

Evaluation of Titanium Exfoliation during Simulated Surgical Insertion of Dental Implants with Different Surface Coatings - An in-Vitro Study

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Abstract

Background: Titanium dental implants have become the standard for tooth replacement due to their mechanical strength, corrosion resistance, and excellent biocompatibility. Despite these advantages, implant insertion procedures may lead to the release of titanium particles due to friction and wear at the bone–implant interface, potentially causing peri-implant tissue inflammation.

Aims: This study aimed to compare and evaluate titanium exfoliation from dental implants with different

surface modifications during simulated surgical insertion procedures.

Settings and Design: An in-vitro experimental study conducted using polyurethane foam blocks simulating human cancellous bone density.

Methods and Material: Sixteen commercially available dental implants were categorized into four groups (n=4 per group) according to their surface characteristics: Group 1 – Sandblasted large-grit acid-etched (SLA) implants, Group 2 – Sandblasted with alumina acid-etched implants, Group 3 – Anodized surface implants, and Group 4 – Hydroxyapatite (HA)-coated implants.

Each implant was inserted into polyurethane foam blocks with a density of 40 PCF following a standardized surgical drilling and insertion protocol. Optical Microscopy, Field Emission Scanning Electron Microscopy (FE-SEM), Energy Dispersive X-ray Spectroscopy (EDS), and Powdered X-Ray Diffraction (XRD) analyses were employed to detect and quantify titanium exfoliation.

Statistical Analysis: Intergroup comparisons were performed using one-way ANOVA followed by post-hoc Bonferroni tests with significance set at $p < 0.05$.

Results: Titanium particle release was observed in all groups, with Group 1 and Group 2 exhibiting significantly higher titanium mass percentages and particle sizes than Group 3 and Group 4. Anodized surface implants demonstrated the least titanium exfoliation.

Conclusions: Implant surface roughness plays a crucial role in titanium particle release. Anodized surfaces showed minimal exfoliation, indicating their potential advantage in reducing peri-implant inflammatory risks.

Keywords: Dental implants; Titanium; Surface properties; Peri-implantitis; Scanning electron microscopy; Hydroxyapatite.

Introduction

Dental implants have been an integral part of restorative dentistry for more than half a century. Since the pioneering work of Brånemark and colleagues established the concept of osseointegration, titanium implants have become the most preferred choice for replacing missing teeth.¹ The exceptional success of titanium implants is primarily attributed to their biocompatibility, corrosion resistance, and ability to form a stable titanium oxide (TiO₂) layer that promotes bone bonding.² However, during implant insertion, the friction between implant threads and the osteotomy walls can

cause the detachment of titanium particles, a phenomenon referred to as titanium exfoliation.³ These exfoliated particles may trigger inflammatory responses, leading to peri-implantitis—a progressive and destructive bone loss around the osseointegrated implant.⁴ Numerous factors such as implant design, insertion torque, surgical instrumentation, and surface characteristics influence the extent of titanium wear and particle release.⁵ Surface modifications are widely used to enhance osseointegration, with techniques such as sandblasting, acid etching, anodization, and hydroxyapatite coating being the most common.⁶ While roughened surfaces improve bone anchorage, they may also increase susceptibility to tribocorrosion and mechanical wear.⁷ Therefore, this study aimed to evaluate and compare the titanium exfoliation in implants with different surface treatments under simulated surgical insertion conditions.

Materials and Methods

This in-vitro study used sixteen commercially available dental implants, divided into four groups (n=4 per group), based on surface modification:

- Group 1 – Sandblasted large-grit acid-etched (SLA) implants of size 4.25mm*10mm IZEN Implants (South Korea)
- Group 2 – Sandblasted with alumina acid-etched implants of size 4.75mm*10mm Swiss Medical Implant (Switzerland)
- Group 3 – Anodized surface implants of size 4.3mm*10mm Nobel Biocare Implants (United States)
- Group 4 – Hydroxyapatite (HA)-coated implants of size 4.75*10mm Osstem Implants (South Korea)

The inclusion criteria were,

1. All implants had the same design, ie tapered and self-tapping.

2. Biomaterials, such as blocks of polyurethane foam, or artificial bone was utilized.
3. Implants with four distinct surface coatings were used.
4. Standardized methods for implant insertion were employed, such as a standardized drilling protocol with particular insertion torque.

The exclusion criteria were,

1. Any damaged or defective implants.
2. Implants that were contaminated or compromised such as those exposed to improper storage conditions or handling be excluded.
3. Implants with pre-existing surface treatment that could potentially interfere with specific focus or objectives of research.

All implants had a tapered, self-tapping configuration with comparable geometry to minimize variability. The study protocol was approved by the Institutional Ethical Committee of Luxmi Bai Institute of Dental Sciences and Hospital, Patiala, Punjab, India. Each implant was inserted into a polyurethane foam block (Sawbones®, Pacific Research Laboratories, USA) with a density of 40 pounds per cubic foot (PCF), simulating D2 bone quality. Two osteotomies were prepared per block using a standardized surgical drilling [Figure 1]. A physio dispenser and torque wrench were used to ensure consistent insertion torque for all implants.

After insertion, the polyurethane blocks containing the implants were sectioned transversely for microscopic analysis [Figure 2]. The optical microscope (Keyence VHX-2000, Japan) was employed to visualize exfoliated titanium particles on the osteotomy walls. Field Emission Scanning Electron Microscopy (FE-SEM) (Carl Zeiss Sigma 500 FEG-SEM, Tokyo, Japan) was used to analyze particle morphology. Energy Dispersive X-ray Spectroscopy (EDS) was performed using ESPRIT

software to confirm the elemental composition of exfoliated particles, while Powdered X-Ray Diffraction (XRD) analysis (SmartLab SE, Rigaku, Japan) determined the crystallinity and metallic nature of the particles through characteristic diffraction peaks.

Statistical analysis: The quantitative data were analyzed using one-way ANOVA followed by Bonferroni post-hoc tests. The level of statistical significance was set at $p < 0.05$ for all comparisons.

Results

Optical microscopy revealed the presence of opaque, metallic particles deposited along the osteotomy walls in all groups. The particles appeared in clusters with differences in structure and density among different implant group. [Figure 3-6]. FE-SEM images confirmed the dispersion of titanium particles with irregular morphology across the sample surfaces. These particles exhibited a spherical morphology, with sizes ranging from (20-100 micro micrometers). In group 1 the particle size of the titanium particles ranged from 29.76-111.3 μm in Group 2 particle size was 26.46-115.7 μm . in Group 3 and Group 4 was 29.76-48.58 μm and 36.35-74.91 μm respectively [Figure 7-10]. The EDS spectra exhibited characteristic peaks for titanium, validating the metallic composition of the exfoliated debris. Along with the titanium particles, Energy-dispersive X-ray spectroscopy (EDS) analysis also indicate. The presence of other elements, such as oxygen (O), carbon, chlorine or nitrogen, and. Gold (Au) particles were seen [Figure 11-14]. Additionally, the XRD diffractograms confirmed metallic titanium through distinct peaks at $2\theta \approx 63^\circ$, indicating a crystalline structure. Group 1 showed the highest peak followed by group 2, group 4 and group 3 respectively [Figure 15-18].

Quantitative analysis demonstrated that Group 1 (SLA implants) exhibited the highest titanium mass percentage

(15.468%), followed by Group 2 (11.890%), Group 4 (10.588%), and Group 3 (9.258%) respectively. [Figure 19]. The mean titanium particle size was also largest in Group 152.255±19.512 μm, followed by Group 250.953±16.859 μm, Group 446.278±14.716 μm, and Group 341.070±7.990 μm. Statistical analysis showed significant differences (p<0.05) between the groups. While Group 3, the anodized surface implants, consistently exhibited the lowest titanium release and smallest particle dimensions.



Figure 1: Showing implant insertion in the block

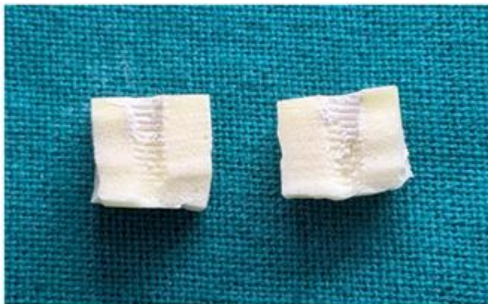


Figure 2: Showing sectioned block



Figure 3: Showing Sandblasted large-grit acid-etched surface under optical microscope

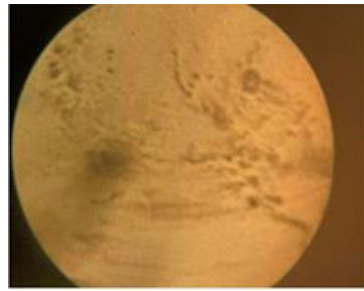


Figure 4: Showing Sandblasted with alumina acid etched surface under optical microscope

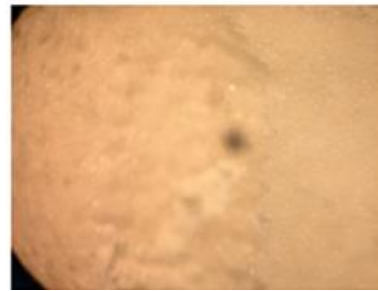


Figure 5: Showing An Anodised surface, under optical microscope



Figure 6: Showing Hydroxyapatite (HA)-coated implant under optical

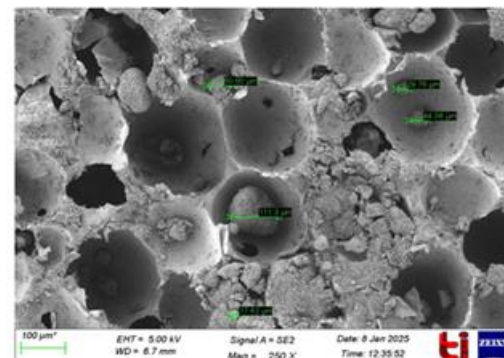


Figure 7: showing titanium particle size under FE-SEM in Group 1

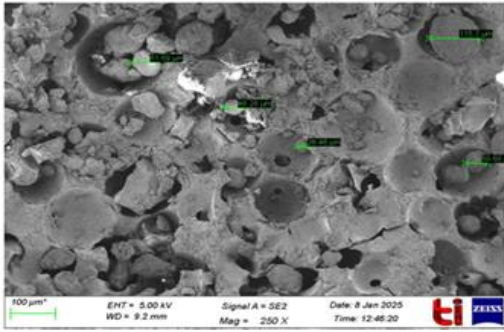


Figure 8: showing titanium particle size under FE SEM in Group 2

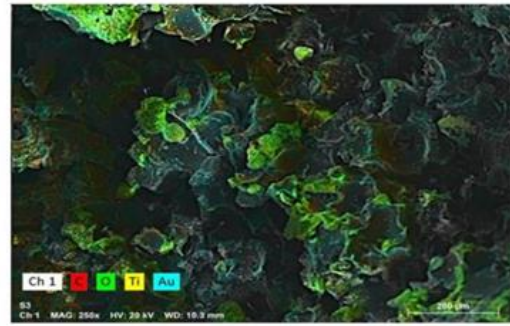


Figure 12: showing elemental mapping of Group 2 implants

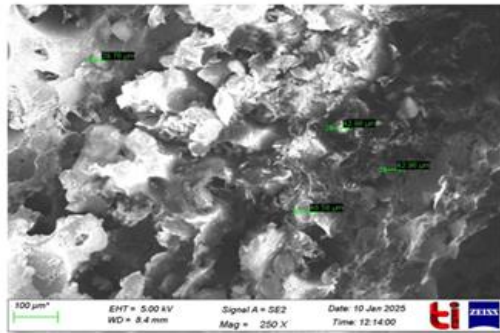


Figure 9: showing titanium particle size under FE SEM in Group 3

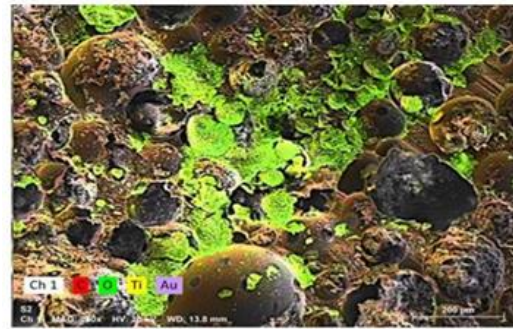


Figure 13: showing elemental mapping of Group 3 implants

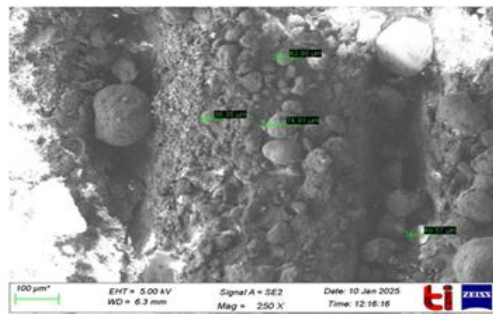


Figure 10: showing titanium particle size under FE SEM in Group 4



Figure 14: showing elemental mapping of Group 4 implants

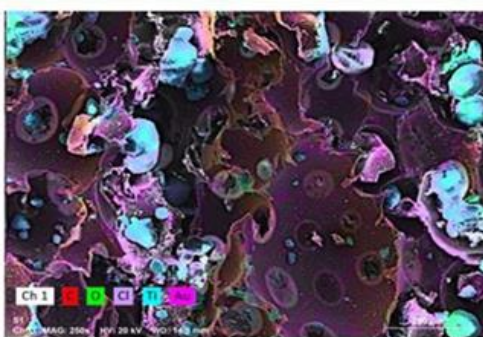


Figure 11: showing elemental mapping of Group 1 implants

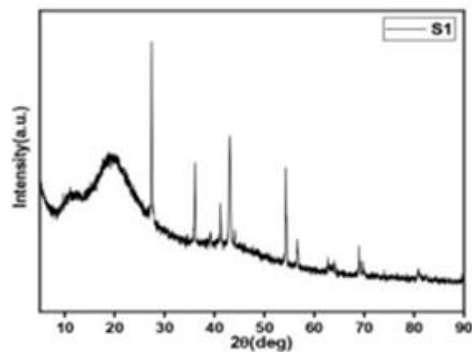


Figure 15: showing XRD Diffractogram peaks Group 1

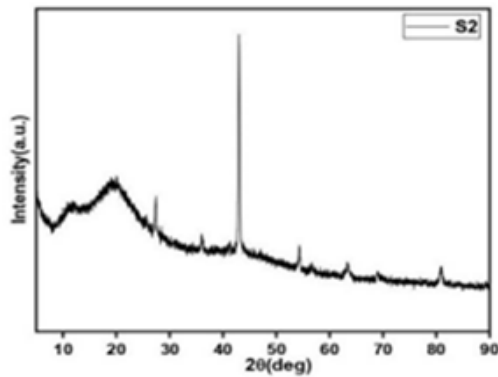


Figure 16: showing XRD Diffractogram peaks Group 2

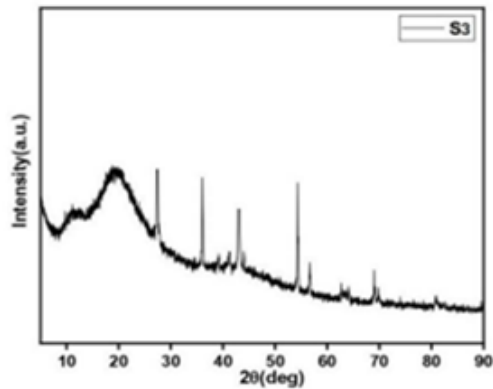


Figure 17: showing XRD Diffractogram peaks Group 3

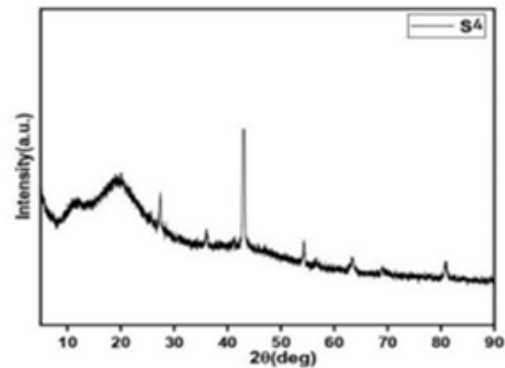
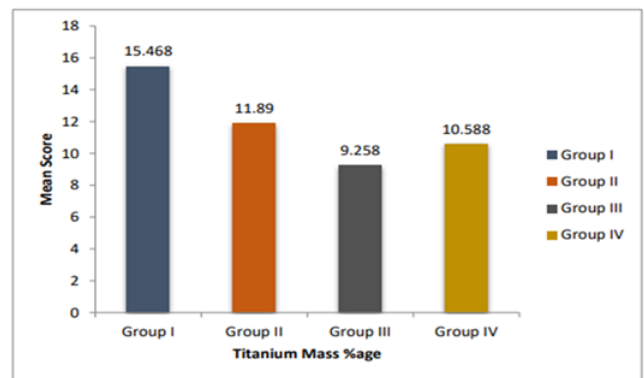


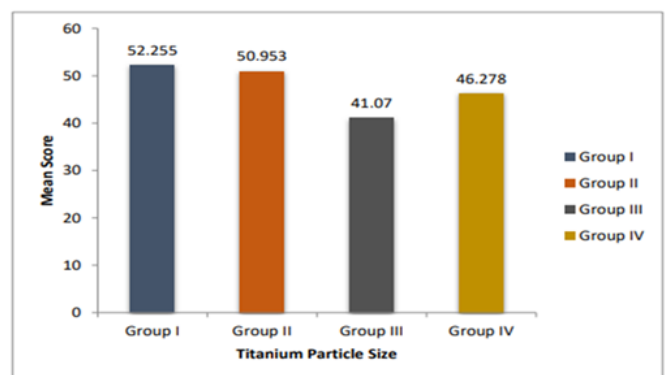
Figure 18: showing XRD Diffractogram peaks Group 4

Table 1 presents the intergroup comparison of the average titanium mass percentage, revealing significant differences between the groups, with a p-value of 0.001 ($F = 25.823$). Table 2 compares the mean differences of the average titanium mass percentage between the groups, with significant differences between Group I and Group III ($p = 0.000$), and Table 3 shows the intergroup

comparison of the average titanium particle size, where no significant differences were found ($p = 0.731$, $F = 0.436$). Graph 1-2 provides a graphical representation of this data, illustrating the comparison of titanium particle sizes and mass percentage among the groups. Finally, Table 4 compares the mass differences of the average titanium particle size across the groups, with significant differences observed between Group III and the other groups ($p = 0.000$ for Group III vs. Groups I and II), highlighting variations in particle size that could influence the properties of the materials studied.



Graph 1: Showing the intergroup comparison of average titanium mass percentage.



Graph 2: Showing Intergroup comparison of average titanium particle size

Table 1: Showing intergroup comparison of average titanium mass percentage

Groups	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		F value	P value	Significant
					Lower Bound	Upper Bound			
Group I	4	15.468	0.905	0.452	14.028	16.907	25.823	0.001	HS
Group II	4	11.890	1.259	0.630	8.886	12.894			
Group III	4	9.258	1.140	0.570	7.444	11.071			
Group IV	4	10.588	0.913	0.456	9.135	12.040			
Total	16	11.551	2.601	0.650	10.165	12.937			

Table 2: Showing intergroup comparison of mean difference of average titanium mass difference

VAR (I)	VAR (J)	Mean Difference (I-J)	Std. Error	P value	95 % Confidence Interval		Significant
					Lower Bound	Upper Bound	
Group I	Group II	4.578	0.753	0.043	2.342	6.813	S
	Group III	6.210	0.753	0.000	3.974	8.446	HS
	Group IV	4.880	0.753	0.010	2.644	7.116	S
Group II	Group I	-4.578	0.753	0.010	-6.813	-2.342	S
	Group III	1.633	0.753	0.187	-0.603	3.868	S
	Group IV	0.303	0.753	0.977	-1.933	2.538	NS
Group III	Group I	-6.210	0.753	0.000	-8.446	-3.974	HS
	Group II	-1.633	0.753	0.187	-3.868	0.603	S
	Group IV	-1.330	0.753	0.965	-3.566	0.906	NS
Group IV	Group I	-4.880	0.753	0.198	-7.116	-2.644	S
	Group II	-0.303	0.753	0.977	-2.538	1.933	NS
	Group III	1.330	0.753	0.935	-0.906	3.566	NS

Table 3: Showing intergroup comparison of mean difference of average titanium particle size

Groups	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		F value	P value	Significant
					Lower Bound	Upper Bound			
Group I	4	52.255	19.512	9.756	21.208	83.302	0.436	0.731	S
Group II	4	50.953	16.859	8.429	24.126	77.779			
Group III	4	41.070	7.990	3.995	28.356	53.784			
Group IV	4	46.278	14.716	7.358	22.861	69.694			
Total	16	47.639	14.480	3.620	39.923	55.355			

Table 4: Showing intergroup comparison of average titanium particle size

Groups	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		F value	P value	Significant
					Lower Bound	Upper Bound			
Group I	4	52.255	19.512	9.756	21.208	83.302			

Group II	4	50.953	16.859	8.429	24.126	77.779	0.436	0.731	S
Group III	4	41.070	7.990	3.995	28.356	53.784			
Group IV	4	46.278	14.716	7.358	22.861	69.694			
Total	16	47.639	14.480	3.620	39.923	55.355			

Discussion

The present in-vitro study highlights the mechanical consequences of different surface treatments on titanium dental implants during simulated surgical insertion. The findings underscore that surface topography exerts a pivotal influence on the degree of titanium particle exfoliation, which could have biological and clinical implications. The present investigation aligns with previous in-vivo and in-vitro studies emphasizing that the combination of mechanical friction and electrochemical reactions, known as tribocorrosion, plays a central role in the generation of metallic debris from titanium implants during placement.^{8,9}

When an implant is inserted into bone, high frictional forces occur at the bone-implant interface, especially at the crestal and apical regions where thread engagement is maximal. This mechanical stress can rupture the native titanium oxide layer, exposing the underlying metal to the physiologic environment. Repassivation of the oxide film follows, but the cyclic process of rupture and reformation results in the detachment of microscopic metallic particles. The quantity and morphology of these particles are significantly influenced by surface roughness, surface chemistry, and the nature of coating materials applied during manufacturing.

According to our study, sandblasted and acid-etched surfaces (Groups 1 and 2) exhibited the highest titanium particle release. This observation can be attributed to the aggressive topography generated by large-grit blasting and acid treatment, which increases the surface area but also introduces micro defects and residual stresses that compromise mechanical stability. Studies by Palmquist et

al. and Gilbert et al. have confirmed that such micro-irregularities amplify tribocorrosive wear during insertion, particularly in dense bone conditions.⁸⁻⁹ Additionally, the use of alumina particles in sandblasting can leave embedded residues that alter surface integrity and exacerbate titanium detachment under torsional stress.

Conversely, anodized surface implants (Group 3) demonstrated the least titanium exfoliation, suggesting that the thicker and more stable oxide layer formed during anodization enhances resistance to both mechanical and electrochemical degradation. The anodic oxide not only provides uniform porosity conducive to osseointegration but also offers a barrier against ionic dissolution and particle release. Sánchez-Siles et al. observed similar findings, noting that anodized surfaces exhibit improved corrosion resistance and mechanical stability compared to conventional roughened surfaces.^[11] The present results reinforce that the anodization process can effectively reduce tribological wear during insertion, thereby minimizing the risk of peri-implant inflammatory reactions linked to titanium particles.

In the present study Hydroxyapatite-coated implants (Group 4) demonstrated intermediate results. While HA coatings improve bioactivity and bone integration, they are brittle and can fracture under compressive or torsional forces during placement. These microfractures may expose the titanium substrate and contribute to localized particle generation. Hanawa et al.¹² reported that such microstructural discontinuities within HA layers could accelerate coating delamination, especially under repeated mechanical loading. Therefore, although

HA coatings confer biological advantages, their mechanical fragility warrants consideration in dense bone scenarios where higher insertion torque is applied.

The biological relevance of titanium particle release has been documented in numerous histological and molecular studies. Exfoliated particles can migrate into surrounding soft tissues, where they are phagocytosed by macrophages, stimulating the release of inflammatory mediators such as TNF- α , IL-1 β , and IL-6¹⁰. This inflammatory cascade may impair osteoblastic activity and enhance osteoclastic bone resorption, predisposing to peri-implantitis and marginal bone loss. Furthermore, recent evidence suggests that metallic nanoparticles can alter local microbiota composition, favoring pathogenic biofilm formation and aggravating peri-implant disease progression. Hence, surface designs that minimize mechanical wear not only preserve implant structural integrity but also contribute to long-term peri-implant tissue health.

Another critical aspect concerns the correlation between implant surface roughness and osseointegration dynamics. While rough surfaces promote mechanical interlocking and bone anchorage, excessive roughness may increase susceptibility to tribocorrosion. This paradox underscores the importance of optimizing surface parameters to balance biological and mechanical performance. Clinicians must also consider surgical variables such as insertion torque, bone density, and irrigation efficiency, which can modulate frictional forces and consequently influence titanium exfoliation.

Future research should incorporate animal and clinical studies to validate these findings and to assess the long-term biological response to titanium particles released during actual implant placement. Moreover, emerging surface modification technologies such as laser texturing, nanostructured coatings, and hybrid oxide layers may

offer promising avenues to achieve optimal osseointegration with minimal particle release.

Hence, the findings of this investigation reaffirm that surface modification is a double-edged sword: while enhancing osseointegration, it also modulates the mechanical wear characteristics of implants. Anodized surfaces appear to strike a favorable balance between bioactivity and mechanical resilience, thus representing a potential benchmark for future implant design innovations.

Conclusion

Within the limitations of this in-vitro investigation, it can be concluded that titanium particle exfoliation occurs across all implant surface types during simulated insertion procedures, although the extent varies significantly with surface modification. Sandblasted and acid-etched implants exhibited the highest degree of titanium release due to their pronounced surface irregularities and embedded abrasive residues, whereas anodized surface implants showed minimal exfoliation, attributed to their uniform oxide barrier and superior corrosion resistance. Hydroxyapatite-coated implants displayed intermediate results, suggesting a trade-off between bioactivity and mechanical durability.

Further in-vivo studies with long-term follow-up are warranted to validate these findings, explore particle-induced immunological effects, and refine surface modification technologies for improved clinical performance.

Clinical Significance

The present study provides important insights into the mechanical wear behavior of dental implants with different surface modifications. Excessive titanium particle release during surgical insertion may serve as an overlooked risk factor for peri-implant inflammation and early implant failure. By identifying anodized surfaces as

the least exfoliative, this research supports the clinical preference for such implants, particularly in patients with high bone density or history of peri-implant disease. Understanding surface–bone interactions at the microscopic level can guide clinicians toward evidence-based implant selection, minimizing inflammatory complications and improving long-term treatment success.

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