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ORIGINAL ARTICLE

Tissue Response to Titanium Implant with Novel Nanoporous Surface Functionalization: Orofacial Stress, Primary Stability, and Osseointegration

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Objective: The aim of this study was to investigate the stress distributions in a surface-treated dental implant and bone under physiological load.
Methods: The nanoporous surface-modification films were characterized by scanning electron microscopy to analyze surface morphology. The novel implant surface used in this study was complex and difficult to represent because of limitations in computer performance. However, this complex geometry could be simplified using a nanoporous film to investigate stresses resulting from treatment of surfaces with 0–10-μm thicknesses.
Results: The study results indicated that the stresses were more uniform in implants coated with nanoporous films that underwent surface treatments, and the stresses were reduced with increasing film thickness.
Conclusion: These nanoporous surface modifications can be potentially beneficial in reducing the stress in dental implants.

1. Introduction

Dental implant treatments have been widely applied in clinical cases for many years.[1–3] A dental implant is one of the most important load-bearing replacements that is responsible for normal masticatory activities and speech.[4] Osseointegration is an important process in dental-implant treatment. Titanium (Ti), either pure or alloyed, has been used in various medical applications because of its corrosion-resistance property and outstanding mechanical performance.[5–7]

Ti has been recognized as a reliable material for restoration of the edentulous areas in the mandible; however, approximately 6 months are required for osseointegration with a mean direct bone-to-implant contact height > 50%.[8] In addition, the success rate of clinical operation is also dependent on bone quality.[9,10] Various modifications of the Ti surfaces have been explored to achieve more rapid osseointegration and higher success rates. Surface-modification methods, such as anodic oxidation, microarc oxidation, and acidic and alkaline etching, change not only the surface geometry but also the chemistry of the implant. Mechanical or chemical properties are thus important factors in maintaining the overall biological bone response to the implant surfaces.[11–13]

Commercially available screw-type dental implants, manufactured from Grade IV Ti, with an external diameter of 4.5 mm and a length of 11.0 mm, were used in this study. Biocompatible sandblasted, large-grit, acid-etched (SLA) specimens with high wettability and a thick TiO_2 film (SLAffinity) were used in the surface treatment of Ti-one 101 (Hung Chun Bio-S Co., Ltd, Kaohsiung, Taiwan) dental implants.

Conflicts of interest: All contributing authors declare no conflicts of interest.

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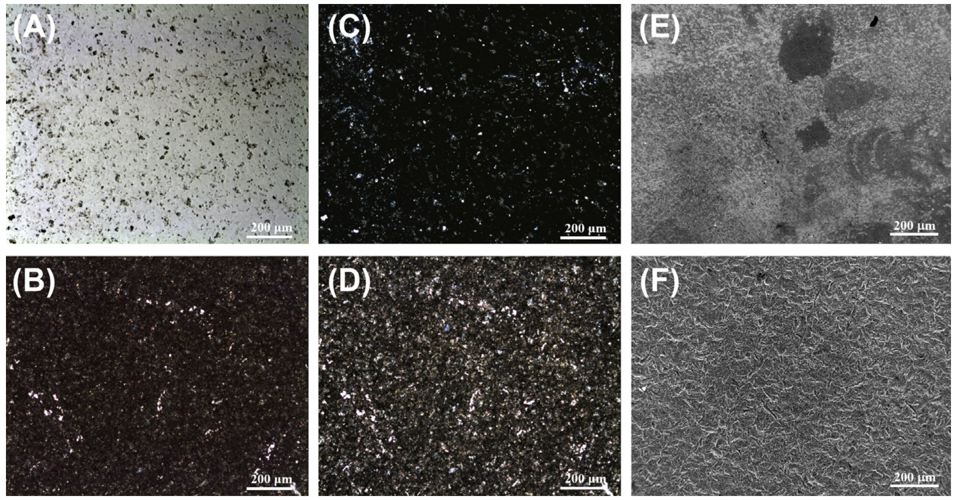

Figure 1 Optical microscopy (OM) bright fields of the (A) M-Ti. (B) SLAffinity-Ti implants and dark fields of the (C) M-Ti. (D) SLAffinity-Ti implants and scanning electron microscope images of the (E) M-Ti and (F) SLAffinity-Ti implants. Surface topographies were qualitatively characterized by OM and scanning electron microscopy.

The finite-element (FE) method is an effective technique that can be applied to quantify stress distributions in dental implants, and it also has been used to study biomechanical behavior in several parts of the body, such as the spine, hip, knee, temporomandibular joint, and tooth, as well as in the prismatic enamel implant.[14–17] Several researchers have developed FE dental-implant models; however, few have used such models to investigate the effects of nanosurface treatment on the bone–implant interface. In this study, simulations of Ti-one 101 dental implants with nanosurface treatments were performed for different thicknesses of the oxide film to determine the stress distributions.

2. Methods

2.1. SLAffinity-Ti specimens

To prepare SLAffinity-Ti specimens, samples of pure Ti were grit blasted with Al_2O_3 particles, acid etched in a solution of HCl/H_2SO_4,

Figure 2 Load and boundary conditions applied to the three-dimensional finite-element method models. The bottom of the model was fixed and the implants were loaded with forces of 17.1 N (F_L), 23.4 N (F_M), and 114.6 N (F_A) in the lingual, mesiodistal, and axial directions, respectively.

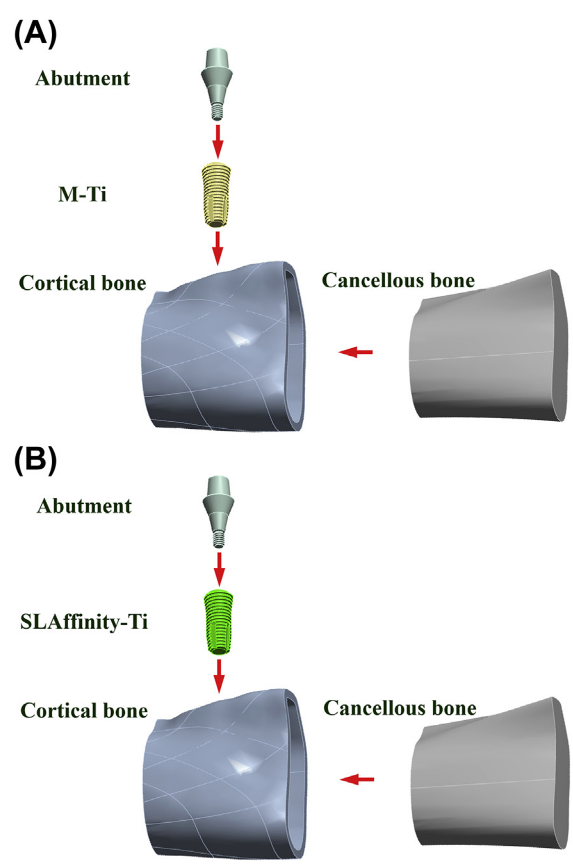

Figure 3 Complete assembly of (A) M-Ti and (B) SLAffinity-Ti implants and the host bone in the jaw.

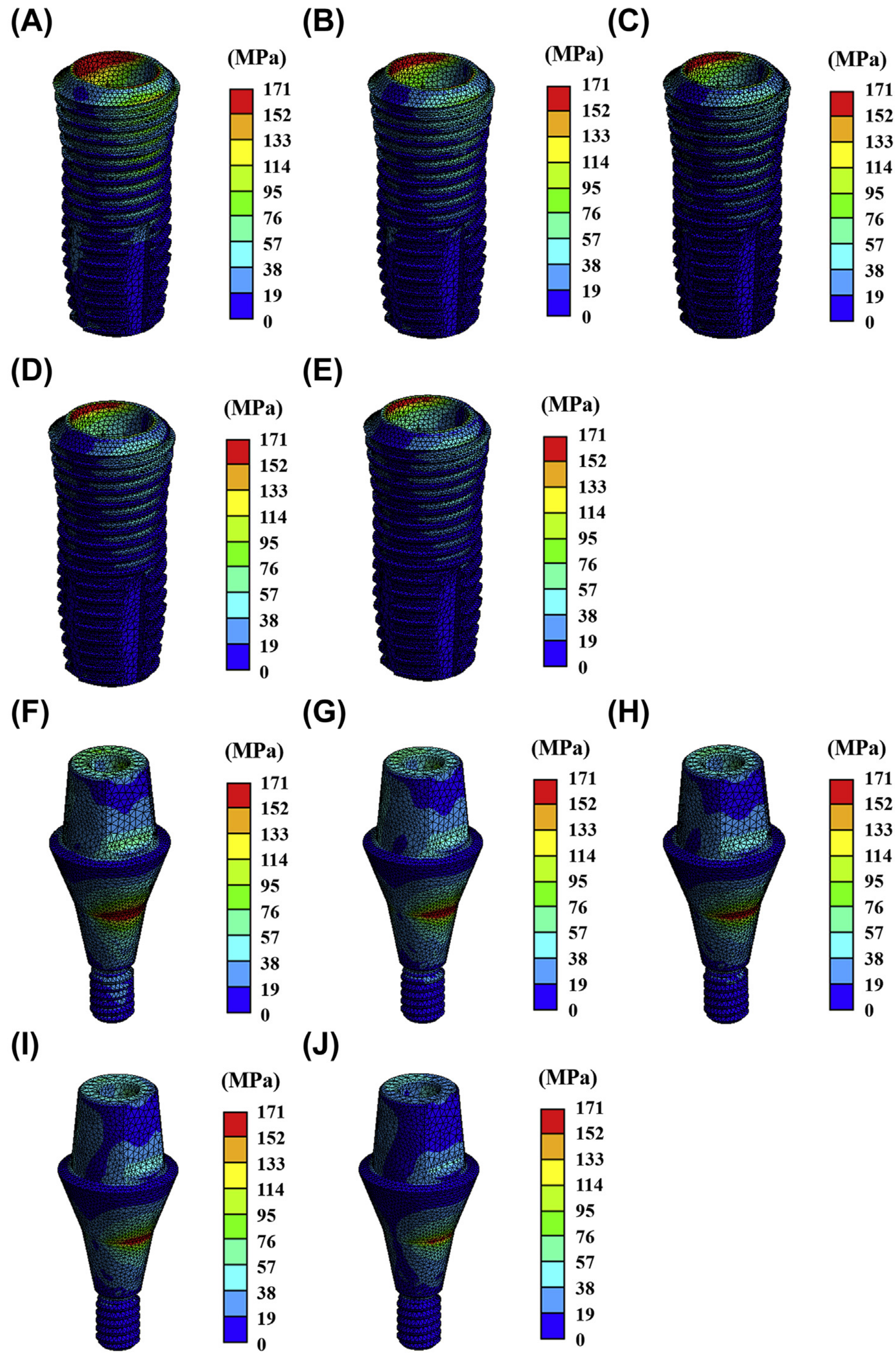

Figure 4 Von Mises stress distributions in dental implants of the (A) control, (B) 100-nm, (C) 500-nm (D) 1 μm, and (E) 10-μm oxide-film groups and those in the abutments of the (F) control, (G) 500-nm, (H) 100 nm, (I) 1-μm, and (J) 10-μm oxide-film groups. The maximum value of the von Mises stress was observed at the interface between the implant and the bone at the first screw location.

and treated by electrochemical functionalization as described earlier.[5] Prior to surface characterization and *in vitro* experiments, test specimens were rinsed with deionized water and then air dried. Surface topographies were qualitatively characterized by optical microscopy (BX51; Olympus, Tokyo, Japan) and scanning electron microscopy (SEM; JEOL JSM-6500F, Tokyo, Japan) as shown in Figure 1. More detailed surface topographies including the nano-level porous structure generated within the micro-level porous structure were observed by SEM.

2.2. Computer tomography

Three-dimensional (3D) FE models of a human mandible, including the cortical and cancellous bones, were obtained from computer tomography (CT) images (Light Speed, GE, Block Imaging International, Inc., Holt, Michigan, USA). For geometry acquisition, a set of images were obtained from CT slices of the mandible and an edge detection algorithm was run using the AVIZO 6.2 (Internet Securities, Inc., USA) program to distinguish the cortical bone from the

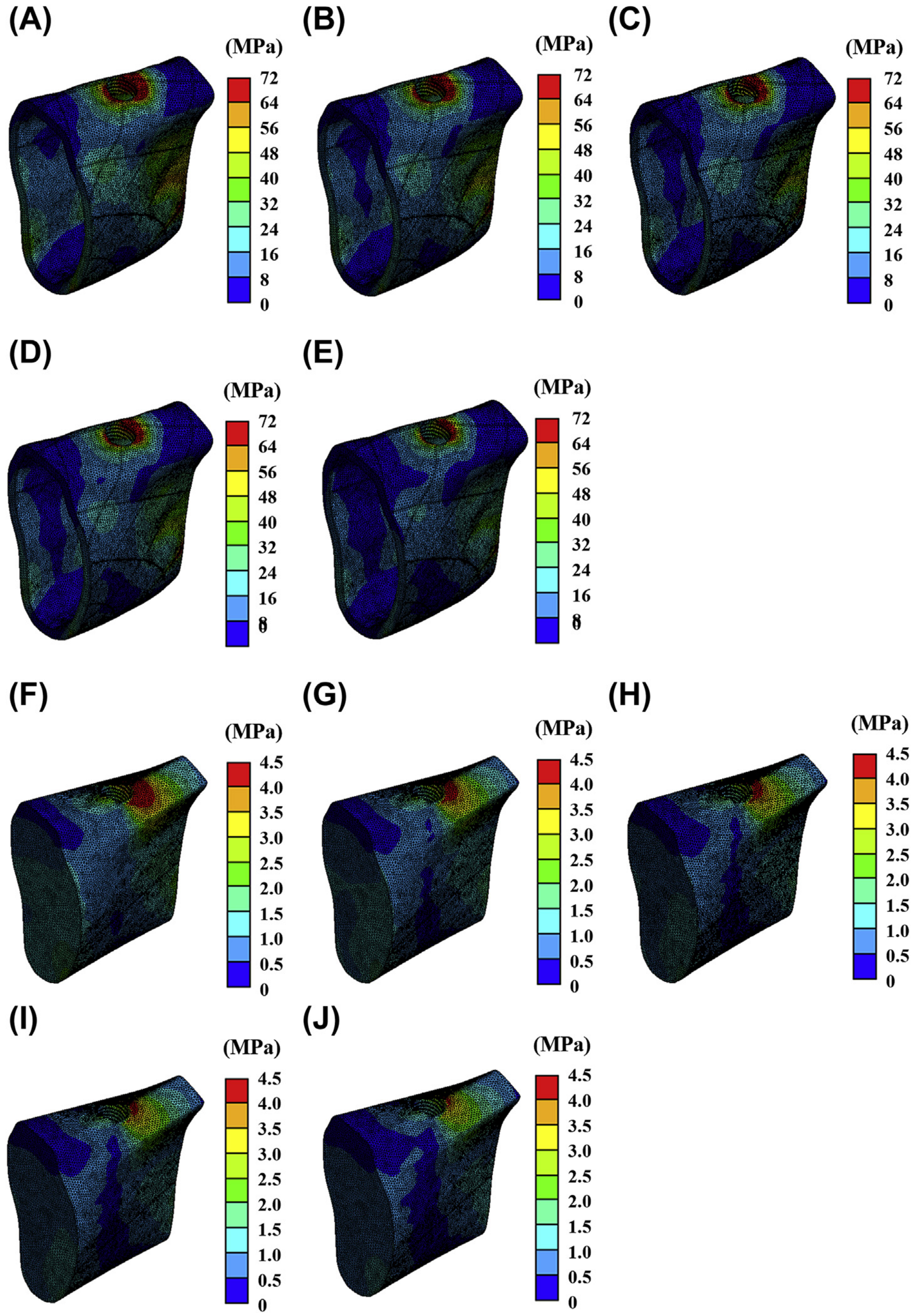

Figure 5 Von Mises stress distributions in the cortical bones of the (A) control, (B) 100-nm, (C) 500-nm (D) 1-μm, and (E) 10-μm oxide-film groups and those in the cancellous bones of the (F) control, (G) 500-nm, (H) 100-nm, (I) 1-μm, and (J) 10-μm oxide-film groups. The stresses were more uniformly distributed in bones coated with nanoporous films groups, and the stresses reduced with increasing film thickness.

cancellous bone and to detect the various boundary components of the mandible.

2.3. FE analysis

This study focused on investigating homogeneous and isotropic behaviors. Von Mises stress for the dental implants was calculated using the ANSYS 12.1 (ANSYS, Inc., Canonsburg, PA, USA) program. The linear elastic properties of the structures were also calculated. The mesh convergence was set at 3% for all models. Mesh refinement was used for important interfaces such as the implant–abutment interface. The average number of nodes and elements in each model was 10,205 and 5142, respectively. A tetrahedral element with 10 nodes was used, that is, each side had a midside node and each node had three degrees of freedom.[18] The model featured a threaded implant, and biomechanical material properties as reported in previous literature were considered.[19] Young's modulus of the SLAffinity film, determined using a TriboLab nanoindenter (Hysitron Inc., Eden Prairie, MN, USA) with a Berkovich diamond indenter tip (radius: 150 nm), was 43.65 GPa.

3. Results

With respect to boundary conditions, the bottom of the model was fixed and the implants were loaded with forces of 17.1 N (F_L), 23.4 N (F_M), and 114.6 N (F_A) in the lingual, mesiodistal, and axial directions, respectively (Figure 2). The nanoporous geometry was reproduced in the 3D FE dental-implant models to investigate the stress distribution in implants with 0-nm (M-Ti), 100-nm (SLAffinity-Ti-1), 500-nm (SLAffinity-Ti-2), 1-μm (SLAffinity-Ti-3), and 10-μm (SLAffinity-Ti-4) thick oxide films (Figure 3).

At different thicknesses, the maximum stress varied from 3.25 MPa to 168.20 MPa. The stress in implants with surface treatment was less than that in the implants without surface treatment (control group). Figure 4 shows the stress distributions of the implants and abutments for different thicknesses of the oxide film. The maximum value of the von Mises stress was observed at the interface between the implant and the bone at the first screw location, and the highest values of the stress in the untreated group and in the 500-nm coating group were 168.20 MPa and 148.72 MPa, respectively, and the stress decreased with increases in coating thickness. In the abutment, the maximum von Mises stress was 166.99 MPa in the untreated group; this also decreased with increases in coating thickness. The stress patterns in both models were similar to each other. By contrast, bone stresses in the surface surface-treatment group decreased slightly and there were no significant differences among the groups of with different coating thickness as shown in Figure 5. Observation of stresses from the top to the bottom of the dental implant revealed that the maximum stress occurred at the 2-mm position, in close proximity to the first screw (Figure 6). Stress decreased with increasing path distance, but increased because of a fillister at the 6-mm position as well as due to the build-up of certain stresses accumulated at the bottom of the implant. Results of FE analysis (FEA) indicated that stresses transferred more uniformly in implants subjected to nanoporous surface treatments.

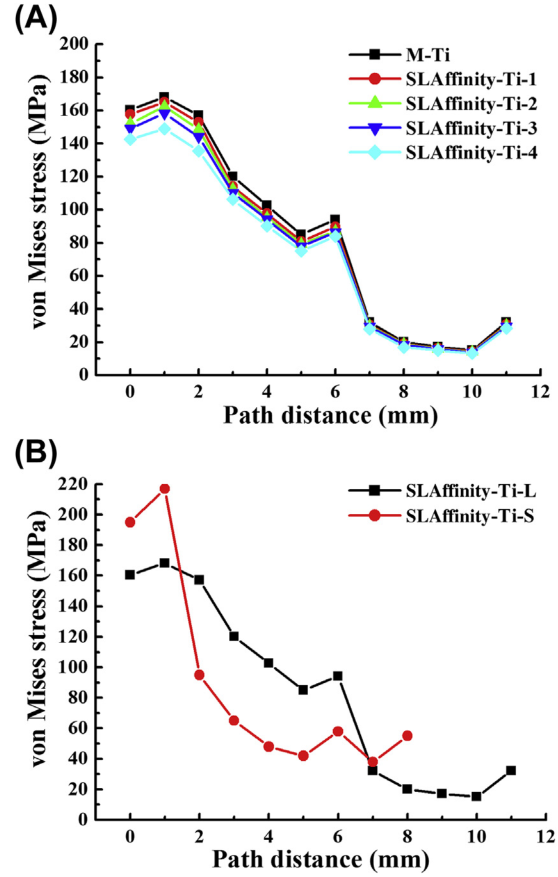

Figure 6 Path plots of stresses in (A) different oxide-film thicknesses of dental implants, and (B) different lengths of dental implants. Stress decreased with increasing path distance and stress concentrations are significantly higher in shorter implants.

4. Discussion

FEA has been applied successfully in various fields of biomechanics. It is possible to approximate a real object by introducing various biomechanical behaviors into the models.[20] It is also practically possible to quantify the internal stresses in the models, and it is simple to change the magnitude and direction of any force to simulate different situations. The von Mises stresses, shear stresses, deformations, and displacements can thus be easily observed. To obtain accurate results by FEA, two important processes to be considered are "converging" and "reinforcing" of the mesh, which allow the model to reproduce the actual object more accurately. In this study, four mesh processes were carried out to validate the model, demonstrating that acceptable element distortion can be achieved by a refinement process.

The FEA results are represented as stress distributions within these 3D structural models. These stresses may occur as compressive stress, tensile stress, shear stress, or a stress combination known as the equivalent von Mises stress. Von Mises stress describes the entire stress field and is widely used as an indicator of damage situations. With FEA simulations and various *in vitro* studies, it is difficult to extrapolate the results directly to a real situation. The structural models were all assumed to have isotropic, homogeneous, and linear elasticity, irrespective of whether the testing is static or dynamic. The inherent limitations should thus be kept in mind.

Surface treatment is one of the most important factors for successful osseointegration in dental implants because ingrowth of bone into a porous surface is the primary method for fixation. Porous-surface and machine-threaded dental implants have been compared in a previous study.[21] The results of that study indicated that the maximum value of the stress in the bone because of the threaded dental implants was approximately two times greater than that predicted for the porous-surface implants. The stress field of the porous-implant model at the bone–implant interface was also predicted to be more uniform than for the threaded-implant model, suggesting that the implants with a porous structure had more uniform stress patterns at the interface between the bone and the dental implant, which is supported by our findings. Bone loss was observed around dental implants of various designs, and a major possible cause of this bone loss was attributed to stress.[22] Based on the results of FEA of porous-coated implants, a stress equal to 1.6 MPa was determined to be sufficient to avoid bone loss because of disuse atrophy in the mandibular premolar region. The relationship between elastic–plastic deformation, layer thickness, and porosity was found to follow the Ou–Cheng equation, which was calculated using SPSS regression analyses in our previous study.[23] If the thickness and porous percentage of the oxide film was were measured, it is possible to predict Young's modulus.

These stresses caused by different lengths of dental implants were compared, specifically between a length of 11 mm for SLAffinity-Ti-L and a length of 8 mm for SLAffinity-Ti-S. The larger stress was found in SLAffinity-Ti-S as shown in Figure 6B. The maximum stress in SLAffinity-Ti-S was approximately 1.3 times higher than that observed in SLAffinity-Ti-L. Moreover, the phenomenon of increasing stresses was observed at the region of the profile groove in both implants. These results indicate that stress concentrations are significantly higher in shorter implants; however, the stresses decrease quickly with increasing path distance from the top of implants.

In contrast to nonporous-surface treatments, porous-surface treatments may contribute to enhancement of the surface roughness because of microstructures or nanostructures.[24,25] These results support the hypothesis that the energy of the implant surfaces is important for initial adhesion of proteins and cells.[26] Both the proliferation rates and the differentiation levels of the osteoblast cells were highest for the coated surfaces as opposed to the non-coated ones. It is thought that physiochemical modifications by CaP precipitation may affect various osteoblast cell responses to the coated surfaces immersed in modified simulated body fluids. The release of Ca^{2+} and PO_4^{3-} from the calcium phosphate precipitate increases the hydration of the Ti surface, affecting protein adsorption and subsequent cell responses.[27] Surface treatment may thus enhance the interaction between implant and bone in the biological environment, consequently improving bone healing and osseointegration of the treated implant.

The results of this study confirmed that stresses transferred more uniformly in the dental implants with nanoporous structures and that the stresses decreased with increasing film thickness, and this information may contribute to elucidating the behavior of dental implants with nanoporous-surface treatments.

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