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Journal of Bone Research

Commentary

Biomechanical Analysis of Titanium-Hydroxyapatite Composite Implants in Critical-Size Femoral Defects

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DESCRIPTION

Large bone defects resulting from trauma, tumor resection, or infection pose significant challenges for orthopedic reconstruction. Traditional approaches using autografts or allografts have limitations including donor site morbidity, limited availability, and risk of disease transmission. Titanium-Hydroxyapatite (Ti-HA) composite materials offer promising alternatives combining the mechanical strength of titanium with the bioactivity of hydroxyapatite. This investigation evaluated the biomechanical properties and osseointegration of Ti-HA composite implants in critical-size femoral defects.

Ti-HA composite implants were fabricated using powder metallurgy techniques, incorporating 30% hydroxyapatite by weight within a titanium matrix. The composite structure was designed with interconnected porosity of 40%-60% to facilitate bone ingrowth while maintaining mechanical integrity. Scanning electron microscopy confirmed uniform hydroxyapatite distribution throughout the titanium matrix, with particle sizes ranging from 10 µm -50 µm. X-ray diffraction analysis verified the crystalline structure of both titanium and hydroxyapatite phases.

Critical-size femoral defects (15 mm) were created in adult New Zealand white rabbits using standardized surgical procedures. Animals were randomized to receive Ti-HA composite implants, pure titanium implants, or remain untreated as defect controls. Implants were secured using internal fixation plates to ensure mechanical stability during healing. Post-operative care included antibiotic prophylaxis and pain management according to established protocols.

Biomechanical testing at 12 weeks post-implantation revealed superior performance of Ti-HA composite implants compared to pure titanium controls. Ultimate compressive strength of the implant-bone interface increased by 78% in Ti-HA group, while elastic modulus improved by 42%. Importantly, the composite implants demonstrated elastic modulus values (18.2 GPa ± 2.1 GPa) closer to cortical bone (17.5 GPa ± 1.8 GPa) compared to pure titanium (112 GPa ± 8 GPa), potentially reducing stress shielding effects.

Histological analysis using undecalcified bone sections revealed enhanced bone formation around Ti-HA composite implants. Bone-Implant Contact (BIC) percentage reached 67% ± 8% for Ti-HA composites compared to 34% ± 6% for pure titanium implants. New bone formation extended into the porous structure of composite implants, with trabecular bone volume within pores reaching 42% ± 7%. Osteoblast activity was significantly enhanced at the composite interface, as evidenced by increased alkaline phosphatase staining.

Micro-computed tomography analysis demonstrated superior osseointegration of Ti-HA composite implants. Bone volume fraction within the defect area increased by 156% compared to pure titanium implants, while trabecular thickness and number showed 89% and 67% improvements, respectively. The enhanced bone formation was accompanied by improved vascular infiltration, with 73% increase in blood vessel density around composite implants.

Finite element analysis incorporating experimental material properties predicted reduced stress concentrations at the implant-bone interface for Ti-HA composites. The more gradual elastic modulus transition from implant to bone reduced peak stress values by 34%, potentially improving long-term implant stability. Additionally, the analysis revealed more uniform stress distribution throughout the surrounding bone tissue, suggesting better load sharing between implant and bone.

Surface characterization studies revealed that hydroxyapatite particles at the implant surface underwent partial dissolution and reprecipitation, creating a calcium phosphate layer that enhanced biological integration. Energy-dispersive X-ray spectroscopy confirmed the presence of calcium and phosphorus at the implant surface, with Ca/P ratios consistent with biological apatite formation. This surface remodeling process appeared to facilitate protein adsorption and subsequent cellular attachment. Long-term follow-up studies at 24 weeks demonstrated maintained biomechanical properties and continued bone remodeling around Ti-HA composite implants. No signs of implant loosening or adverse tissue reactions were observed.

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Received: 03-Mar-2025, Manuscript No. BMRJ-25-38130; **Editor assigned:** 05-Mar-2025, PreQC No. BMRJ-25-38130 (PQ); **Reviewed:** 19-Mar-2025, QC No. BMRJ-25-38130; **Revised:** 26-Mar-2025, Manuscript No. BMRJ-25-38130 (R); **Published:** 02-Apr-2025, DOI: 10.35841/2572-4916.25.13.318

Citation: Prajapati B (2025). Biomechanical Analysis of Titanium-Hydroxyapatite Composite Implants in Critical-Size Femoral Defects. J Bone Res. 13:318.

CONCLUSION

Ti-HA composite implants demonstrate superior biomechanical properties and osseointegration compared to pure titanium implants in critical-size bone defects. The combination of enhanced bone formation, improved mechanical compatibility, and reduced stress shielding suggests significant clinical potential for these materials in orthopedic applications. The findings support continued development of Ti-HA composites as alternatives to traditional bone grafting approaches for large bone defect reconstruction. The composite implants showed evidence of continued osseointegration, with increasing bone-implant contact percentages over time.