral) by osteoblasts on dental implants are of paramount importance. In vitro functions of osteoblasts have been well documented on conventional orthopedic and dental materials composed of metals (such as commercially pure titanium^{12,13,14}, metal alloys (for example, Ti-6Al-4V¹⁵, Co-Cr-Mo, and 316L stainless steel¹⁶ and ceramics (such as hydroxyapatite and bioglasses).¹⁷

Reports in the literature demonstrated increased osteoblast adhesion, cell spreading, proliferation, synthesis of extracellular matrix proteins (such as alkaline phosphatase), and deposition of extracellular matrix calcium on conventional titanium surfaces with increased microsize roughness (i.e., sandblasted, heated treated, acid-etched, and machined surfaces).^{12,13,18} Besides promoting functions of osteoblasts, increased microsurface roughness of conventional ceramic surfaces (acid-etched hydroxyapatite) enhanced synthesis of tartrate-resistant acid phosphatase (TRAP) and bone-resorption activity of osteoclast cells.¹⁹

To date, enzymes (i.e., glucose oxidases, or glutamate oxidase), antibodies (such as antimouse immunoglobulin G, and specific peptide sequences (such as arginine-glycine-aspartic acid-serine and lysine-arginine-serine-arginine have been immobilized on various materials (i.e., glass, polymers, and metal oxides) to enhance osteoblast functions.²⁰

Next Generation of Dental Implants: Nanophase Ceramics

Nanophase materials are new formulations of materials that are composed of grains of the same atoms but with fewer (less than tens of thousands) and smaller (less than 100 nm in diameter) atoms than in conventional forms (which contain several billion atoms and have grain sizes of micrometers to millimeters in diameter).² Nanocrystalline materials exhibit enhanced magnetic, catalytic, electrical and optical properties when compared to conventional formulations of the same material.^{2,3} It is imperative to determine properties of nanoceramics that enhance osteoblast and osteoclast

functions ;Webster et al.^{21,22} proposed the following:

1. Enhanced osteoblast and osteoclast functions on nanophase ceramics is due to increased nanosize surface roughness (Fig. 1). Compared to conventional ceramics, nanophase ceramics possess increased surface roughness (by 35 to 50%) resulting from both decreased grain size and decreased diameter of surface pores.

2. Enhanced osteoblast and osteoclast functions on nanophase is ceramics due to increased surface wettability. Compared to conventional ceramics, nanophase ceramics exhibit enhanced surface wettability.

Nanophase ceramics may be synthesized to possess hardness, bending and compressive and tensile strengths that are different than properties of conventional ceramics but similar to those of physiological bone. Indeed, greater mechanical properties (such as hardness, ductility, and enhanced strain to failure) have been reported for ceramics with a reduction in grain size into the nanometer range.²³ Compared to conventional formulations, therefore, the bending modulus of nanophase ceramics may be the result of the combined effects of (1) increased grain-boundary sliding mechanisms due to a larger number of grain boundaries present in nanophase ceramics, and/or (2) smaller crack initiation sites due to smaller diameters of individual surface pores (i.e., fewer and less surface flaws) present on nanophase ceramics.

CONCLUSION

Nanostructured ceramics provide alternatives not yet fully explored for orthopedic and dental implant applications; the improved mechanical properties of these novel ceramic formulations, in addition to their established exceptional biocompatibility, constitute characteristics that promise improved orthopedic and dental efficacy. Requirements applicable for the design of nanophase ceramics for orthopedic and dental applications include the following :

1. Mechanical properties (such as bending, hardness, and compressive and tensile strength) of bioceramics similar to human bone can be obtained by decreasing the grain size of ceramic formulations into the nanometer regime .
2. Surface properties (such as topography and wettability) of bioceramics similar to human bone can be obtained by decreasing the grain size of ceramic formulations into the nanometer regime .

As the disciplines of cell-tissue engineering and nanophase material science develop and mature, the preceding design criteria will be expanded and refined. Undoubtedly, nanophase ceramics have great potential to become the next generation of choice proactive biomaterials for innovative biotechnology and biomedical applications that could have profound clinical impact.

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