



CHEMICAL VERSUS PHYSICAL SURFACE MODIFICATION OF TITANIUM DENTAL IMPLANTS: A COMPARATIVE REVIEW OF SANDBLASTED, LARGE-GRIT, ACID-ETCHED (SLA) AND FEMTOSECOND LASER-ABLATED SURFACES

Dr.Sushmitha S¹, Dr.Saishree², Dr.H.Annapoorni³, Dr. D. Narmadha⁴

¹Postgraduate, Meenakshi Ammal Dental College and Hospital, Chennai, Tamil Nadu, India. ORCID ID: <https://orcid.org/0009-0001-4595-919X>

²Corresponding Author, Postgraduate, Meenakshi Ammal Dental College, Chennai, Tamil Nadu, India. ORCID ID: 0000-0002-5660-2938

³ MDS, PhD, Professor and Head of the Dept. of Prosthodontics, Meenakshi Ammal Dental College and Hospital, Chennai, Tamil Nadu, India. ORCID ID: <https://orcid.org/0000-0003-1175-5882>

⁴ Assistant Professor, Meenakshi Ammal Dental College and Hospital, Chennai, Tamil Nadu, India. ORCID ID: <https://orcid.org/0009-0004-3772-1597>.

Received:- 06/07/2026

Revised:- 20/09/2026

Accepted:- 02/10/2026

Published:- 29/10/2026

Abstract

Surface topography governs the rate and quality of osseointegration of titanium dental implants. The sandblasted, large-grit, acid-etched (SLA) surface represents the established chemical-subtractive paradigm and remains the clinical benchmark²¹[SP1.1], whereas femtosecond (fs) laser ablation has emerged as a physical-subtractive alternative that promises deterministic topographic control, superior surface purity and a thickened, crystalline oxide without the mechanical penalties of acid etching. This review critically compares the two paradigms across four domains: surface metrology and chemistry, In-vitro biological response, In-vivo biomechanical fixation and histomorphometry, and clinical implications. Evidence indicates that SLA reliably produces a moderately rough (Sa 1–2 µm) surface with high bone-to-implant contact and more than 95% five-year survival, but is constrained by residual alumina embedding, hydrogen-induced embrittlement and stochastic topography. Femtosecond laser processing generates hierarchical micro/nano structures (laser-induced periodic surface structures, LIPSS) with a five-fold thicker oxide, controllable anatase/rutile content, contaminant-free chemistry and markedly enhanced osteoblast adhesion, at the cost of frequently hydrophobic wettability, limited long-term in vivo data and a modest fatigue reduction. The strongest bone-bonding biomechanical data derived from laser-structured (predominantly nanosecond) surfaces, while fs-specific evidence remains largely in vitro and material-scientific. It is concluded that fs-laser ablation is a credible, and in several respects superior, engineering platform whose osteogenic and antibacterial promise is not yet matched by clinical validation. Rational, scenario-based selection guidelines and future directions toward “smart” dual-function surfaces are proposed.

Keywords: Dental implants; Osseointegration; Surface topography; Sandblasted acid-etched; Femtosecond laser; Titanium.

Introduction

The clinical success of endosseous dental implants depends on osseointegration, defined as a direct structural and functional connection between ordered living bone and the surface of a load-carrying implant. Following the foundational demonstration that commercially pure titanium screws achieve a durable, direct bone anchorage when material, design, surface condition, bone status, surgical technique and loading are jointly optimised, implant surfaces rather than bulk composition have become the principal variable manipulated to accelerate and strengthen bone fixation.¹ Titanium interacts with biological fluids within seconds of placement; the resulting protein layer, cellular recruitment and mineralisation are all modulated by surface composition, energy, wettability and roughness, which are interrelated determinants of the biological response.^{2,23}

Surface roughness is conventionally resolved at three scales. Macro-roughness (millimetres to tens of microns) governs primary mechanical interlocking but raises the risks of ionic leakage and peri-implantitis; micro-roughness (1–10 μm) maximises interlocking between mineralised bone and the surface; and nano-roughness guides protein adsorption and osteoblast adhesion. A moderately rough window of Sa 1–2 μm is widely accepted as optimal, with smoother surfaces showing weaker fixation and rougher surfaces increasing biological risk.^{2,20,27} Within this framework two philosophically distinct routes to the ideal surface have developed. The chemical-subtractive route—epitomised by the sandblasted, large-grit, acid-etched (SLA) surface—combines grit blasting with strong-acid etching to create a stochastic micro/macro texture.⁴ The physical-subtractive route uses focused laser energy to remove material with spatial precision; in its ultrafast femtosecond (fs) form it can inscribe deterministic, self-organised topographies while depositing negligible heat into the surrounding lattice.¹⁴

The central question of this review is whether fs-laser-treated surfaces can equal or exceed the osseointegration and biomechanical stability of the SLA gold standard while offering superior surface purity, reduced fatigue risk and programmable topography for control of the biological—including bacterial—response. To address this, the peer-reviewed literature is synthesised across four objectives: (i) quantitative surface metrology and chemistry; (ii) In- vitro biological response; (iii) In- vivo biomechanical fixation and histomorphometry; and (iv) clinical implications, followed by an evidence-based synthesis and projection of future directions. This is a critical narrative review rather than a systematic review; studies were drawn from a curated pool of peer-reviewed reports on titanium implant surface modification and interpreted comparatively rather than through a formal search protocol.

Methods

Peer-reviewed original studies, reviews addressing titanium implant surface modification were examined and grouped by their primary contribution: surface characterisation, in vitro cellular response, in vivo/animal biomechanics and histomorphometry, and clinical outcomes. Reports were compared according to the four objectives above, with priority given to studies providing quantitative metrology (Sa, Sdr, Sdq, contact angle, oxide thickness, crystalline phase), biological endpoints (protein adsorption, cell adhesion, alkaline phosphatase activity, mineralisation, macrophage response), biomechanical endpoints (removal torque, push-out strength, bone-to-implant contact) or clinical endpoints (survival, marginal bone level, peri-implant health). Because the two paradigms are rarely tested head-to-head, comparisons are necessarily drawn across studies with differing models, and this limitation is made explicit throughout.²⁵

Surface Metrology And Chemistry

Roughness and topographic architecture:

SLA surfaces are produced by blasting with large alumina (or corundum) grit followed by etching in hot HCl/H₂SO₄, yielding overlapping macro-pits from blasting and superimposed micro-pits (0.5–2 μm) from etching. Reported roughness clusters in the moderately rough band, with Sa/Ra values typically 1–2 μm and cleaned surfaces reaching Ra $\approx$ 2.15 μm after etching.⁶ Dual acid etching alone can drive Ra as high as 3.65 μm under aggressive protocols, confirming that the etch step is the dominant contributor to fine texture.⁹ The resulting topography is, however, stochastic: feature size, spacing and orientation cannot be prescribed, and roughness co-varies uncontrollably with chemistry.²⁰

Femtosecond laser ablation removes material through non-thermal, multiphoton-driven breakdown, enabling deterministic patterns and self-organised laser-induced periodic surface structures (LIPSS). Reported architectures span micro-columns and micro-holes overlaid with nano-ripples and sub-wavelength ripples—length scales unattainable by acid etching.^{15,16,24} On implant-grade material, LIPSS surfaces reach Sa up to 2.66 μm versus 0.72 μm for comparator SLA in the same study, and fs texturing of porous titanium produces micro-columns decorated with LIPSS that raise roughness while remaining tunable through porosity.^{18,15} Critically, the additional design freedom (Sdr, Sdq—developed area and slope) is where fs processing most

clearly exceeds SLA: fs patterning can target surface slope and developed area directly rather than inheriting them stochastically as SLA does.¹⁴

Wettability and surface energy:

Wettability is the domain in which the paradigms most sharply diverge, and in which SLA presently holds an advantage. Standard SLA is hydrophobic owing to hydrocarbon adsorption during air storage (contact angle $\sim 138^\circ$), a limitations overcome by the chemically modified hydrophilic SLA (SLActive), produced by nitrogen rinsing and storage in saline to preserve high surface energy and near- 0° contact angle.^{2,5,22} Hydrophilic surfaces promote fibrin adhesion, osteoblast migration and accelerated early healing.⁵ Femtosecond LIPSS, by contrast, frequently render titanium markedly hydrophobic or even superhydrophobic (contact angles of $90\text{--}160^\circ$ depending on porosity and pattern), which is theoretically unfavourable for initial protein and cell interactions.^{14,15} This is the principal metrological weakness of the physical route as currently implemented, although post-processing (e.g., hydroxyapatite immersion, ultraviolet photo functionalisation or controlled ageing) can recover hydrophilicity, and some fs surfaces support mineralisation despite low wettability.^{14,28}

Oxide layer thickness, crystallinity and chemical purity:

The oxide layer is where fs ablation offers its most compelling metallurgical advantage. Acid etching leaves a thin native oxide ($\sim 10\text{--}14$ nm), whereas laser structuring thickens it several-fold— $\sim 50\text{--}53$ nm on laser-modified titanium versus $\sim 10\text{--}14$ nm on machined controls—and high-fluence fs irradiation can grow microporous nanocrystalline oxide coatings tens of microns thick.^{12,13,14,16} Femtosecond processing also controls crystalline phase: irradiation generates mixed anatase/rutile TiO_2 (with anatase favoured at lower fluence and rutile dominating at high accumulated fluence), and self-assembled fs-generated TiO_2 nanofibrous layers rich in anatase/rutile markedly accelerate apatite nucleation in simulated body fluid.^{16,19} Because anatase is the phase most associated with apatite induction, the ability to bias the anatase/rutile ratio is a genuine functional lever absent from conventional SLA.¹⁹

On chemical purity the contrast is decisive. Alumina from blasting is acid-insoluble and frequently remains embedded in “clean” commercial SLA surfaces; a survey of nine sandblasted/acid-etched systems from seven manufacturers found residual alumina on most, with the highest counts on widely used products and only isolated systems achieving a particle-free surface.⁷ Embedded Al_2O_3 introduces chemical heterogeneity that can depress corrosion resistance and disturb the biological interface. Femtosecond ablation, being a physical process requiring no blasting medium or acid, yields an intrinsically contaminant-free surface—one of the strongest arguments advanced for the physical paradigm.²⁹ Table 1 summarises the comparative metrology and chemistry of SLA and Femtosecond laser ^{6,9,12,13,16}

Table 1. Comparative surface metrology and chemistry of SLA and femtosecond laser-ablated titanium surfaces.

Parameter	SLA (chemical-subtractive)	Femtosecond laser (physical-subtractive)
Roughness (Sa/Ra)	Moderately rough, Sa $\sim 1\text{--}2$ μm ; up to 3.65 μm (aggressive dual etch)	Tunable; LIPSS Sa up to ~ 2.66 μm ; hierarchical micro+nano
Topographic control	Stochastic; size/spacing not prescribable	Deterministic; sub- μm LIPSS; Sdr/Sdq targetable
Wettability	Hydrophobic ($\sim 138^\circ$); hydrophilic SLActive $\sim 0^\circ$	Often hydrophobic/superhydrophobic ($90\text{--}160^\circ$)
Oxide thickness	Thin native oxide $\sim 10\text{--}14$ nm	$\sim 50\text{--}53$ nm; up to tens of μm at high fluence
Crystalline phase	Not specifically controlled	Tunable anatase/rutile; anatase aids apatite
hemical purity	Residual embedded Al_2O_3 common	Contaminant-free (no media/acid)

In Vitro Biological Response

Protein adsorption and osteoblast adhesion:

Both paradigms exploit the principle that micro-rough surfaces bind fibrin and adhesive proteins (notably fibronectin) that guide osteogenic-cell migration. SLA surfaces support extensive osteoblast spreading with abundant pseudopodia relative to the flattened morphology seen on machined titanium, and blasted/etched surfaces increase cell attachment area, alkaline phosphatase (ALP) activity and mineralised-nodule formation

two- to three-fold over smooth controls.⁶ Comparative topography studies confirm that grit-blasted and blasted-plus-etched surfaces roughly double osteoblast proliferation and ALP activity relative to machined or purely acid-etched surfaces.¹¹ For fs surfaces, the headline in vitro result is adhesion: LIPSS surfaces have been reported to bind up to ten times more human gingival fibroblasts per unit area than SLA controls, with cell adhesion correlating strongly with Sa, and without cytotoxicity.¹⁸

Osteogenic differentiation and mineralisation:

Moderately rough, hydrophilic chemical surfaces enhance osteogenic differentiation and mineralised-matrix deposition, and hydrophilic SLA-type surfaces raise early bone apposition relative to conventional SLA and machined surfaces.⁵ Femtosecond-textured surfaces achieve comparable biological performance despite reduced wettability: fs-textured Ti-alloy supported mineralisation by human bone-progenitor cells equivalent to state-of-the-art sandblasted biphasic calcium-phosphate surfaces after 28 days, and fs-textured porous titanium showed cell viability above 80% with roughly two-fold higher ALP activity at optimal porosity.^{14,15} The apatite-inducing capacity of fs-generated anatase/rutile oxide layers further supports osteogenic potential.¹⁹ Thus, on differentiation endpoints the two paradigms are broadly comparable, with SLA better characterised and fs surfaces achieving parity through oxide chemistry and topography rather than wettability.

Immunomodulation, ion release and cytocompatibility:

Surface chemistry and energy modulate macrophage activation, so purity and ion release matter to the peri-implant inflammatory milieu. Here fs surfaces show a specific advantage: ultraviolet-wavelength fs LIPSS on Ti-6Al-4V reduced lactate-dehydrogenase release (less cell death) and lowered titanium-ion release relative to polished controls, although aluminium release from textured alloy surfaces was higher and warrants monitoring.¹⁷ The contaminant-free fs surface, coupled with a thick protective oxide, offers a plausible route to a quieter immune response, whereas residual alumina in SLA is a potential pro-inflammatory and corrosion-related liability.^{7,17} Table 2 collates the in vitro comparison of SLA/acid etched surfaces and Femtosecond/laser structured surfaces^{6,7,17,19}

Table 2. Comparative in vitro biological response (representative findings).

Endpoint	SLA / acid-etched surfaces	Femtosecond / laser-structured surfaces
Cell adhesion	Extensive spreading, pseudopodia; ~2× vs machined	LIPSS up to ~10× more cells/mm ² vs SLA
ALP activity	~2× vs machined (blasted/etched)	~2× vs comparator (optimal porosity)
Mineralisation	High on hydrophilic SLA (SLActive)	Parity with BCP at 28 d; apatite in SBF
Ion release / cytotox.	Alumina heterogeneity a liability	Lower Ti-ion & LDH release; Al release higher

In Vivo Biomechanical Fixation And Histomorphometry

Bone-to-implant contact:

The SLA surface has a deep in vivo record. In miniature pigs, SLA achieved bone-to-implant contact (BIC) of ~50–60%, significantly exceeding titanium plasma-sprayed and machined surfaces; in the canine mandible SLA exceeded 70% BIC at twelve weeks and tolerated early loading without loss of integration.^{3,4} Hydrophilic SLA further raised early BIC (~60% and ~70% at two and four weeks) over conventional SLA.⁵ In human posterior maxilla, SLA reached 18.5% and 33.7% BIC at four and six weeks, exceeded modestly by nanostructured calcium-incorporated surfaces but confirming contact osteogenesis on SLA.^{10,30} Direct in vivo BIC data for strictly femtosecond surfaces are comparatively sparse; the most informative laser data come from laser-structured (predominantly nanosecond Nd:YAG) implants, which achieved BIC comparable to controls (~75–80%) while transforming the failure mechanism (below).^{12,13,26}

Removal torque, push-out strength and failure mode:

Biomechanically, laser structuring produces the most striking results in the literature. Laser micro/nano-structured titanium delivered 153% higher removal torque than machined controls, and in bone-anchored-hearing-implant models laser-modified surfaces reached ~58 N·cm versus ~23 N·cm for machined.^{12,13} Decisively, the fracture plane shifted from the bone-implant interface into the bone itself (30–50 µm from the surface), indicating that the bone-implant bond exceeded the cohesive strength of bone—evidence of true bone bonding rather than mere interlocking, corroborated by transmission electron microscopy showing mineralised collagen in direct contact with the thickened oxide.^{12,13} For chemical surfaces, removal and push-out data are also strong but interlocking-dominated: micro-rough acid-etched and blasted surfaces

substantially raise removal torque and BIC over machined titanium, yet fixation is achieved by mechanical interlock rather than the chemical bone bonding seen at laser-grown oxides.^{3,4,20} This distinction—interlocking for chemical surfaces versus true bonding for laser oxides—is the central biomechanical difference between the paradigms. Table 3 summarises the *in vivo* comparison of biomechanical and histomorphometric findings^{3,4,5,10}

Table 3. Comparative *in vivo* biomechanical and histomorphometric findings.

Surface	Model	BIC	Biomechanics / failure mode
SLA	Minipig; dog mandible	~50–60%; >70% at 12 wk	High BIC; withstands early loading
Hydrophilic SLA	Minipig	~60–70% (2–4 wk)	Accelerated early fixation
SLA (human)	Posterior maxilla	18.5%–33.7% (4–6 wk)	Contact osteogenesis confirmed
Laser-structured	Rabbit tibia	~75–80%	Torque +153%; fracture within bone

Clinical Implications

Biofilm, peri-implantitis and soft-tissue seal:

Roughness is a double-edged clinical variable: it favours osteogenesis but can promote biofilm retention, and rough surfaces ($S_a > 2 \mu\text{m}$) are associated with increased peri-implantitis risk.²⁰ Importantly, within the moderately rough range bacterial adhesion may be topography-insensitive: across machined, acid-etched, grit-blasted and blasted-plus-etched titanium, no significant differences in adhesion of four oral species were detected despite large roughness differences, implying that antibacterial function must be engineered separately from osteogenic roughness.¹¹ This is precisely where fs laser's deterministic patterning is strategically attractive—sub-cellular LIPSS geometries and tailored wettability could, in principle, discourage bacterial colonisation while promoting osteoblast function, a selectivity unattainable with stochastic SLA. On the soft-tissue seal, micro/nano-structured surfaces guide fibroblast contact and orientation, suggesting fs patterning could be tuned for the transmucosal zone as well as the endosseous body.¹⁸

Loading protocols, survival and mechanical durability:

SLA's accelerated healing underpins reduced healing times and early/immediate loading, and commercial moderately rough surfaces report >95% five-year survival—a clinical evidence base fs surfaces have not yet accumulated.^{3,4,5,21} Against this, the chemical route carries a specific durability penalty: acid etching causes hydrogen embrittlement and titanium-hydride formation, generating microcracks that lower fatigue resistance and have been implicated in thread fracture of retrieved implants.⁸ Femtosecond processing avoids hot acid entirely; although fs texturing can modestly reduce bulk fatigue (~15% in one Ti-alloy study) it causes far less grain refinement, a more favourable mechanical trade-off than embrittlement.¹⁴ Femtosecond laser's early bone bonding and thick oxide are therefore consistent with early-loading ambitions, but the absence of longitudinal survival and marginal-bone-level data remains the decisive clinical gap.

Synthesis And Future Directions

Weighing the four domains, the SLA surface remains the benchmark on the strength of decades of *in vivo* and clinical validation, reliable moderately rough topography, and—in its hydrophilic form—excellent early wettability and bone response.^{3,4,5} Its intrinsic weaknesses are equally clear: stochastic topography, residual alumina contamination, and acid-induced embrittlement.^{7,8} Femtosecond laser ablation answers each of these weaknesses directly—contaminant-free chemistry, a thick tunable anatase/rutile oxide, deterministic hierarchical topography and superior osteoblast adhesion—and where laser-structured surfaces have been tested biomechanically they demonstrate genuine bone bonding rather than mere interlocking.^{12,13,14,16,19} The central hypothesis—that fs surfaces can equal or exceed SLA—is therefore supported at the level of surface engineering and early biology, but not yet at the level of *in vivo* biomechanics specific to femtosecond processing or of long-term clinical outcome, and it is qualified by the frequently hydrophobic wettability of as-produced fs surfaces. Much of the compelling bone-bonding evidence derived from nanosecond Nd:YAG rather than femtosecond sources, and the single most direct fs-versus-SLA comparison concerns *in vitro* cell adhesion rather than clinical performance.^{13,18} Honest appraisal thus places fs ablation

as a highly promising platform whose osteogenic superiority is demonstrated in vitro and metallurgically, but whose clinical equivalence to SLA is plausible yet unproven.

Pragmatic, scenario-based guidance follows from this balance. Where predictability and long-term evidence dominate—routine cases, standard bone—hydrophilic SLA remains the rational default. Where surface purity and fatigue safety are paramount—thin ridges, parafunction, or patients in whom alumina contamination is a concern—fs-laser surfaces are conceptually preferable. Where poor bone quality demands maximal early fixation, the bone-bonding behaviour of laser-structured oxides is attractive, provided wettability is restored by post-processing. Where periodontitis history and peri-implantitis susceptibility dominate, fs laser's potential to decouple antibacterial topography from osteogenic roughness is its most distinctive future advantage.¹¹

The forward trajectory is convergent rather than competitive. The demonstrated value of hybrid post-treatments (hydroxyapatite immersion or photofunctionalisation of LIPSS) points toward “smart” surfaces that combine fs-programmed micro/nano-architecture, an engineered anatase-rich oxide, restored hydrophilicity and, potentially, incorporated antibacterial ions or biomolecules—selectively promoting osteogenesis while inhibiting bacterial adhesion.^{14,19} Realising this requires standardised three-dimensional metrology (Sa, Sdr, Sdq) reported consistently, direct fs-versus-SLA in vivo trials with removal-torque and histomorphometric endpoints, and longitudinal clinical studies capturing survival and marginal bone level. Until such data exist, fs-laser ablation should be regarded as an engineering-superior but clinically-unvalidated challenger to a still-formidable SLA standard.

Conclusion

Sandblasted, large-grit, acid-etched surfaces remain the clinical gold standard for titanium dental implants, delivering reliable moderately rough topography, strong osseointegration and proven long-term survival, but are limited by stochastic topography, residual alumina and acid-induced embrittlement. Femtosecond laser ablation offers a physically clean, deterministically patterned alternative with a thick, phase-tunable oxide and superior in vitro osteoblast response, and laser-structured oxides can achieve true bone bonding. 6- fs ablation matches or exceeds SLA in surface engineering and early biology while remaining unproven in femtosecond-specific in vivo biomechanics and long-term clinical outcome, and is currently constrained by hydrophobic wettability. Femtosecond technology is best viewed not as a replacement but as the enabling route to next-generation “smart” implant surfaces that reconcile osteogenic and antibacterial demands—contingent on standardised metrology and direct comparative clinical trials.

References

1. Albrektsson T, Brånemark PI, Hansson HA, Lindström J. Osseointegrated titanium implants. Requirements for ensuring a long-lasting, direct bone-to-implant anchorage in man. *Acta Orthop Scand*. 1981;52(2):155-70.
2. Le Guéhennec L, Soueidan A, Layrolle P, Amouriq Y. Surface treatments of titanium dental implants for rapid osseointegration. *Dent Mater*. 2007;23(7):844-54.
3. Buser D, Schenk RK, Steinemann S, Fiorellini JP, Fox CH, Stich H. Influence of surface characteristics on bone integration of titanium implants. A histomorphometric study in miniature pigs. *J Biomed Mater Res*. 1991;25(7):889-902.
4. Cochran DL, Schenk RK, Lussi A, Higginbottom FL, Buser D. Bone response to unloaded and loaded titanium implants with a sandblasted and acid-etched surface: a histometric study in the canine mandible. *J Biomed Mater Res*. 1998;40(1):1-11.
5. Buser D, Broggini N, Wieland M, Schenk RK, Denzer AJ, Cochran DL, et al. Enhanced bone apposition to a chemically modified SLA titanium surface. *J Dent Res*. 2004;83(7):529-33.
6. Orsini G, Assenza B, Scarano A, Piattelli M, Piattelli A. Surface analysis of machined versus sandblasted and acid-etched titanium implants. *Int J Oral Maxillofac Implants*. 2000;15(6):779-84.
7. Schupbach P, Glauser R, Bauer S. Al₂O₃ particles on titanium dental implant systems following sandblasting and acid-etching. *Materials*. 2019;12(11):1735.
8. Yokoyama K, Ichikawa T, Murakami H, Miyamoto Y, Asaoka K. Fracture mechanisms of retrieved titanium screw thread in dental implants. *Biomaterials*. 2002;23(12):2459-65.
9. Madaan VU, Mapara M, Padhye AM. Comparative evaluation of microroughness created on titanium alloy subjected to two different acid etching techniques: an in vitro study. *J Contemp Dent*. 2016;6(1):1-8.
10. Makary C, Menhall A, Zammare C, Lombardi T, Lee SY, Stacchi C, et al. Bone-to-implant contact of machined, SLA and nanostructured calcium-incorporated surfaces in human posterior maxilla: a randomized split-mouth study. *Nanomaterials*. 2023;13(2):357.

11. Rodriguez-Gonzalez R, Monsalve-Guil L, Jimenez-Guerra A, Velasco-Ortega E, Moreno-Munoz J, Nunez-Marquez E, et al. Relevant aspects of titanium topography for osteoblastic adhesion and inhibition of bacterial colonization. *Materials*. 2023;16(9):3553.
12. Palmquist A, Lindberg F, Emanuelsson L, Brånemark R, Engqvist H, Thomsen P. Biomechanical, histological, and ultrastructural analyses of laser micro- and nano-structured titanium alloy implants: a study in rabbit. *J Biomed Mater Res A*. 2010;92(4):1476-86.
13. Shah FA, Johansson ML, Omar O, Simonsson H, Palmquist A, Thomsen P. Laser-modified surface enhances osseointegration and biomechanical anchorage of commercially pure titanium implants for bone-anchored hearing systems. *PLoS One*. 2016;11(6):e0157504.
14. Lackington WA, Schweizer P, Khokhlova M, Cancellieri C, Guimond S, Chopard-Lallier AL, et al. Femtosecond laser-texturing the surface of Ti-based implants to improve their osseointegration capacity. *Adv Mater Interfaces*. 2022;9(31):2201164.
15. Beltran AM, Giner M, Rodriguez A, Trueba P, Rodriguez-Albelo LM, Vazquez-Gamez MA, et al. Influence of femtosecond laser modification on biomechanical and biofunctional behavior of porous titanium substrates. *Materials*. 2022;15(9):2969.
16. Kolobov YR, Zhidkov MV, Golosov EV, Vershinina TN, Kudryashov SI, Ionin AA, et al. The formation of oxide layers on a titanium surface by irradiation with femtosecond laser pulses. *Tech Phys Lett*. 2018;44(12):1092-5.
17. Schweitzer L, Schoon J, Cunha A, Pereira T, Mika K, do Rego AMB, et al. Preclinical in vitro assessment of submicron-scale laser surface texturing on Ti6Al4V. *Materials*. 2020;13(23):5342.
18. Hadzik J, Kubasiewicz-Ross P, Simka W, Gebarowski T, Barg E, et al. Fractal dimension and texture analysis in the assessment of experimental laser-induced periodic surface structures (LIPSS) dental implant surfaces – in vitro study. *Materials*. 2022;15(8):2713.
19. Tavangar A, Tan B, Venkatakrishnan K. Synthesis of three-dimensional TiO₂ nanofibrous structures by femtosecond laser processing for bioactivation of titanium. [Date unknown – verify against source PDF].
20. Wennerberg A, Albrektsson T. Effects of titanium surface topography on bone integration: a systematic review. *Clin Oral Implants Res*. 2009;20(Suppl 4):172-84.
21. Buser D, Janner SF, Wittneben JG, Brägger U, Ramseier CA, Salvi GE. 10-year survival and success rates of 511 titanium implants with a sandblasted and acid-etched surface: a retrospective study in 303 partially edentulous patients. *Clin Implant Dent Relat Res*. 2012;14(6):839-51.
22. Rupp F, Scheideler L, Olshanska N, de Wild M, Wieland M, Geis-Gerstorfer J. Enhancing surface free energy and hydrophilicity through chemical modification of microstructured titanium implant surfaces. *J Biomed Mater Res A*. 2006;76(2):323-34.
23. Albrektsson T, Wennerberg A. On osseointegration in relation to implant surfaces. *Clin Implant Dent Relat Res*. 2019;21 Suppl 1:4-7.
24. Vorobyev AY, Guo C. Direct femtosecond laser surface nano/microstructuring and its applications. *Laser Photon Rev*. 2013;7(3):385-407.
25. Jemat A, Ghazali MJ, Razali M, Otsuka Y. Surface modifications and their effects on titanium dental implants. *Biomed Res Int*. 2015;2015:791725.
26. Faeda RS, Tavares HS, Sartori R, Guastaldi AC, Marcantonio E Jr. Evaluation of titanium implants with surface modification by laser beam: biomechanical study in rabbit tibias. *Braz Oral Res*. 2009;23(2):137-43.
27. Gittens RA, Olivares-Navarrete R, Schwartz Z, Boyan BD. Implant osseointegration and the role of microroughness and nanostructures: lessons for spine implants. *Acta Biomater*. 2014;10(8):3363-71.
28. Att W, Hori N, Takeuchi M, Ouyang J, Yang Y, Anpo M, et al. Time-dependent degradation of titanium osteoconductivity: an implication of biological aging of implant materials. *Biomaterials*. 2009;30(29):5352-63.
29. Mombelli A, Hashim D, Cionca N. What is the impact of titanium particles and biocorrosion on implant survival and complications? A critical review. *Clin Oral Implants Res*. 2018;29 Suppl 18:37-53.
30. Berglundh T, Abrahamsson I, Lang NP, Lindhe J. De novo alveolar bone formation adjacent to endosseous implants. *Clin Oral Implants Res*. 2003;14(3):251-62.