Research Article

Al₂O₃ Particles on Titanium Dental Implant Systems following Sandblasting and Acid-Etching Process

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Dental implants with moderately rough surfaces show enhanced osseointegration and faster bone healing compared with machined surfaces. The sandblasting and acid-etching (SA) process is one technique to create moderately rough dental implant surfaces. The purpose of this study was to analyse different commercially available implant systems with a SA-modified surface and to explore the widespread notion that they have similar surface properties regarding morphology and cleanliness. SA-modified surfaces of nine implant systems manufactured by Alpha-Bio Tec Ltd, Camlog Biotechnologies AG, Dentsply Sirona Dental GmbH, Neoss Ltd, OsstemImplant Co. Ltd, Institute Straumann AG, and Thommen Medical AG were analyzed using scanning electron microscopy (SEM) and energy dispersive X-rayspectroscopy (EDX) and examined for surface cleanliness. Six implants from three different lots were selected per each implant system. Mean particle counts for each implant and the mean size of the particles were calculated from three different regions of interest and compared using ANOVA and Tukey’s test. SEM analysis showed presence of particles on the majority of analyzed implant surfaces, and EDX evaluations determined that the particles were made of Al₂O₃ and thus remnants of the blasting process. SPI ELEMENT INICELL® and Bone Level (BL) Roxolid® SLActive® implant surfaces showed the highest mean particle counts, 46.6 and 50.3 per area, respectively. The surface of BL Roxolid® SLActive® implant also showed the highest variations in the particle counts, even in samples from the same lot. The mean size of particles was 1120 ± 1011 µm², measured for USIIIC AFixture implants, while the biggest particle was 5900 µm² found on a BL Roxolid® SLActive® implant. These results suggest that not all manufacturers are able to produce implant surfaces without particle contamination and highlight that the surface modification process with the SA technique should be appropriately designed and controlled to achieve a clean and consistent final medical device.

1. Introduction

Dental implant surfaces play a key role in osseointegration and thus continue to drive biomedical research investigations on how surface modifications affect osteogenic potential [1]. In the first decades since their introduction by P-I Brånemark [2, 3], dental implants had primarily machined surfaces, which were created by milling, turning, or polishing techniques. Although machined implants demonstrate high long-term survival rates following osseointegration process [4, 5], ex ante they require a relatively long healing time of 3 to 6 months depending on the anatomical location and the quality of bone [6] and are characterized by a relatively high rate of early failures [7]. One hypothesis to account for these early failures is that machined surfaces have an insufficient surface roughness to promote osteogenic cell attachment and bone deposition to form enough bone-to-implant interface. Subsequent research has revealed that moderate surface roughness, i.e., Sa range of 1-2 µm, provides optimal conditions to promote osseointegration [8]. In clinical studies, implants with moderately rough surfaces have demonstrated faster osseointegration and higher long-term survival rates compared with machined implants [4, 5, 9–12]. An increased surface area of moderately rough implant surfaces allows for better cell attachment, contact osteogenesis, and bone ingrowth, which result in improved implant stability and enable application of immediate and early loading protocols [13, 14].
Several processes to increase the surface roughness of titanium implant surfaces based on additive, subtractive, chemical, and electrochemical surface treatments can be used [1]. Major surface modification techniques include titanium plasma spraying, coating with hydroxyapatite, sandblasting, acid-etching, sandblasting combined with acid-etching, laser ablation, and anodization. Today, sandblasting and acid-etching (SA) and anodization are the two main surface modification techniques which are used for most of the available implants systems in the market. Anodization is an electrochemical treatment of the implant surface, where the thickness of the titanium oxide layer is increased using an electrolytic process [15]. New topography, chemistry, and degree of crystallinity of the implant surface after anodization depend on the amount of time and level of voltage during the electrolytic process. In the SA process, small hard ceramic particles such as Al\textsubscript{2}O\textsubscript{3} and TiO\textsubscript{2} or calcium phosphates are used to blast and create craters on the surface of machined implants (see Figure 1(a)). These particles range in size from 10 to several 100 μm and are projected at a high velocity through a nozzle by compressed air or a fluid [16]. Following blasting, the implants are immersed in a strong acid (e.g., HCl, H\textsubscript{2}SO\textsubscript{4}, HF, or HNO\textsubscript{3}) solution at elevated temperatures (see Figure 1(b)) to remove remnant blasting particle remnants on the surface of nine commercially available major implant systems produced by seven different manufacturers using a SA process [17, 18]. The anodization process in itself does not lend to the roughness is created by bombarding with particles that may potentially remain on the implant surface even after acid-etching [18–21]. Despite the large number of studies to investigate the surface properties of commercially available implant systems, a comprehensive study on the cleanliness of SA-modified implants systems is not yet available.

In this investigation, the quantity and distribution of blasting particle remnants on the surface of nine commercially available major implant systems produced by seven different manufacturers according to the SA process were analyzed: SPI NanoTec™ (Alpha-Bio Tec Ltd, Israel), Conealog® Promote® (Camlog Biotechnologies AG, Switzerland), Ankylos® Friadent plus® (Dentsply Sirona Dental GmbH, USA), ProActive® Straight Implant (Neoss Ltd, UK), USIII CA Fixture (Osstem Implant Co Ltd, USA), BLX Roxolid® SLActive® (Institute Straumann AG, Switzerland), Bone Level (BL) Roxolid® SLA® (Institute Straumann AG, Switzerland), BL Roxolid® SLActive® (Institute Straumann AG, Switzerland), and SPI*ELEMENT INICELL® (Thommen

![Figure 1: Schematic representation of the sandblasting (a) and acid-etching process (b).](image-url)

2. Materials and Methods

2.1. Samples. Nine commercially available implant systems produced by seven manufacturers using a SA process were analyzed: SPI NanoTec™ (Alpha-Bio Tec Ltd, Israel), Conealog® Promote® (Camlog Biotechnologies AG, Switzerland), Ankylos® Friadent plus® (Dentsply Sirona Dental GmbH, USA), ProActive® Straight Implant (Neoss Ltd, UK), USIII CA Fixture (Osstem Implant Co Ltd, USA), BLX Roxolid® SLActive® (Institute Straumann AG, Switzerland), Bone Level (BL) Roxolid® SLA® (Institute Straumann AG, Switzerland), BL Roxolid® SLActive® (Institute Straumann AG, Switzerland), and SPI*ELEMENT INICELL® (Thommen
were excluded from quantification. Additionally, an image Glattbrugg, Switzerland) and particles smaller than 10 were marked and numbered. The size of each particle quantify the number of particles in each ROI. Particles /two.fitted./two.fitted. Scanning Electron Microscopy (SEM) Analysis.

presentation in Table 1. between September 2018 and January 2019. Six implants selected from at least 3 different lots were analyzed for each implant system (total of 54 implants). The information on diameter, length, and lot of the investigated implants is presented in Table 1.

2.2. Scanning Electron Microscopy (SEM) Analysis. Implant surfaces were analyzed by SEM using a Zeiss Supra® 40 VP microscope (Oberkochen, Germany). The implants were carefully fixed in a clamp holder without touching their surface. Implants packed and delivered in a storage solution, i.e., Straumann implants with SLActive® surface, were rinsed before fixation in the clamp holder for 30 seconds with deionized water and dried with nitrogen. The implants were examined without surface sputtering. Images were acquired with an acceleration voltage of 20 kV using a backscatter electron detector.

Three zones were defined to evaluate the surface at the same position for all implants (see Figure 2): zone 1 (1 mm from the collar in the apical direction); zone 2 (4 mm from the collar in the apical direction); and zone 3 (2 mm from the apex in the coronal direction). Following the evaluation of the three zones, each implant was rotated by 180 degrees around the long implant axis and the evaluation repeated for the corresponding zones on the opposite side. Overview images at a magnification of x64 were captured in three regions of interest (ROI) corresponding to the three zones. ROI was a rectangle of 3 mm x 1.5 mm, except for zone 3 in SPI NanoTec™ and BL Roxolid® SLActive® implants, in which the ROI was measured to be 2.046 mm x 2.2 mm due to the narrow apex of the implants. Consequently, each ROI was a rectangle of 4.5 mm².

The SEM backscatter electron detector was used to quantify the number of particles in each ROI. Particles were marked and numbered. The size of each particle was measured using IMS software (Imagic Imaging Ltd., Glattbrugg, Switzerland) and particles smaller than 10 µm were excluded from quantification. Additionally, an image of each particle was taken and its elemental composition was determined using energy-dispersive X-ray spectroscopy (EDX) with backscatter electron detector.

2.3. Statistical Analysis. Statistical analyses were performed using R 3.5.1 (R Foundation for Statistical Computing, https://www.R-project.org) with algorithms based on standard libraries. Analysis of Variance (ANOVA) modelling was used to compare particle counts and particle sizes based on the implant brand, lot, and zone of measurement. Fitted ANOVA values of implant brands were compared using Tukey’s Honest significance test (family-wise significance level of 0.05). Variances were compared using two-sample F-tests.

3. Results

3.1. Presence of Particles on the SA-Modified Implant Surface. SEM showed presence of remnant particles on all tested implant surfaces, with the exclusion of Ankylos® Friadent plus® (see Figure 3). The mean counts of remnant particles in the six zones per implant varied between different implant systems. The mean particle counts were higher for surfaces manufactured by Thommen Medical and Institute Straumann compared with the other implant systems (see Figure 4(a) and Table 2). According to the ANOVA model, the difference between particle counts on SPI®ELEMENT INICELL®, BL Roxolid® SLActive®, BL Roxolid® SLA®, and BLX Roxolid® SLActive® implant surfaces and the other tested implant systems was statistically significant (all p<0.05), with the exception of the difference between BLX Roxolid® SLActive® and SPI NanoTec™ (p=0.20).

3.2. Variation in Particle Counts. Variation in the counts of remnant particles was evaluated for a combination of implants from the same or different manufactured lots for each implant system. Implant systems BL Roxolid® SLActive® and BL Roxolid® SLA® showed a higher variation in particle counts compared with those in other implant systems (see Figure 4(b)). Moreover, BL Roxolid® SLActive® and BL Roxolid® SLA® implant surfaces obtained from the same lot displayed a high degree of variation in particle counts (see Figure 4(b)). According to two-sample F-tests used for pairwise comparisons, variances of particle count were significantly different for all implant systems (all p<0.05), with the exclusion of SPI NanoTec™ vs. BLX Roxolid® SLActive® (p=0.56), ProActive® Straight Implant vs. USIII CA Fixture (p=0.05), and SPI®ELEMENT INICELL® versus BL Roxolid® SLA® (p=0.27).

3.3. Elemental Composition, Morphology, and Size of the Particles. EDX analysis showed that the particles were composed of Al and O (see Figure 5), suggesting that they were Al2O3 particle remnants of the blasting process. Most particles revealed a brittle and cracked morphology (see Figure 6(a)) and were protruding from the surface up to 30 microns (see Figure 6(b)). Mean size of the particles varied from 159 to 1120 µm², with particles remaining on BL Roxolid® SLActive® implant showing an individual size of up to 5900 µm² (see Table 2 and Figure 7).
Table 1: Implant size (ø [mm]x length [mm]) and lot number for 6 tested implant specimens per each implant system.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Implant system</th>
<th>Alpha-BioTec</th>
<th>Camlog Biotechnologies</th>
<th>Dentsply Sirona</th>
<th>Neoss</th>
<th>Ostem</th>
<th>Institute Straumann</th>
<th>Thonnmen Medical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SPI NanoTec™</td>
<td>Conelog™</td>
<td>Ankylos™</td>
<td>ProActive™</td>
<td>USII CA Fixture</td>
<td>BL Roxolid™</td>
<td>BL Roxolid™</td>
<td>BL Roxolid™</td>
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<tr>
<td>Specimen 1</td>
<td>4.2 x 10.0</td>
<td>4.3 x 9.0</td>
<td>4.5 x 9.5</td>
<td>4.0 x 9.0</td>
<td>4.0 x 10.0</td>
<td>4.5 x 10.0</td>
<td>4.1 x 10.0</td>
<td>4.1 x 10.0</td>
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<td></td>
<td>17188537</td>
<td>7.8276</td>
<td>BI80004244</td>
<td>23229</td>
<td>PW721</td>
<td>NZ528</td>
<td>PM914</td>
<td>17983</td>
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<tr>
<td>Specimen 2</td>
<td>4.2 x 10.0</td>
<td>4.3 x 9.0</td>
<td>4.5 x 9.5</td>
<td>4.0 x 9.0</td>
<td>4.0 x 10.0</td>
<td>4.5 x 10.0</td>
<td>4.1 x 10.0</td>
<td>4.1 x 10.0</td>
</tr>
<tr>
<td></td>
<td>18091176</td>
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<td>23921</td>
<td>PW721</td>
<td>RJ536</td>
<td>RK729</td>
<td>17029</td>
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<td>Specimen 3</td>
<td>4.2 x 11.5</td>
<td>4.3 x 11.0</td>
<td>4.5 x 11.0</td>
<td>4.0 x 11.0</td>
<td>4.0 x 11.0</td>
<td>4.5 x 12.0</td>
<td>4.1 x 12.0</td>
<td>4.1 x 12.0</td>
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<td>17128176</td>
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<td>BI80002597</td>
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<td>PM658</td>
<td>PZ373</td>
<td>16987</td>
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<tr>
<td>Specimen 4</td>
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<td>4.3 x 11.0</td>
<td>4.5 x 11.0</td>
<td>4.0 x 11.0</td>
<td>4.0 x 11.0</td>
<td>4.5 x 12.0</td>
<td>4.1 x 12.0</td>
<td>4.1 x 12.0</td>
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<tr>
<td></td>
<td>18106872</td>
<td>81025</td>
<td>BI70008678</td>
<td>23832</td>
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<td>RG324</td>
<td>PK477</td>
<td>17911</td>
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<td>4.5 x 14.0</td>
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<td>17077554</td>
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<td>MN169</td>
<td>KT049</td>
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<td>4.5 x 14.0</td>
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<td>4.0 x 13.0</td>
<td>4.5 x 14.0</td>
<td>4.1 x 14.0</td>
<td>4.1 x 14.0</td>
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<td></td>
<td>18079733</td>
<td>78279</td>
<td>BI70084366</td>
<td>23338</td>
<td>RA929</td>
<td>RA926</td>
<td>NZ636</td>
<td>18030</td>
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Table 2: Quantification of remnant particle counts and sizes in the ROIs.

<table>
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<tr>
<th>Implant manufacturer</th>
<th>SPI NanoTec™</th>
<th>Camlog Biotechnologies</th>
<th>Dentsply Sirona</th>
<th>Neoss</th>
<th>Ostem</th>
<th>Institute Straumann</th>
<th>Thommen Medical</th>
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<tbody>
<tr>
<td><strong>Particle count</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Mean ± SD</td>
<td>5.3 ± 5.7</td>
<td>1.7 ± 1.9</td>
<td>0.0 ± 0.0</td>
<td>0.1 ± 0.2</td>
<td>0.2 ± 0.4</td>
<td>16.4 ± 5.0</td>
<td>38.9 ± 13.5</td>
</tr>
<tr>
<td>Range (min; max)</td>
<td>(0;13)</td>
<td>(0;6)</td>
<td>NA</td>
<td>(0;1)</td>
<td>(0;1)</td>
<td>(0;33)</td>
<td>(0;134)</td>
</tr>
<tr>
<td><strong>Particle size</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean ± SD [μm²]</td>
<td>508 ±318</td>
<td>457 ±398</td>
<td>NA</td>
<td>159</td>
<td>1120 ±1011</td>
<td>909 ±511</td>
<td>570 ±413</td>
</tr>
<tr>
<td>Range (min; max)</td>
<td>(114; 2283)</td>
<td>(189; 2407)</td>
<td>NA</td>
<td>(159; 159)</td>
<td>(348; 2266)</td>
<td>(196;3082)</td>
<td>(26; 3357)</td>
</tr>
<tr>
<td>n of particles</td>
<td>96</td>
<td>30</td>
<td>NA</td>
<td>1</td>
<td>3</td>
<td>296</td>
<td>752</td>
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</table>

**Note:** In some cases, data is not available (NA).
4. Discussion

Dental implants with moderately rough surfaces osseointegrate faster and their use has significantly decreased early failures and enabled application of immediate loading protocols [4, 5, 10]. Different dental implant manufacturers have developed different techniques to achieve moderate roughness, including titanium plasma spraying, coating with hydroxyapatite, sandblasting, acid-etching, laser ablation, sandblasting combined with acid-etching (SA), and anodization (Figure 8).

Since its introduction in the early 1990s [22], the SA process has become widely used by several implant manufacturers. However, because this manufacturing process involves bombarding the implant surface with particles that may potentially remain on the implant surface even after acid-etching, it is possible that the resulting products contain remnant particle contamination [18–21].

The results of the current analysis on 9 major dental implant systems modified with the SA process demonstrate that most surfaces of sterile-packaged, commercially available dental implants contain particle contamination. EDX analysis demonstrated that the detected particles were Al₂O₃, indicating that they were remnants from the blasting step of the manufacturing process. These results confirm the findings of a previously published study, which showed that Al₂O₃ particles might cover up to 14.4% of the implant surface [18].

Overall, the present study reveals that the analyzed titanium dental implants do not have similar surface properties, even though they were all created using the SA process. Lack of adequate control over the blasting and acid etching process appears to result in blasting particles being wedged into the surface of the implant and not being fully removed during acid etching. In consequence, the final product may contain high numbers of blasting particle remnants, as detected for investigated Straumann BL and BLX implants as well as for Thommen INICELL implant line. Moreover, the low count of particle remnants observed in other implant systems manufactured by, e.g., Dentsply Sirona suggested that the SA manufacturing process can be controlled to achieve minimal levels of particle remnants.
Figure 4: Particle count variation in 9 implant systems: (a) box plot of surface particle counts in 9 implant systems; (b) variations in surface particle counts; different markers indicate implants of different lots.
Variation in the count of remnant particles also differed within manufacturer and their implant lines, with the BL Roxolid® SLActive® surface showing the highest variation, even when the assessment was made on implants originating from the same manufacturing lot. This finding supports our hypothesis that the SA manufacturing parameters and process control are not similar across brands.

Furthermore, the size of the remnant particles was different. The largest measured size of a particle was 5900 $\mu$m$^2$ for BL Roxolid® SLActive® implant system, and the largest mean was 1120±101 $\mu$m$^2$ measured for USIII CA Fixture. SEM analysis revealed that the blasting particle remnants have a brittle, cracked morphology and are protruding from the surface, suggesting an unstable arrangement of these particles on the implant surface. One might expect that, due to their partial inclusion to respective surface, these particles may become dislodged and migrate during implant insertion. This hypothesis is supported by a recent study showing that the surface roughness of the SLA implant system decreases significantly after insertion [21, 23]. The clinical relevance of the remnant particles is unknown today; however, possible local or systemic adverse effects of this contamination cannot be fully excluded. Because surface contamination can be avoided in the production process as
Figure 7: Box plot of particle size on 9 implant systems.

Figure 8: SEM micrographs of different moderately rough implant surfaces in the market: (a) hydroxyapatite coated, (b) acid etched, (c) Ca₃(PO₄)₂ blasted, (d) TiO₂ blasted, (e) sandblasted and acid-etched, and (f) anodized. Scale bar: 20 μm.

shown by some manufacturers, clinicians should be able to expect a clean implant surface when treating their patients.

5. Conclusions

Implant surface quality cannot be assessed by visual inspection. Clinicians must be able to trust the implant manufacturer that the manufacturing process was appropriately designed and adequately controlled so that the final product meets their quality expectations. This study revealed that not all manufacturers provide such quality assurance. The findings highlight that adequate process control over surface modification using the SA technique is paramount for achieving a clean and consistent final medical device prior to placement in a patient.
Data Availability

The raw data used to support the findings of this study are restricted due to commercial confidentiality. Data are available from Sebastian Bauer for researchers who meet the criteria for access to confidential data.

Disclosure

This research did not receive any grants from funding agencies in the public, commercial, or not-for-profit sectors. Investigated implants were provided by Nobel Biocare Services AG, Kloten, Switzerland.

Conflicts of Interest

The authors declare no potential conflicts of interest with respect to the authorship and/or publication of this article. Peter Schüpbach and Roland Glauser act as consultants to Nobel Biocare Services AG outside the submitted work. Sebastian Bauer is currently an employee of Nobel Biocare Services AG and participated in the study as a contributing scientist.

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