

Assessment of Surface Roughness and Early Bacterial Adhesion on Machined, SLA, Anodized and Laser-Modified Titanium Implant Surfaces: An In-Vitro Study

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Abstract Background: Implant surface characteristics influence both osseointegration and early microbial colonization. The present in-vitro study compared machined, sandblasted and acid-etched (SLA), anodized and laser-modified titanium surfaces to determine how different modification protocols affect roughness and 24-hour bacterial adhesion. **Methods:** Eighty commercially pure titanium grade 4 discs were randomly allocated to four groups (n = 20 each): machined, SLA, anodized and laser-modified. Surface characterization was performed using optical profilometry (Ra, Rz, Rq, Rsk and Rku) and scanning electron microscopy. Early bacterial adhesion at 24 hours was assessed using *Streptococcus mutans* under aerobic conditions and *Porphyromonas gingivalis* under anaerobic conditions. Colony-forming units (CFU/mm²) and fluorescence microscopy coverage percentages quantified adhesion. One-way ANOVA, Tukey post-hoc testing and Pearson correlation analysis were applied at a significance level of p<0.05. **Results:** SLA surfaces exhibited the highest roughness (Ra 2.34±0.28µm), followed by laser-modified (1.87±0.23µm), anodized (1.12±0.18µm) and machined surfaces (0.43±0.09µm) (p<0.001). SLA also showed the greatest bacterial adhesion. Compared with SLA, laser-modified surfaces demonstrated approximately 38.2% lower *S. mutans* counts and 38.8% lower *P. gingivalis* counts despite remaining moderately rough. Strong positive correlations were observed between Ra and bacterial adhesion parameters (r = 0.80-0.85; p<0.001). **Conclusion:** Surface modification protocols significantly influence both roughness and early bacterial adhesion on titanium. Within the limitations of this 24-hour single-species in-vitro model, laser-modified surfaces showed a favourable balance between moderate roughness and lower bacterial adhesion than SLA surfaces and therefore appear promising rather than definitive for future implant surface design.

Key Words Dental Implants, Surface Roughness, Bacterial Adhesion, Titanium, SLA, Anodization, Laser Surface Modification, Osseointegration

INTRODUCTION

Dental implants are a predictable treatment option for replacement of missing teeth, but their long-term success depends on both stable osseointegration and maintenance of peri-implant tissue health [1-3]. Surface topography and chemistry influence the early biological response at the bone-implant interface and also influence the initial events of bacterial attachment [3-6]. This dual effect creates a biologic trade-off in implant design.

Implant surface modification techniques such as machining, sandblasting and acid etching, anodization and laser treatment generate distinct topographies and oxide characteristics. In general, SLA surfaces produce higher microroughness, anodization creates a porous oxide layer

and laser processing can create controlled micro-patterned or hierarchical architectures [5-8]. Moderately rough surfaces have often shown favourable bone responses; however, the same features may also provide retention sites for bacterial adhesion [7,8].

The concept of the “race to the surface” describes the competition between host tissue cells and microorganisms to colonize a newly exposed biomaterial surface [3]. In the oral cavity, this competition is particularly important because peri-implant biofilm formation can lead to peri-implant mucositis and peri-implantitis. Reported prevalence estimates for peri-implantitis vary widely because of differences in case definitions, study populations, implant function time and follow-up protocols [9,32].

No implant in the mouth remains a truly bare titanium surface; proteins and salivary components rapidly form a conditioning film that modulates subsequent microbial attachment. In addition, peri-implant disease is caused by complex multispecies communities rather than a single organism. Nevertheless, early single-species adhesion models remain useful for controlled mechanistic comparisons between candidate implant surfaces [11-14,33]. In the present study, *Streptococcus mutans* was selected as an early colonizer model and *Porphyromonas gingivalis* as a peri-pathogen model, while recognizing that these organisms do not represent the full peri-implant microbiome.

Accordingly, the present in-vitro study aimed to compare four titanium surface protocols - machined, SLA, anodized and laser-modified - with respect to primary outcomes of surface roughness parameters and 24-hour bacterial adhesion (CFU/mm²). Secondary outcomes included fluorescence microscopy coverage percentage and the correlation between surface roughness and bacterial adhesion. The null hypothesis was that surface modification protocol would not significantly affect roughness or early bacterial adhesion.

METHODS

Study Design and Specimen Preparation

This in-vitro experimental study was conducted at the Dental Biomaterials Research Laboratory using commercially pure titanium grade 4 discs (10 mm diameter x 2 mm thickness) manufactured from a single production lot to improve compositional uniformity. Eighty specimens were prepared by computer numerical control machining. Because this was an in-vitro laboratory investigation using standard biomaterial specimens and reference bacterial strains, ethics committee approval was not applicable.

The sample size was calculated using G*Power version 3.1.9.7 with an effect size of 0.50, alpha error probability of 0.05 and power of 0.85, indicating a minimum requirement of 18 discs per group. Twenty discs were prepared per group to allow for possible specimen loss during processing. [Please insert the exact pilot outcome used to derive the effect-size assumption if available in the study records.]

Surface Modification Protocols

Computer-generated randomization was used to allocate the discs into four groups (n = 20 each): machined control, sandblasted and acid-etched (SLA), anodized and laser-modified surfaces. Allocation concealment was not relevant because all interventions were laboratory-based and preplanned; however, all groups underwent the same cleaning, sterilization, storage and testing workflow.

Machined discs were sequentially polished with silicon carbide papers (grit 400-1200) followed by 3 µm and 1 µm diamond suspensions. SLA discs were sandblasted with 250-500µm aluminium oxide particles at 5 bar pressure for 30 seconds at a standoff distance of 10 mm and then acid etched in heated hydrochloric acid and sulfuric acid (60°C for 30 minutes), followed by deionized water rinsing.

Anodized discs underwent direct-current anodic oxidation in 1 M phosphoric acid at 100 V for 60 seconds using titanium as the anode and platinum as the cathode. Laser-modified discs were treated with an Nd:YAG laser (1064 nm) in pulsed mode using a pulse energy of 0.5 J, pulse duration of 10 ns, repetition rate of 10 Hz and spot size of 100 µm. A crosshatch pattern with 100µm spacing between tracks was created. [Please insert scanning speed and overlap if these parameters were recorded.]

Post-Treatment Processing and Surface Characterization

After surface treatment, all discs were ultrasonically cleaned in acetone, ethanol and deionized water for 15 minutes each, dried under nitrogen gas, stored in sterile closed containers and sterilized by gamma irradiation (25 kGy) prior to microbiological testing. The possibility that sterilization may influence surface chemistry was recognized but was not directly measured in the present study.

Non-contact optical profilometry (ContourGT-K, Bruker, Billerica, MA, USA) in vertical scanning interferometry mode was used to assess surface topography over a standardized 500×1000 µm² evaluation area. Five random readings were obtained per specimen and averaged. The recorded parameters were Ra (arithmetic mean roughness), Rz (maximum profile height), Rq (root mean square roughness), Rsk (surface skewness) and Rku (surface kurtosis).

Field-emission scanning electron microscopy (JSM-7500F, JEOL, Tokyo, Japan) was used to examine representative surface morphology at 500x, 2000x and 5000x magnifications after sputter coating with a 10 nm gold-palladium layer.

Bacterial Culture and Adhesion Assay

Early bacterial adhesion was evaluated at 24 hours and therefore the present outcomes represent early colonization rather than mature biofilm behaviour. *Streptococcus mutans* (ATCC 25175) was cultured in Brain Heart Infusion broth under aerobic conditions at 37°C. *Porphyromonas gingivalis* (ATCC 33277) was cultured in Tryptic Soy Broth supplemented with hemin (5µg/mL) and menadione (1µg/mL) under anaerobic conditions (80% N₂, 10% H₂, 10% CO₂). Bacterial suspensions were adjusted to 1x10⁸ CFU/mL at mid-logarithmic growth phase.

Sterile titanium discs were placed in 24-well tissue culture plates and immersed in bacterial suspension for 24 hours. Each disc was then washed three times with phosphate-buffered saline to remove non-adherent bacteria. Adherent bacteria were detached by sonication (40 kHz, 5 minutes) and vortexing for 2 minutes in 1mL phosphate-buffered saline. Serial dilutions were plated and colony counts were reported as CFU/mm² after incubation for 48 hours for *S. mutans* and 7 days for *P. gingivalis*.

Bacterial surface coverage was assessed using SYTO 9 fluorescence staining and fluorescence microscopy (BX51, Olympus, Tokyo, Japan) at 200x magnification. Five random fields per disc were imaged. Coverage percentage

was quantified in ImageJ using the same thresholding approach for all samples within each organism-specific analysis set to reduce operator bias.

Statistical Analysis

Data were analysed using SPSS version 26.0 (IBM Corp., Armonk, NY, USA). Normality and homogeneity of variance were assessed using the Shapiro-Wilk and Levene tests, respectively. One-way ANOVA was used to compare surface roughness parameters and bacterial adhesion among groups, followed by Tukey HSD post-hoc testing to control type-I error across multiple comparisons. Pearson correlation coefficients evaluated the association between Ra and bacterial adhesion variables. Statistical significance was set at $p < 0.05$. Effect sizes and surface chemistry analyses were not performed and are acknowledged as limitations.

RESULTS

Surface roughness differed significantly among the four modification protocols ($p < 0.001$). SLA showed the highest Ra, Rz and Rq values, while machined discs remained the smoothest. Laser-modified discs were moderately rough and showed the highest kurtosis value, consistent with a controlled hierarchical surface pattern (Table 1).

Bacterial adhesion also differed significantly among the groups for both *S. mutans* and *P. gingivalis*. SLA surfaces demonstrated the highest CFU counts and coverage percentages. Relative to SLA, laser-modified surfaces showed approximately 38% lower counts for both bacterial species, despite retaining moderate roughness. Anodized and laser-modified groups did not differ significantly from each other in bacterial outcomes, suggesting that factors beyond Ra alone may contribute to early adhesion behaviour (Table 2).

Pearson correlation analysis demonstrated strong positive associations between Ra and all bacterial adhesion parameters ($r = 0.812$ to 0.847 ; $p < 0.001$). Regression

calculations described in the source manuscript suggested that Ra accounted for approximately 68-72% of the variance in bacterial adhesion, indicating that topography is important but not the sole determinant of colonization (Table 3).

The roughness ranking was SLA > laser-modified > anodized > machined. According to accepted roughness categories, SLA was rough, laser was moderately rough, anodized was minimally to moderately rough and machined was smooth.

Across both organisms, the bacterial adhesion ranking was SLA > laser-modified \approx anodized > machined. The lower-than-expected bacterial adhesion on laser-modified discs relative to their roughness should be interpreted as a hypothesis-generating observation because surface chemistry and wettability were not measured.

Although the correlations were strong, they were not perfect. This indicates that early adhesion was influenced by roughness together with other unmeasured surface features such as oxide composition, surface energy or wettability.

DISCUSSION

The present study showed that the method of surface modification significantly altered titanium roughness and early bacterial adhesion. The null hypothesis was therefore rejected. As expected, SLA treatment produced the roughest surfaces and the greatest 24-hour adhesion for both *S. mutans* and *P. gingivalis*. These findings are consistent with the established view that increased microtopography can enhance surface area and provide sheltered retention sites for microorganisms [16,21].

Laser-modified surfaces were moderately rough yet supported significantly lower bacterial adhesion than SLA surfaces. This finding is relevant because moderately rough surfaces are often considered favourable for bone response, but a similar roughness range does not guarantee equivalent microbial behaviour. The present results therefore support the idea that surface architecture and possibly surface chemistry,

Table 1. Surface roughness parameters by surface modification protocol (Mean±SD)

Parameter	Machined	SLA	Anodized	Laser-Modified	p-value
Ra (µm)	0.43±0.09 ^a	2.34±0.28 ^b	1.12±0.18 ^c	1.87±0.23 ^d	<0.001*
Rz (µm)	2.87±0.34 ^a	15.67±1.89 ^b	7.45±0.92 ^c	11.23±1.45 ^d	<0.001*
Rq (µm)	0.56±0.11 ^a	2.98±0.35 ^b	1.45±0.22 ^c	2.34±0.29 ^d	<0.001*
Rsk	-0.12±0.08 ^a	0.45±0.12 ^b	0.23±0.09 ^c	-0.34±0.11 ^d	<0.001*
Rku	2.89±0.23 ^a	3.67±0.34 ^b	3.12±0.28 ^{ac}	4.23±0.41 ^d	<0.001*

Table 2: Bacterial adhesion by surface modification protocol (Mean±SD)

Surface Type	<i>S. mutans</i> CFU ($\times 10^5$ /mm ²)	<i>S. mutans</i> Coverage (%)	<i>P. gingivalis</i> CFU ($\times 10^4$ /mm ²)	<i>P. gingivalis</i> Coverage (%)
Machined	1.23±0.21 ^a	8.45±1.23 ^a	0.87±0.15 ^a	5.67±0.89 ^a
SLA	4.82±0.56 ^b	34.67±4.56 ^b	3.45±0.42 ^b	26.78±3.45 ^b
Anodized	2.34±0.32 ^c	16.23±2.34 ^c	1.56±0.23 ^c	11.45±1.67 ^c
Laser-Modified	2.89±0.38 ^c	19.45±2.78 ^c	1.78±0.28 ^c	13.23±1.89 ^c
p-value	<0.001*	<0.001*	<0.001*	<0.001*

Table 3: Correlation between Ra and bacterial adhesion parameters

Bacterial Parameter	Correlation Coefficient (r)	95% CI	p-value
<i>S. mutans</i> CFU	0.847	0.76-0.91	<0.001*
<i>S. mutans</i> Coverage (%)	0.823	0.73-0.89	<0.001*
<i>P. gingivalis</i> CFU	0.812	0.71-0.88	<0.001*
<i>P. gingivalis</i> Coverage (%)	0.798	0.69-0.87	<0.001*

may modulate microbial attachment beyond Ra alone. Because no XPS, EDS, contact-angle or surface-energy measurements were performed, any chemistry-based explanation must remain hypothetical rather than conclusive [22,27,34].

Anodized surfaces also showed intermediate roughness with lower bacterial adhesion than SLA. The comparable bacterial outcomes of the anodized and laser-modified groups, despite different roughness values, further suggest that roughness alone cannot fully explain early adhesion. Oxide characteristics, pore geometry and nanoscale organization may contribute to these differences, but this requires direct physicochemical testing in future work [20,30,34].

The biologic interpretation of these findings should remain cautious. The present study assessed only 24-hour single-species adhesion under static laboratory conditions. In the oral cavity, implant surfaces are rapidly conditioned by salivary pellicle proteins and exposed to multispecies communities, fluid shear, host immunity and oral hygiene forces. Recent studies have shown that salivary pellicles on titanium can significantly modulate biofilm development, underscoring the gap between bare-surface in-vitro assays and the clinical environment [33].

From a clinical standpoint, the most important message is not that one surface is definitively “best,” but that extremely rough surfaces may carry a greater early bacterial burden, whereas controlled moderate roughness may offer a more favourable balance. This supports ongoing efforts in implant surface engineering to optimize both tissue integration and resistance to early biofilm establishment. However, early adhesion data alone do not predict long-term peri-implantitis risk, which is influenced by prosthetic design, soft-tissue seal, patient hygiene and maintenance [9,23,32].

CONCLUSIONS

Within the limitations of this in-vitro study, SLA surfaces exhibited the greatest roughness and the highest early bacterial adhesion, whereas machined surfaces were the smoothest and least colonized. Laser-modified surfaces showed moderate roughness with lower bacterial adhesion than SLA surfaces, suggesting promise as a surface-engineering strategy rather than proof of clinical superiority. Future studies should combine pellicle conditioning, multispecies biofilms, longer observation periods and direct physicochemical analyses to determine whether these early in-vitro advantages translate into clinically meaningful reduction of peri-implant disease risk.

Strengths and Limitations

The strengths of the study include standardized specimen preparation from a single titanium lot, adequate sample size, optical profilometry and SEM characterization, use of two clinically relevant bacterial models and quantification of adhesion by both CFU/mm² and fluorescence coverage.

Correlation analysis further strengthened interpretation by linking roughness to microbial outcomes.

The study also has important limitations. First, it used a disc model rather than threaded implants or implant-abutment assemblies. Second, only single-species adhesion at 24 hours was assessed, so mature multispecies biofilm behaviour cannot be inferred. Third, no salivary pellicle conditioning, dynamic flow, toothbrushing simulation or host factors were included. Fourth, surface chemistry, oxide composition and wettability were not measured. These limitations require cautious clinical interpretation.

REFERENCES

- [1] Brånemark, P.I. *et al.* *Osseointegrated Implants in the Treatment of the Edentulous Jaw: Experience from a 10-Year Period.* *Scandinavian Journal of Plastic and Reconstructive Surgery Supplement*, vol. 16, 1977, pp. 1-132. <https://pubmed.ncbi.nlm.nih.gov/356184/>.
- [2] Albrektsson, T. and P.I. Brånemark. “Osseointegrated titanium implants: requirements for ensuring a long-lasting, direct bone-to-implant anchorage in man.” *Acta Orthopaedica Scandinavica*, vol. 52, no. 2, 1981, pp. 155-170. <https://doi.org/10.3109/17453678108991776>.
- [3] Le Guéhennec, L. *et al.* “Surface treatments of titanium dental implants for rapid osseointegration.” *Dental Materials*, vol. 23, no. 7, 2007, pp. 844-854. <https://doi.org/10.1016/j.dental.2006.06.025>.
- [4] Junker, R. *et al.* “Effects of implant surface coatings and composition on bone integration: a systematic review.” *Clinical Oral Implants Research*, vol. 20, suppl. 4, 2009, pp. 185-206. <https://doi.org/10.1111/j.1600-0501.2009.01777.x>.
- [5] Wennerberg, A. and T. Albrektsson. “Effects of titanium surface topography on bone integration: a systematic review.” *Clinical Oral Implants Research*, vol. 20, suppl. 4, 2009, pp. 172-184. <https://doi.org/10.1111/j.1600-0501.2009.01775.x>.
- [6] Dohan Ehrenfest, D.M. *et al.* “Classification of osseointegrated implant surfaces: materials, chemistry and topography.” *Trends in Biotechnology*, vol. 28, no. 4, 2010, pp. 198-206. <https://doi.org/10.1016/j.tibtech.2009.12.003>.
- [7] Wennerberg, A. and T. Albrektsson. “Suggested guidelines for the topographic evaluation of implant surfaces.” *International Journal of Oral and Maxillofacial Implants*, vol. 15, no. 3, 2000, pp. 331-344. <https://pubmed.ncbi.nlm.nih.gov/10874798/>.
- [8] Shalabi, M.M. *et al.* “Implant surface roughness and bone healing: a systematic review.” *Journal of Dental Research*, vol. 85, no. 6, 2006, pp. 496-500. <https://doi.org/10.1177/154405910608500603>.
- [9] Derks, J. and C. Tomasi. “Peri-implant health and disease: a systematic review of current epidemiology.” *Journal of Clinical Periodontology*, vol. 42, suppl. 16, 2015, pp. S158-S171. <https://doi.org/10.1111/jcpe.12334>.
- [10] Heitz-Mayfield, L.J. and N.P. Lang. “Comparative biology of chronic and aggressive periodontitis vs peri-implantitis.” *Periodontology 2000*, vol. 53, 2010, pp. 167-181. <https://doi.org/10.1111/j.1600-0757.2010.00348.x>.
- [11] Busscher, H.J. *et al.* “Biofilm formation on dental restorative and implant materials.” *Journal of Dental Research*, vol. 89, no. 7, 2010, pp. 657-665. <https://doi.org/10.1177/0022034510368644>.

- [12] Subramani, K. *et al.* "Biofilm on dental implants: a review of the literature." *International Journal of Oral and Maxillofacial Implants*, vol. 24, no. 4, 2009, pp. 616-626. <https://pubmed.ncbi.nlm.nih.gov/19885401/>.
- [13] Lindhe, J. and J. Meyle. "Peri-implant diseases: consensus report of the Sixth European Workshop on Periodontology." *Journal of Clinical Periodontology*, vol. 35, no. 8 suppl., 2008, pp. 282-285. <https://doi.org/10.1111/j.1600-051X.2008.01283.x>.
- [14] Heuer, W. *et al.* "Analysis of early biofilm formation on oral implants in man." *Journal of Oral Rehabilitation*, vol. 34, no. 5, 2007, pp. 377-382. <https://doi.org/10.1111/j.1365-2842.2006.01675.x>.
- [15] Cunha, A. *et al.* "Femtosecond laser surface texturing of titanium as a method to reduce the adhesion of *Staphylococcus aureus* and biofilm formation." *Applied Surface Science*, vol. 360, 2016, pp. 485-493. <https://doi.org/10.1016/j.apsusc.2015.10.102>.
- [16] Buser, D. *et al.* "Influence of surface characteristics on bone integration of titanium implants: a histomorphometric study in miniature pigs." *Journal of Biomedical Materials Research*, vol. 25, no. 7, 1991, pp. 889-902. <https://doi.org/10.1002/jbm.820250708>.
- [17] Cochran, D.L. *et al.* "The use of reduced healing times on ITI implants with a sandblasted and acid-etched (SLA) surface." *Clinical Oral Implants Research*, vol. 13, no. 2, 2002, pp. 144-153. <https://doi.org/10.1034/j.1600-0501.2002.130204.x>.
- [18] Faeda, R.S. *et al.* "Evaluation of titanium implants with surface modification by laser beam: biomechanical study in rabbit tibias." *Brazilian Oral Research*, vol. 23, no. 2, 2009, pp. 137-143. <https://doi.org/10.1590/S1806-83242009000200008>.
- [19] Coelho, P.G. *et al.* "Basic research methods and current trends of dental implant surfaces." *Journal of Biomedical Materials Research Part B: Applied Biomaterials*, vol. 88, no. 2, 2009, pp. 579-596. <https://doi.org/10.1002/jbm.b.31264>.
- [20] Sul, Y.T. *et al.* "Characteristics of the surface oxides on turned and electrochemically oxidized pure titanium implants up to dielectric breakdown." *Biomaterials*, vol. 23, no. 2, 2002, pp. 491-501. [https://doi.org/10.1016/S0142-9612\(01\)00131-4](https://doi.org/10.1016/S0142-9612(01)00131-4).
- [21] Teughels, W. *et al.* "Effect of material characteristics and/or surface topography on biofilm development." *Clinical Oral Implants Research*, vol. 17, suppl. 2, 2006, pp. 68-81. <https://doi.org/10.1111/j.1600-0501.2006.01353.x>.
- [22] Ren, N. *et al.* "Antibacterial enhancement of laser-textured titanium surfaces with silver and hydrophobic/hydrophilic surface modification." *Materials Science and Engineering C: Materials for Biological Applications*, vol. 92, 2018, pp. 84-91. <https://doi.org/10.1016/j.msec.2018.06.012>.
- [23] Fürst, M.M. *et al.* "Bacterial colonization immediately after installation on oral titanium implants." *Clinical Oral Implants Research*, vol. 18, no. 4, 2007, pp. 501-508. <https://doi.org/10.1111/j.1600-0501.2007.01381.x>.
- [24] Schmidlin, P.R. *et al.* "Effects of different surface decontamination and microtopography on microbial colonization of titanium." *Clinical Oral Implants Research*, vol. 24, no. 1, 2013, pp. 37-44. <https://doi.org/10.1111/j.1600-0501.2011.02357.x>.
- [25] Heitz-Mayfield, L.J. "Peri-implant diseases: diagnosis and risk indicators." *Journal of Clinical Periodontology*, vol. 35, no. 8 suppl., 2008, pp. 292-304. <https://doi.org/10.1111/j.1600-051X.2008.01275.x>.
- [26] Gristina, A.G. "Biomaterial-centered infection: microbial adhesion versus tissue integration." *Science*, vol. 237, no. 4822, 1987, pp. 1588-1595. <https://doi.org/10.1126/science.3629258>.
- [27] Vorobyev, A.Y. and C. Guo. "Direct femtosecond laser surface nano/microstructuring and its applications." *Laser and Photonics Reviews*, vol. 7, no. 3, 2013, pp. 385-407. <https://doi.org/10.1002/lpor.201200017>.
- [28] Ren, P. *et al.* "Biological effects of laser surface modification on titanium alloy." *Materials Science and Engineering C: Materials for Biological Applications*, vol. 58, 2016, pp. 1027-1032. <https://doi.org/10.1016/j.msec.2015.09.069>.
- [29] Yao, C. and T.J. Webster. "Anodization: a promising nano-modification technique of titanium implants for orthopedic applications." *Journal of Nanoscience and Nanotechnology*, vol. 6, no. 9-10, 2006, pp. 2682-2692. <https://doi.org/10.1166/jnn.2006.447>.
- [30] Sul, Y.T. *et al.* "Optimum surface properties of oxidized implants for reinforcement of osseointegration." *International Journal of Oral and Maxillofacial Implants*, vol. 20, no. 3, 2005, pp. 349-359. <https://pubmed.ncbi.nlm.nih.gov/15973946/>.
- [31] Rupp, F. *et al.* "Surface characteristics of dental implants: a review." *Dental Materials*, vol. 34, no. 1, 2018, pp. 40-57. <https://doi.org/10.1016/j.dental.2017.09.007>.
- [32] Díaz, P. *et al.* "What is the prevalence of peri-implantitis? A systematic review and meta-analysis." *BMC Oral Health*, vol. 22, 2022, pp. 449. <https://doi.org/10.1186/s12903-022-02493-8>.
- [33] Martínez-Hernández, M. *et al.* "Salivary pellicle modulates biofilm formation on titanium and enamel surfaces." *Clinical Oral Investigations*, 2023. <https://link.springer.com/article/10.1007/s00784-023-05230-9>.
- [34] Yu, J. *et al.* "Antibacterial adhesion strategy for dental titanium implant surfaces." *Bioengineering*, vol. 13, no. 4, 2022, pp. 169. <https://www.mdpi.com/2079-4983/13/4/169>.