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Mini Review

Recent advances in the influence of SLA implant surface topography on osseointegration: a review

Yibo Liu,[1,5] Hanqi Su,[1] Junjiang Hao,[1] Yucheng Su[2-4]

[1]Beijing CRS Medical Device Co., Ltd, China

[2]Beijing Citident Hospital of Stomatology, China

[3]Beijing Implant Training College (BITC), China

[4]Dental Implant Center, Peking Union Medical College Hospital, Chinese Academy of Medical Sciences, China

[5]Stomatology College of Jiamusi University, Jiamusi University, Jiamusi, Heilongjiang Province, China

***Correspondence:** Junjiang Hao , Beijing CRS Medical Device Co., Ltd, Beijing 102600, China, Email Haojunjiang@caresimplant.com

Yucheng Su, Beijing Citident Hospital of Stomatology, Beijing Implant Training College (BITC), Dental Implant Center, Peking Union Medical College Hospital, Chinese Academy of Medical Sciences, China Email Yuchengsu@163.com

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Abstract

The long-term stability of dental implants depends on high-quality osseointegration, and implant surface topography is regarded as one of the most critical and controllable determinants. Sandblasted, large-grit, acid-etched (SLA) surfaces have been widely adopted in clinical practice; however, the differences between a conventional single-scale micro rough topography and hierarchical architectures created by superimposing nanoscale features on this micro rough base, particularly with respect to osteogenesis and osteoimmunity, have not yet been systematically reviewed. Against this background, the present review focuses on the influence of SLA surface topographical characteristics on osseointegration, and summarizes recent advances regarding SLA and its micro/submicron- and micro/nanoscale hierarchical structures in regulating osteogenic cell behavior and macrophage responses. Conventional SLA surfaces typically exhibit a moderately micro rough topography, with Sa values of approximately 1–2μm. Building additional submicron or nanoscale features on this micro rough base further increases surface area and morphological complexity, while largely maintaining cell proliferative activity and enhancing cell adhesion, osteogenic differentiation, and mineralization. Emerging evidence also indicates that such hierarchical structures can amplify pro-osteogenic signaling by activating pathways involving autophagy and exosomes, and, in some designs, confer additional antibacterial effects, thereby accelerating osseointegration through the synergistic contributions of microscale mechanical interlocking, nanoscale cell stimulation, and osteoimmunity modulation.

Keywords: dental implants, sandblasted, large-grit, acid-etched (SLA), surface topography, micro-Nano-hierarchical structures, osteogenesis, osteoimmunology

Introduction

The long-term success of dental implants is highly dependent on stable and durable osseointegration, and surface topography is regarded as one of the key modifiable determinants of bone–implant interface quality.[1–3] Systematic reviews, together with preclinical and clinical studies, consistently indicate that, when material properties, loading conditions, and patient-related factors are comparable, converting a machined smooth surface to a moderately micro rough surface (such as the classical SLA) can markedly increase early bone-to-implant contact (BIC) and implant survival rates.[1–3] Such surfaces, characterized by 1–3μm-scale micro-pits and a moderate roughness, facilitate thrombus formation and the spreading of adhesive proteins, thereby promoting subsequent osteogenic cell adhesion and mechanical interlocking at the interface.[2,3]

However, SLA systems characterized solely by micrometer-scale roughness have increasingly revealed a limitation of being “close to a plateau without a true breakthrough.” In a systematic review of implants with nanoscale features, Komatsu et al.[4] reported that classical SLA, TiUnite, and other micro rough surfaces in patients with adequate bone volume achieve 5–10-year survival rates generally exceeding 90%, with BIC values remaining at approximately 50–75%, suggesting that conventional micro rough surfaces may have reached a performance plateau and can hardly be pushed closer to complete bone encasement.[4] Against this background, an important direction for further improving the quality of osseointegration is to superimpose finer submicron and nanoscale features on the micro rough base, thereby preserving microscale mechanical interlocking while enabling more precise regulation of protein adsorption and cellular behavior.[4,5]

Within this conceptual framework, the present review focuses on the different hierarchical surface morphologies generated by SLA treatment-from single-scale micro roughness to combined micro/submicron and micro/nanostructured surfaces-and systematically summarizes their effects on osteogenesis-related cells. It further attempts to provide an integrated analysis of the current advances and limitations in implant surface design from the perspective of "microscale mechanical anchorage plus nanoscale cellular stimulation."

SLA surface topography and hierarchical structures

Overview of SLA and related surface treatments

Clinically, commonly used titanium implant surfaces include machined smooth surfaces, sandblasted surfaces, acid-etched surfaces, and sandblasted, large-grit, acid-etched (SLA) surfaces.[1-7] Machined surfaces are characterized by turning marks, exhibit a regular profile and low roughness, and are usually classified as smooth or minimally rough.[1,6]

Purely sandblasted surfaces are typically produced using Al_2O_3 or TiO_2 particles, which generate 10–50μm impact craters and a plastically deformed surface layer, markedly increasing Ra/Sa and the developed surface area but often leaving sharp peaks and valleys as well as residual abrasive particles.[2-8] The study by Iwaya et al.[9] demonstrated that, after single-step etching with HCl or H_2SO_4, polished titanium surfaces develop relatively homogeneous corrosion pits larger than 0.5μm, whose depth and morphology are strongly dependent on the type of acid and processing parameters.[9] The SLA process combines the advantages of sandblasting and acid etching: sandblasting creates large 10–50μm craters that can be regarded as primary pores, whereas subsequent double acid-etching produces 1–3μm micro-pits on the crater walls and bottoms, which can be regarded as secondary pores.[2,7,8]

In recent years, modified SLA procedures have largely been based on the classical "sandblasting plus double acid-etching" scheme. By adjusting the HCl/H_2SO_4 ratio and acid concentration or by adding further chemical treatments, these approaches refine the secondary pores and introduce even smaller-scale features, such as nanosheets and nanoparticles, on the walls of the primary craters without altering their overall geometry.[10-13]

Quantitative descriptors of surface morphology

Height-based roughness parameters such as Sa and Ra

For SLA and related surfaces, the average height-based roughness parameters Ra (one-dimensional line profile) and Sa (two-dimensional areal topography) remain the most commonly reported quantitative descriptors.[1-6] According to Sa-based classification, implant surfaces are typically categorized as smooth or minimally rough ($Sa<0.5$μm), moderately rough ($Sa\approx1–2$μm), and rough ($Sa>2$μm), among which moderately rough surfaces have shown higher BIC values and better long-term crestal bone stability in both animal and clinical studies.[1-14]

Developed interfacial area ratio (Sdr) and three-dimensional complexity

Beyond height-based parameters, the developed interfacial area ratio (Sdr) has become an increasingly important descriptor for evaluating hierarchical SLA surfaces. Sdr reflects the percentage increase of the true surface area relative to its projected area and is jointly influenced by the number of peaks and valleys, local slope, and pit density.[1-8] Studies comparing various sandblasted, acid-etched, and SLA surfaces have shown that, even when Sa values are similar, Sdr remains substantially higher for sandblasted plus double acid-etched surfaces than for surfaces treated by sandblasting or acid etching alone, indicating a denser micro-porosity and a more complex three-dimensional morphology.[2,3]

Different hierarchical architectures: from single-scale microroughness to micro/nano-composite structures

Single-scale micro rough SLA surfaces

Classical SLA surfaces are typically characterized by densely distributed 1–3μm micro-pits along the thread valleys and sidewalls, with the interiors of the larger craters displaying relatively smooth micro-pore walls and only limited submicron features.[2-8] Microscopic analyses of implants from multiple manufacturers suggest that, although such "single-scale micro rough" SLA surfaces exhibit a relatively simple morphology, they are sufficient to significantly enhance BIC and torque removal strength, and they have demonstrated reliable survival rates in both animal experiments and long-term clinical follow-up.[1-16]

Micro/submicron and micro/Nano hierarchical structures

Building additional micro/submicron or micro/nano-scale features on the conventional SLA micro-pitted surface has become one of the main directions of surface modification in recent years. Common strategies include applying H_2O_2/HCl treatment, alkali-heat treatment, or hydrothermal calcification after sandblasting plus acid-etching, thereby generating 50–300nm Nano sheets, nanoparticles, or Nano pores on the walls of the 1–3μm micro-pits and ultimately forming a hierarchical topology of "micrometer-scale craters plus nanoscale structures".[12-18]

Risk of over-etching: transition from hierarchical to single-scale structures

It should be emphasized that the formation of hierarchical structures is subject to a pronounced "window effect." When the parameters of acid-etching or thermochemical treatment are set too low, it is difficult to generate stable submicron or nanoscale features within the micro-pits. Conversely, excessively high acid concentration, temperature, or treatment time can lead to surface over-etching, blunting of pit walls, and even local delamination, causing the originally distinct primary and secondary pores to become blurred and the surface to degenerate into a rough but non-hierarchical, single-scale structure.[10-19]

Effects of hierarchical SLA surface topography on osteogenesis

Protein adsorption and the initial interface

Multiscale roughness directly influences early thrombus formation and protein adsorption. Compared with turned or mildly sandblasted surfaces, moderately rough SLA surfaces more readily support the formation of a dense fibrin network and a stable blood clot. Fibrin fibers can span and partially fill the micrometer-scale pits, thereby enhancing the mechanical stability of the clot on the implant surface.[1-,9] Superimposing nanoscale features on this micro rough base further increases the effective surface area and markedly reduces the contact angle.[3-13] These changes in topography and wettability jointly shape the "first layer of the protein carpet." On hierarchical micro/Nano surfaces, fibronectin (FN) tends to accumulate along the pit edges and within the transition zones of the Nano network, and platelet adhesion and activation are correspondingly increased.[6-18] Three-dimensional analyses of micro–Nano topography have further suggested that micrometer-scale features primarily stabilize the blood clot and the extracellular matrix (ECM) protein scaffold,

whereas nanoscale features modify protein adsorption conformation and charge distribution, thereby providing more exposed RGD sequences and strengthening α5β1 and other osteogenesis-related integrin-mediated adhesion at the molecular level.[18] Thus, the micrometer-scale pits of SLA surfaces provide the quantitative foundation, whereas the superimposed nanoscale textures predominantly determine the qualitative properties of the adsorbed protein layer.

Osteoblastic cells and BMSCs

Cell adhesion, spreading morphology, and cytoskeleton

On purely micro rough SLA surfaces, the initial number of adherent osteoblastic cells and bone marrow-derived mesenchymal stem cells (BMSCs) is generally higher than on turned surfaces, and cell morphology shifts from a flat, spread configuration to a star-like, highly protrusive pattern following the edges of the pits and the thread sidewalls.[2-7] Microscopic observations reveal that osteoblastic cell lamellipodia and filopodia can span multiple pits on SLA surfaces, forming bridge-like adhesions at the pit margins, and that cytoskeletal stress fibers are predominantly aligned along the edges of the pits.[2,3] Superimposing nanoscale structures on the micro rough SLA pits further remodels cell morphology and cytoskeletal organization. On hierarchically mixed micro/Nano-textured surfaces, MC3T3-E1 cells adopt an elongated spindle-like or multipolar morphology, with abundant lamellipodia and filopodia extending deep into the Nano network on the pit walls; focal adhesions align along the edges of the micro-pits and connect with the nanoscale textures to form continuous belt-like structures.[13,17] These findings support the notion that micrometer-scale pits provide macroscopic mechanical interlocking and cellular "anchor points," whereas nanoscale features increase the cell–material contact interface and the number of adhesion sites, thereby further strengthening cytoskeletal remodeling and resistance to mechanical perturbation.[5-20]

Proliferation, ALP activity, osteogenic gene expression, and mineralization

Over time, the effects of SLA and its micro/nano-derived surfaces on proliferation and differentiation generally follow a pattern of "early equivalence and later enhancement." Some studies have reported that early (1–3d) proliferation of MC3T3-E1 cells on conventional SLA surfaces is slightly lower than on polished controls, whereas by day 7 alkaline phosphatase (ALP) activity and the expression of RUNX2 and COL1A1 are already markedly upregulated.[17] When an additional alkali-heat treatment is applied on this basis to generate a micro/Nano topology, cell viability and proliferation at 1–3d are comparable to those on SLA surfaces, whereas ALP, OCN, and OPN expression and the area of calcium nodules at 7–14 d are significantly increased.[13,17] Taken together, these data suggest that micrometer-scale structures mainly enhance baseline osteogenesis through increased roughness and mechanical interlocking, whereas superimposing nanoscale features onto a similar or slightly higher roughness background can markedly potentiate ALP activity, osteogenic gene expression, and mineralization responses without substantially compromising cell proliferation.[3-20]

Conclusion

Current evidence indicates that moderately micro rough SLA surfaces, represented by sandblasted, large-grit, acid-etched topographies, achieve a favorable balance between mechanical interlocking and bone biology and constitute one of the most extensively documented implant surfaces in clinical practice.[1-16] Building on this micro rough foundation by superimposing nanotubes, Nano networks, or nanoparticle-based structures to construct a micro/Nano hierarchical topology can further increase Sdr and the density of active sites, and enhance osteoblastic adhesion and differentiation as well as "amplifier" pathways such as autophagy and exosome signaling. In animal models, these modifications have been shown to improve early BIC and bone volume fraction.[5-21]

However, caution is warranted because approaches and parameters for nanoscale modification are highly heterogeneous, and overly rough or unstable coatings may increase the risk of inflammatory responses or particle detachment, while long-term clinical data in this area remain relatively limited.[4-22] Future studies should, within a unified system of three-dimensional morphological and chemical characterization, systematically delineate the dose–response relationships linking micrometer-scale roughness, nanoscale size/density, and osteogenic/immune phenotypes, thereby defining parameter windows suitable for clinical application. In parallel, prospective studies in high-risk populations such as patients with osteoporosis or diabetes are needed to verify the real-world benefits of "immune-friendly" micro/nano SLA surfaces in complex bone environments.[4-24]

Overall, SLA should not be regarded merely as a fixed processing technique but rather as a micro/Nano hierarchical platform that can be finely tuned. By simultaneously considering mechanical anchorage, pro-osteogenic effects, and immune modulation on this platform, it may be possible to design a new generation of implant surfaces tailored to different patient profiles and loading demands, thereby achieving faster and more reliable osseointegration.

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Conflicts of interest

Authors declare that there is no conflict of interest.

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