In Vitro Evaluation of Titanium Exfoliation During Simulated Surgical Insertion of Dental Implants

Sathyanarayanan Sridhar, MS
Thomas G. Wilson Jr, DDS
Pilar Valderrama, DDS
Pilanda Watkins-Curry, PhD
Julia Y. Chan, PhD
Danieli C. Rodrigues, PhD*

Dissolution of titanium wear particles in the oral environment, and their accumulation in the surrounding tissues have been associated with failure of dental implants (DI). The goal of this study is to investigate the effect of mechanical forces involved in surgical insertion of DI on surface wear and metal particle generation. It was hypothesized that mechanical factors associated with implant placement can lead to the generation of titanium particles in the oral environment. The testing methodology for surface evaluation employed simulated surgical insertion, followed by removal of DI in different densities of simulated bone material. Torsional forces were monitored for the insertion and removal of DI. The surface of the simulated bone materials was inspected with optical microscopy to detect traces of metallic particles that may have been generated during the procedure. Further characterization of the composition of powders collected from osteotomy cavities was conducted with powder X-ray diffraction. The results showed that the different densities of simulated bone material affected the torsional forces associated with implant insertion. However, the mechanical factors involved in the implant insertion/removal procedure did not generate wear particles, as confirmed by powder X-ray experiments.

Key Words: dental implant, titanium, peri-implantitis

INTRODUCTION

The ability of titanium to osseointegrate propelled the titanium (Ti) dental implants (DI) industry into accelerated development and commercial success.1 In the United States, approximately 500 000 patients undergo surgical insertion of DI every year2 with reported success rates of about 95%.3 It has been demonstrated that the success of an implant depends on bone quality and volume, peri-implant clinical parameters, and implant stability.4,5 It can be noted that bone quality and degree of surgical trauma correlate with biological failure of implants.6 Higher ratio of compact to trabecular bone in the mandible leads to higher survival rates of implants inserted in the anterior mandible than in the maxilla.7 In addition, bone density along the same jaw can vary considerably. For example, the density of bone in the mandible is reported to vary from 0.31 g/cm³ to 0.55 g/cm³.8 Clinical failures of dental implants have also been associated with early postsurgical stages where blood supply, bone healing, and primary stability play key roles.9

To promote successful osseointegration and faster bone healing, various types of surface treatments can be imparted on the surface of DI. These include surface blasting, acid etching, plasma spraying, and anodization, among others.10 These surface treatments could generate loose titanium particles in bone tissues.11 The release of abraded wear particles depends on the structure of the surface, roughness, and topographical configuration.12 It has been suggested that increased surface roughness may enhance the progression of peri-implantitis.13 Peri-implantitis is the continuous loss of bone surrounding an osseointegrated implant due to destructive inflammatory reactions.14 There is an increasing prevalence of this clinical condition, leading to failure of DI.15 There are several potential etiological factors for peri-implantitis,16–20 among which the release of titanium particles remains to be a potential cause for peri-implant disease.21 The accumulation of titanium particles and ions in tissues surrounding implants has been reported in the literature.22,23 These free titanium ions were shown to form complexes with native protein leading to type IV hypersensitive reaction.24 This allergic reaction was confirmed in a study involving 1500 patients with dental implants.25 It was also reported that failure of implants can occur in patients who are sensitive to any other metals.26
Release of titanium may occur even before functional loading of an implant. Insertion of a dental implant can cause friction and abrasion against hard tissues. Dynamic localized spots are randomly created during insertion procedures, generating areas of stress concentration that may compromise the integrity of surface features and release metal particles. Previous in vivo studies have shown the effect of insertion and dissemination of titanium particles to lymph nodes, distant organs of the body in beagle dogs and in sheep. Cellular uptake and subsequent lysosomal degradation may occur, leaving some partially degraded particles so that subsequent transport into local blood vessels and to distant organs is likely. Previous research also reveals that insertion procedures can release up to 0.5 mg of particles at bone-implant interfaces. It has been reported that only 0.2–0.3 mg of loose titanium particles is required for triggering aseptic loosening of implants.

The possibility of titanium wear from implant insertion procedures and its contribution to peri-implantitis make it important to develop a better evaluation of the potential for surface exfoliation during implantation. Therefore, the primary goal of this work is to evaluate the effect of surgical insertion of DI in different densities of simulated bone materials. The current study considers a worst-case scenario of effects of insertion and removal of an implant on the premature exfoliation of titanium. Microscopy was carried out to evaluate the surface features of the osteotomy sites postextraction of implants from simulated bone materials, and powder X-ray diffraction was used to determine the composition of wear products generated during the procedures.

### Materials and Methods

#### Materials

Sixteen (Straumann USA LLC, Andover, Mass) sandblasted, large grit, and acid etched, and freshly packaged commercial DI consisting of two groups were used for the in vitro insertion testing. No additional surface treatment, cleaning, or sterilization procedure was performed after opening the implant package. Group 1 consisted of 8 (4.8 × 7.0 mm) dental implants, and group 2 consisted of 8 (4.1 × 6 mm) dental implants. Polyurethane foam blocks of different densities—referred to as “sawbones” (Sawbone Inc, Vashon, Wash)—were used as the simulated bone materials. A simulated bone material was used because of the variations in quality and density found with natural bones, which could affect the reliability and validity of the results. Also, polyurethane foam blocks are the ASTM recommended material substitute for bone because of its anisotropy and heterogeneity. In addition, these materials are available in composite models. Four different densities of sawbones (10, 20, 30, and 40 pounds per cubic foot [PCF]) were selected to simulate the varying bone densities of the population receiving DI. Misch classification of bone density is elaborated in Table 1.

#### Table 1

<table>
<thead>
<tr>
<th>Sawbone Density (Per Cubic Foot)</th>
<th>Bone Density (g/cm³)</th>
<th>Representative Bone Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.16</td>
<td>Low density bone (D1)</td>
</tr>
<tr>
<td>20</td>
<td>0.32</td>
<td>Low density bone (D1)</td>
</tr>
<tr>
<td>30</td>
<td>0.48</td>
<td>Medium density (D2)</td>
</tr>
<tr>
<td>40</td>
<td>0.64</td>
<td>Medium density (D2)</td>
</tr>
<tr>
<td>50</td>
<td>0.80</td>
<td>High density (D3)</td>
</tr>
</tbody>
</table>

**Figure 1.** Sawbone block prepared for implant insertion testing and schematics of full cycle of insertion and removal of an implant.
**Table 2**

Torsional forces measured during insertion and removal of dental implants in/from sawbones of increasing densities. Results are illustrated for two implant specimens (#1 and #2) per density group.

<table>
<thead>
<tr>
<th>Sawbone Density (Per Cubic Foot)</th>
<th>Insertion Torque</th>
<th>Removal Torque</th>
<th>Insertion Torque</th>
<th>Removal Torque</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#1 (N.cm)</td>
<td>#1 (N.cm)</td>
<td>#2 (N.cm)</td>
<td>#2 (N.cm)</td>
</tr>
<tr>
<td>Group 1: Dental implants (4.8 × 7.0 mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>–20</td>
<td>20</td>
<td>–20</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>40</td>
<td>60+</td>
<td>60+</td>
<td>60+</td>
<td>60+</td>
</tr>
<tr>
<td>Group 2: Dental implants (4.1 × 6.0 mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>&lt;15</td>
<td>&lt;15</td>
<td>&lt;15</td>
<td>&lt;15</td>
</tr>
<tr>
<td>20</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>30</td>
<td>35</td>
<td>40</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>40</td>
<td>50</td>
<td>35</td>
<td>50</td>
<td>30</td>
</tr>
</tbody>
</table>

**Implant insertion**

Sawbones of each density of (PCF) were cut in blocks of 50 mm × 25 mm. Each density that was investigated received insertion of two dental implants. The preparation of implant site and insertion were performed following actual surgical procedures and using surgical instrumentation, as illustrated in Figure 1. Two “osteotomies” were drilled in each sawbone block using a standard surgical drill sequence (round burr, 2.2 mm, 2.8 mm, and 3.5 mm drills). After insertion of two implants in these osteotomies, each implant was de-torqued using a torque wrench and removed from the block. The procedure is summarized and illustrated in Figure 1. The torque required for the insertion and removal of the specimens was monitored with a standardized surgical torque wrench, which has an upper limit of 60 N.cm.

**Surface analysis**

The surface of the insertion site in the sawbone blocks was analyzed with digital optical microscopy post-testing (Keyence VHX 2000, Itasca, Ill). The analysis was performed to verify the presence of particle debris or other features that may have been produced by insertion or removal of the implants. The blocks were then sectioned transversally for further microscopic and diffraction analysis. For each density of sawbone block (10, 20, 30, and 40 PCF), two implants were subjected to insertion/removal procedures. Post-implant removal, powdered samples extracted from sawbone osteotomy walls were characterized by powder X-ray diffraction (XRD) (D8 Advance Powder X-Ray Diffractometer, Bruker, Billerica, Mass) operated at 40 kV and 30 mA with a Cu Kα radiation source equipped with a Lynxeye XE detector. X-ray diffraction data were collected using Bragg Brentano geometry from 10° to 80° using a step size of 0.02° at a rate of 0.1 second per step. Control samples (powdered sawbone block material that did not come in contact with an implant) were also evaluated with XRD for comparison with the material obtained from the insertion/removal test.

**Results**

**Implant insertion**

The normal recommended torque value for implant insertion by the manufacturer is 35 N.cm. Table 2 shows the measured insertion and removal torques during insertion of the two groups of implants using increasing densities of sawbones. The insertion torque for both groups of implants in 10 and 20 PCF was less than or equal to 20 N.cm. The 30 PCF materials provided the ideal conditions for implants to be inserted with an insertion force of 35 ± 5 N.cm for both group 1 and 2. The maximum torque of 60+ N.cm was recorded for the insertion of group 1 (4.8 × 7.0 mm) implants in 40 PCF block, whereas a lesser force of 50 N.cm (in 40 PCF) was needed for group 2 (4.1 × 6.0 mm) insertion. Removal torque was the same as the insertion torque with respect to each implant in group 1, while group 2 implants involved a lesser removal torque compared to the insertion procedure. It is clear from the results that insertion and removal torisional forces increased with an increase in sawbone density (from 10–40 PCF). It should be noted that insertion of group 1 (Table 2) dental implants in 40 PCF foam blocks was difficult due to the compact density of the material; therefore, only 3 mm of the implant body could be inserted. This was reflected in the torque required for insertion and removal, which was more than the actual limit (60 N.cm) of the torque wrench. The procedure simulated actual insertion and removal of a dental implant. Note that the low-density materials (10 and 20 PCF) were selected to simulate soft (cancellous) bone, while denser sawbones simulated the properties of hard (cortical) bone. The test could not be performed with sawbone material with a density of 50 PCF, because insertion of the implants in such dense material proved to be impossible. Hence, 30 and 40 PCF materials were considered to be representative of cortical bones. The density of 30 and 40 PCF was equivalent to the range of bone densities in the mandibular region, which range from 0.31 g/cm³ to 0.55 g/cm³.

**Analysis of sawbone**

Microscopic analysis of sections of sawbone blocks showed a presence of exfoliated materials deposited on the osteotomy walls of the testing blocks. Figures 2a and e and Figures 2b and f show an aggregate of particles (arrow marks) on the 10 PCF and 20 PCF blocks, respectively. Figures 2c and g and Figures 2d and h show a much more scattered spread of particles (arrow marks) on the surface of 30 PCF and 40 PCF blocks. The particles appeared to be of a metallic nature as shown by the dark coloration when macroscopically inspected. The same trend was seen in both groups of dental implants. Therefore, powdered samples from the sections of the sawbone blocks containing these particles were further characterized by powder XRD for confirmation of materials composition.

Diffraction analysis of the powdered samples extracted from the sites of blocks inserted with the implants did not show any presence of metal traces, specifically titanium or other alloy components, as shown in Figures 3 and 4. The XRD analysis of all specimens investigated from the different sawbone densities or groups showed similar diffraction patterns to those of control samples. Figure 3 shows diffraction patterns of group 1,
FIGURE 2. (a through d) Group 1 dental implants. (e through h) Group 2 dental implants. Particle deposition (marked with black arrows) observed in the site of insertion (osteotomy) postremoval of implants in sawbone of different densities: (a, e) 10 per cubic foot (PCF), (b, f) 20 PCF, (c, g) 30 PCF, (d, h) 40 PCF.

FIGURE 3. X-ray diffraction patterns of ground specimen extracted from sawbone blocks with densities of (a) 10 per cubic foot (PCF), (b) 20 PCF, (c) 30 PCF, (d) 40 PCF, subjected to insertion/removal of Group 1 implants. Red and blue trace represents two specimens obtained from sawbone extraction from the site of insertion (osteotomy) postremoval of implants. Black trace represents sawbone specimen that was not subjected to insertion of implant.
where the red and blue traces represent diffraction patterns of specimens collected from two implant cavities of each density of sawbone blocks. The black trace refers to the diffraction pattern of the control specimen extracted from blocks that were not subjected to insertion/removal of implants. It can be noted that diffraction patterns are not significantly different from the control sample.

Figure 4 shows four diffraction patterns for each sawbone block density postremoval of group 2 implants. Two curves (red and blue) belong to the powdered sawbone specimen extracted from the two implant cavities. The third curve (green) was an additional sawbone sample with a combination of powdered specimen from both implant cavities. This was done because the dimension of group 2 implants was small and the area available for sample extraction was limited. Hence, to confirm and eliminate the possibility of titanium dispersion, an additional specimen was analyzed. The fourth curve (black) was the control sample. As in group 1, XRD patterns of group 2 and microscopy analysis confirmed that the particle deposition observed on the blocks were not of metallic nature.

**DISCUSSION**

This study evaluated the effect of the mechanical forces involved in the surgical insertion on the surface of dental implants by using sawbones of several densities to simulate insertion in bones of varying densities. It was hypothesized that insertion forces could induce premature breakage of the titanium oxide layer, resulting in particle debris generation. Wear debris depositing in surrounding tissues can induce an inflammatory response if the debris remains in the implantation site.\(^{21-23}\)

An insertion test showed the incremental torque required for implant insertion/removal with increasing density of the sawbone material used, as expected. This is in agreement with previous studies where insertion tests were performed to understand the primary stability of the implant. The maximum insertion and removal torque previously recorded was 115.2 ± 31.1 N.cm and 102.9 ± 36.4 N.cm, respectively, for an etched implant using undersized technique.\(^{37}\) In our study, the maximum torque experienced was 60+ N.cm recorded for group 1 implants inserted in 40 PCF sawbone blocks. This was less than the reported maximum because the implant was...
torqued inside until it reached the maximum limit of the surgical torque wrench (60 N.cm). In another study, the insertion torque required for placing an implant in 40 PCF sawbone was recorded to be approximately 31.7 ± 7.53 N.cm.\(^3\) In this experiment, the insertion torque for insertion in 40 PCF ranged between 30–60 N.cm over two different groups of implants with varying dimensions. Implant dimension has been suggested to be one of the important implant-related factors affecting insertion torque.\(^3\) In addition, clinical studies have established several factors in vivo that could affect the insertion torque, such as (1) implant flanges impinging on crestal cortical bone, (2) implant bottoming out at a base of prepared bone, (3) engagement of lower cortical bone layer by apical portion of implant, (4) generation of friction as full length inserts into bone, and (5) resistance of interfacial bone to local compression in a tapered implant.\(^4\)

Insertion torque is also a very important parameter in the surgical insertion of dental implants because excessive forces—exceeding physiological limits—can lead to bone resorption and implant failure due to pressure-induced necrosis.\(^1,4\) Clinical results indicate that insertion torques of about 40 N.cm increase the success rate of implants.\(^3\) In the present study, it was noted that implant removal torques were equal to or less than insertion torques. This correlated with a previous study under a similar scenario, where the restricted viscoelastic property of surrounding artificial bone was considered as the main reason.\(^4\) The removal step performed with the implants in this study was not meant to replicate actual surgical removal of an implant, but it was conducted to remove the implant and expose the osteotomy site for further analysis. It also provided a worst-case scenario for titanium exfoliation because the implant was subjected to both insertion and removal forces.

Postexperiment microscopic analysis of the surface of the sawbone blocks showed particle deposition (in the form of black deposits) surrounding the implant osteotomy. These particles were concentrated in the 10 and 20 PCF blocks, and deposition was observed to be more scattered with the 30 and 40 PCF blocks, as illustrated in Figures 2a through h. Inspection of the particles raised the question whether the particles were metallic or polyurethane (from friction of the implant against the sawbone walls) in nature. It is important to understand the nature of particles deposited on the sawbone surface because metallic debris has been observed in peri-implant tissues and peri-implantitis biopsies.\(^2,23\) Dissolution of metal ions in the oral environment has been considered as one of the triggering factors for peri-implantitis, and also has been shown to trigger type IV hypersensitivity.\(^2,14\) Synergistic effects of bacterial biofilm and occlusal overloading in the oral environment have been considered as a triggering factor for surface degradation.\(^2\) Thus, it is essential to understand the effects of abrasion of the implant surface against bone during surgical insertion procedures. Hence, powdered samples were obtained from the sawbone blocks and further inspected with XRD. The diffraction patterns of all powdered samples showed curves similar to the control sample. Hence, it was confirmed that the powdered samples contained no traces of Ti or Ti oxide with all the sawbones densities (10–40 PCF) investigated, as shown in Figures 3 and 4. Thus, it can be concluded that particle deposition shown in the microscopic analysis (Figure 2a through h) was not from titanium wear, but rather polyurethane (sawbone material) debris. The debris could have resulted from the drilling performed in preparation of the implant site. The particle deposition could have also resulted from the frictional effect generated against the surface of the sawbone walls during implant insertion.

The results of this study indicate that the likelihood of prematurely damaging the surface of a dental implant with a sandblasted, large grit, acid-etched surface, and inducing metallic particle debris during insertion procedures may be low. These observations were purely based on microscopy and diffraction results; therefore, future testing is warranted to evaluate the occurrence of such phenomenon using dental implants with different surfaces and additional techniques. This study is part of a series of testing conditions that will investigate the effect of mechanical and electrochemical factors on the surface of dental implants. Future studies will include evaluation of the synergistic effects of bacteria and mechanical loads, as well as their individual roles, on triggering corrosion and wear of the surface of dental implants.

**Conclusion**

An in vitro evaluation was carried out regarding premature exfoliation of metallic particles during surgical insertion of dental implants in different densities of simulated bone material. The results clearly showed that different bone densities affect the mechanical forces associated with the insertion procedure. It was hypothesized that torsional insertion would generate titanium oxide particles due to abrasion during insertion. However, XRD analysis confirmed that there was no premature exfoliation due to the implant insertion procedure. The evaluation of sources of metallic particle generation is critical, given that recent studies have shown that metallic ion and particles released from implant surface can contribute to inflammatory processes.

**Abbreviations**

DI: dental implants  
PCF: pounds per cubic foot  
Ti: titanium  
XRD: X-ray diffraction

**Acknowledgments**

The authors would like to thank the American Academy of Implant Dentistry Foundation (grant number 1590) for providing financial support for conducting this research. The authors also acknowledge Saad Hasan Gul and Anie Thomas for technical support.

**References**

In Vitro Evaluation of Titanium Exfoliation


