A Comparison Study of the Osseointegration of Zirconia and Titanium Dental Implants. A Biomechanical Evaluation in the Maxilla of Pigs

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ABSTRACT

Objectives: The purpose of the present study was to investigate the osseointegration of microstructured zirconia implants in comparison with sandblasted and acid-etched (SLA) titanium implants in a biomechanical study.

Materials: Zirconia implants (4.1 mm in diameter, 10 mm in length) were produced using a new low pressure injection molding technique. After that the implants were acid-etched with hydrofluoric acid. Standard Ti-SLA implants of the exact same shape served as controls. Six months after extraction of incisors 2 and 3, 16 adult pigs received a total of 64 implants in the maxillae. After 4, 8, and 12 weeks the animals were sacrificed, and 59 implants could be analyzed to removal torque (RTQ) testing.

Results: The mean RTQ values for zirconia implants were 42.4 Ncm at 4 weeks, 69.6 Ncm at 8 weeks, and 69.3 Ncm at 12 weeks of healing, whereas RTQ values for the Ti-SLA implants were 42.1 Ncm, 75.0 Ncm, and 73.1 Ncm at corresponding time intervals. There is no statistical difference in RTQ values between Ti-SLA and zirconia implants at 8 weeks.

Conclusions: Within the limits of the present study it was concluded that acid-etching of zirconia implants enhances bone apposition resulting in RTQ values which were equivalent to that of Ti-SLA.

KEY WORDS: biomechanical testing, dental implants, pigs, titanium, zirconia

INTRODUCTION

Dental implant therapy has become a well-documented and scientifically accepted treatment in partially and completely edentulous patients. The quality of the interface between the bone and the implant is recognized as one of the most important factors for the functional capacity of the implant to bear load. The osseointegration is largely dependent on the implant material and its surface.[1] The most often used implant material is titanium.[1,2] A disadvantage from an aesthetic point of view is the grey colour of titanium, which may create a problem in cases of visible titanium or thin soft tissues because of the soft peri-implant tissue recessions paired with bone resorption.[3–5] One approach to avoid this is the use of zirconia implants instead of titanium because of the material's tooth-like color.[6–10]

Zirconia has higher fracture toughness and bending strength compared with other ceramics.[10,11] No mechanical problems, such as fractures of the implant material, were reported neither under loaded nor unloaded conditions in the mandibles of eight monkeys and maxillae of six monkeys, respectively.[8,10] Although the optimal surface modification has not yet been found, histological investigations on different zirconia implant surfaces have demonstrated enhanced bone apposition.[6–8,10,12–14]

The topography of titanium dental implants has been extensively investigated. Surfaces with microscale roughness have been favoured over more conventional

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DOI 10.1111/j.1708-8208.2009.00168.x

surfaces such as machined surfaces.[15–18] Micro-roughened titanium surfaces could be achieved through processes such as machining, particle blasting, Ti plasma spraying, chemical/electrochemical etching, or particle blasting and chemical etching.[19] Different approaches have been also reported for micro-roughening zirconia implant surfaces, such as sandblasting or coating with zirconia powder.[6–8] In a recently published study, Gahlert and colleagues[6] demonstrated that after 8 and 12 weeks of implantation machined zirconia implants showed statistically significant lower removal torque (RTQ) values than sandblasted zirconia implants and sandblasted and acid-etched titanium (Ti-SLA) implants. In addition Ti-SLA implants showed significantly higher RTQ values than sandblasted zirconia implants after 8 weeks. These findings suggested that sandblasted zirconia implants can achieve a higher mechanical stability in bone than conventionally machined zirconia implants. Roughening the surface of machined zirconia implants enhances bone apposition and enhances the ability to withstand shear stress.[6]

Another advantage of zirconia is the fact that zirconia displays a significantly reduced plaque affinity, thereby reducing the risk of inflammatory changes in the adjacent soft tissue.[10] Thus, the available documentation indicates that zirconia ceramics are suitable materials to be used as dental implants.[6–8,10]

The aim of the present study was to investigate the interfacial strength of zirconia implants that were produced by a low-pressure injection molding technique and subsequent micro-roughening of the surface by acid-etching in comparison with Ti-SLA implants.

MATERIAL AND METHODS

Animals

Sixteen pigs with an average age of 18 months and a weight between 60 and 110 kg were used in this study. The animals were kept in small groups, in stalls designed for experimental purposes and fed with a standard diet. Only 12 hours prior to and after surgery the animals were not given access to food, but had water accessible ad libitum. The protocol of the study was designed according to § 8 of the German law against cruelty to animals and was approved by the local authorities.

Implant Design

Screw-type zirconia implants were manufactured using a low pressure injection molding technique. The implants had a four-cornered shaft and were 4.1 mm in diameter and 10 mm in length (Figure 1, left panel). Zirconia implants were chemically treated with a hot solution of hydrofluoric acid according to a proprietary process of Institut Straumann AG (Institut Straumann AG, Basel, Switzerland). Ti-SLA grade 4 implants also had a four-cornered shaft and were 4.1 mm in diameter and 10 mm in length as per the zirconia implants (see Figure 1, right panel). The surface was blasted with alumina large grit particles (average particle size 250 μm) and subsequently acid-etched with a hot solution of HCl/H_2SO_4 according to a proprietary process of Institut Straumann AG.

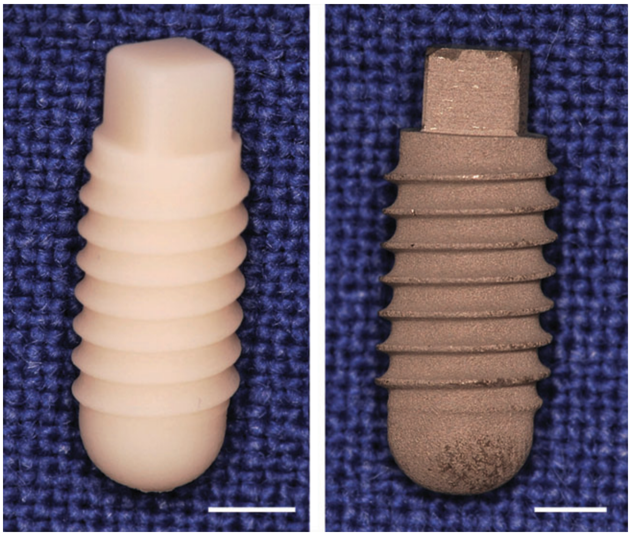

Figure 1 Macroscopic image of the two types of implants used in this investigation: zirconia (left panel); and sandblasted and acid-etched titanium (right panel) (scale bars: 2 mm).

Surface topography was qualitatively examined using scanning electron microscopy (SEM, XL 30, Philips Electron Optics, Eindhoven, The Netherlands) and quantitatively measured using a confocal, three-dimensional, white light microscopy (μSurf, NanoFocus AG, Oberhausen, Germany) over an area of 770 μm × 770 μm to calculate three-dimensional roughness parameters S_a (arithmetic mean deviation of the surface), S_q (root-mean-square deviation of the surface), S_t (maximum peak-to-valley height of the surface) and S_k (amplitude distribution skew) using a Gaussian filter with a cut-off wavelength of 31 μm. The chemical purity of all surfaces was proven by energy-dispersing x-ray spectroscopy (EDX, Philips) at different magnifications.

Surgical Procedures

The animals were sedated by intramuscular (im) injection of ketamin (10–15 mg/kg; Chassot AG, Ravensburg, Germany), Azaperon (2 mg/kg; Janssen-Cilag GmbH, Neuss, Germany), and atropine sulphate (0.5 mg/animal; B. Braun Melsungen AG, Melsungen, Germany). Anesthesia was induced with an intravenous bolus of propofol 1% (5 mL; Fresenius Kabi Austria GmbH, Graz, Austria) followed by intubation and maintenance of anesthesia by inhalation of 1.5% isofluran (Abbott GmbH, Wiesbaden, Germany) and 2% propofol (Fresenius Kabi Austria GmbH). For general analgesia, the animals received a first injection of caprofen (4 mg/kg; Pfizer GmbH, Karlsruhe, Germany) im 24 hours prior to surgery and a premedication with metamizol (40 mg/kg; Ratiopharm GmbH, Ulm, Deutschland), solved in Ringers solution (Berlin Chemie AG, Berlin, Germany). Additionally 2% lidocaine (8–15 mL; Astra Zeneca GmbH, Wedel, Germany) was used as analgesia by local injection. For postsurgical treatment, an injection of enrofloxacin (2.5 mg/kg; Bayer AG, Leverkusen, Germany) was applied im for 2 days.

During the first surgical procedure, the second and third incisors of the maxilla were removed under general anesthesia using extended mucoperiostal flaps to provide sufficient access to the alveolar crest containing the teeth to be removed. If necessary, careful osteotomy was conducted. Following tooth removal, the elevated flaps were repositioned and sutured with non-resorbable interrupted sutures.

The second surgery was performed after 6 months of healing. The recipient sites in the created edentulous areas of the maxilla were exposed by the elevation of buccal mucoperiostal flaps. When necessary, the alveolar crest was flattened to allow for precise preparation of the implant recipient sites, using precise spiral drills of increasing diameter at 500 rpm and copious irrigation with sterile physiological saline (Baxter GmbH, Unterschleißheim, Germany). Subsequently, the thread was cut into the bone cavity with a tap. Two zirconia implants and two Ti-SLA implants were inserted in the maxilla of each pig. A PEEK cap was placed on each four-cornered shaft to avoid bone growth at the shaft. All implants healed in a submerged position. Figure 2 shows representatively a Ti-SLA and a zirconia implant with the PEEK caps prior wound closure. Thus, primary stability with the bone walls of the implant beds was achieved by the press-fit design and the screw thread.

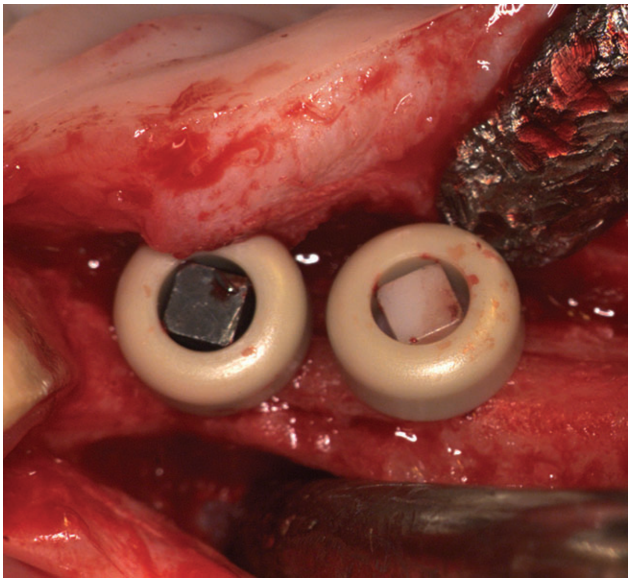

Figure 2 Representative picture of sandblasted and acid-etched titanium and zirconia implants with the PEEK caps prior to wound closure.

Animal Sacrifice and RTQ Testing

The animals were sacrificed with an overdose of pentobarbital (Merial GmbH, Halbergmoos, Germany) and potassium chloride (Baxter GmbH) after a healing period of 4, 8, and 12 weeks including five, six, and five animals per group, respectively. Immediately after sacrifice, the soft tissues in the edentulous areas of the maxilla were removed to expose the integrated implants. Subsequently, the maxilla was excised and the left and right halves were isolated with a diamond-plated saw. Each of the specimens was then examined by microfocus radiography and stored in saline. RTQ testing was performed on a universal testing machine (Wolpert TZZ 707, Instron GmbH, Darmstadt, Germany) as previously reported.[6] The measurement of the torque was registered by a special torque sensor (type 8625-5005, 5 Nm, SN 64105, Burster GmbH, Germany). The implant was attached to the actuator and the implant/bone complex was lowered into a tub on the rigid part of the machine, which was then filled with molten temperature metal alloy (AIM 44, Cockson Electronics, Naarden, the Netherlands). The solidification of the alloy effectively fixed the implant/bone complex to the machine. The melting point of the metal alloy is 48°C; thus no negative changes to the quite massive bone samples occurred during the time to solidification of the alloy. Solidification took place within approximately 10 minutes. This test setup was used to ensure that pure axial moments

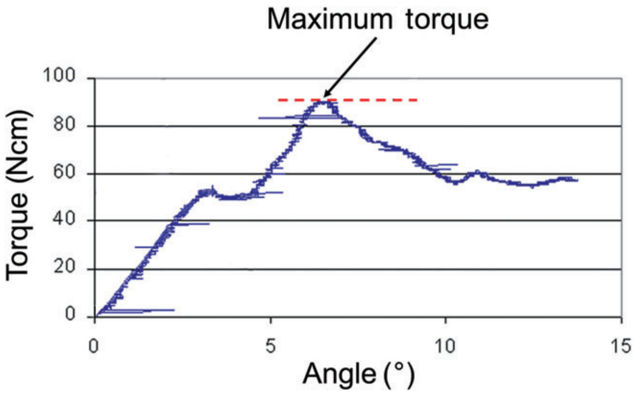

Figure 3 Representative torque rotation curve from the removal testing. The removal torque was taken from the maximum peak of the curve.

could be applied during the test. The axis of the implant to be tested corresponded exactly with the axis of the testing machine. The mechanical torque tests were performed at room temperature in air. After the testing of each implant was completed, the alloy was melted to remove the implant/bone complex from the fitting tub. The next implant was secured to the actuator and the entire process was repeated until all implants were tested. For each implant, the torque-rotation curve was recorded by special computer software (Lab View, version 7.1, National Instruments GmbH, Germany). To quantify the bone-implant interface, the resulting torque-rotation curve (Figure 3) was analyzed to determine the RTQ value and interfacial stiffness.

Clinical Observation

After the sacrifice of the 4-week group, dehiscences were observed by three experienced clinicians. The origin of the dehiscences and the resulting bone resorption could probably be found in the presence of microgaps between the implants and the PEEK caps in combination with the septic environment and anatomical situation. Based on these findings, the PEEK caps were removed after 4 weeks and the four-cornered shafts of the implants were cleaned with 0.1% H_2O_2 rinsed with saline. To document the resulting bone resorption at any given time point, each specimen was photographed from an oral and a vestibular view by using a digital camera (Fujifilm FinePix S1 Pro, Fujifilm Europe GmbH, Germany) with a standard objective (Sigma GmbH, Rödermark, Germany). To describe the grade of the dehiscences, an evaluation score had been defined: 0 means no bone resorption; 1 means bone resorption to the first thread; 2 means bone resorption to the second thread; 3 means bone resorption to the third thread; and 4 means bone resorption to more than three threads.

Statistical Analysis

The statistical analysis was performed calculating the confidence intervals for the intra-animal mean difference between the Ti-SLA and rough zirconia implants using the open-source software R (R project).[20] The intra-animal mean was used to avoid possible problems caused by conceivable animal dependencies of the RTQ level. For this purpose the mean for both materials for every animal was calculated separately followed by the calculation of the mean difference for the animal. Because of missing values for one material for some of the animals for the analysis, data from four animals were available at 4 weeks, six animals at 8 weeks, and four animals at 12 weeks. The confidence interval for the mean of the mean difference was calculated using the sample mean and sample standard deviation. The method is equivalent to a paired *t*-test.

RESULTS

EDX analysis indicated pure zirconia implant surfaces. Ti-SLA surfaces were characterized by a Ti oxide surface. Surface roughness is given in Table 1. The mean roughness (S_a) of the Ti-SLA surface was 1.17 μm, double that of the zirconia surface with an S_a value of 0.55 μm. The scanning electron microscope micrographs showed a rough microstructure for the zirconia implant surface

TABLE 1 Results from Topographic Analyses of the Implants Used in the Study ($n = 5$)

Type	S_a (μm)	S_t (μm)	Sk (μm)
Sandblasted and acid-etched titanium	1.23 ± 0.04	7.59 ± 0.60	3.91 ± 2.17
Zirconia	0.59 ± 0.01	3.84 ± 0.14	−0.27 ± 0.12

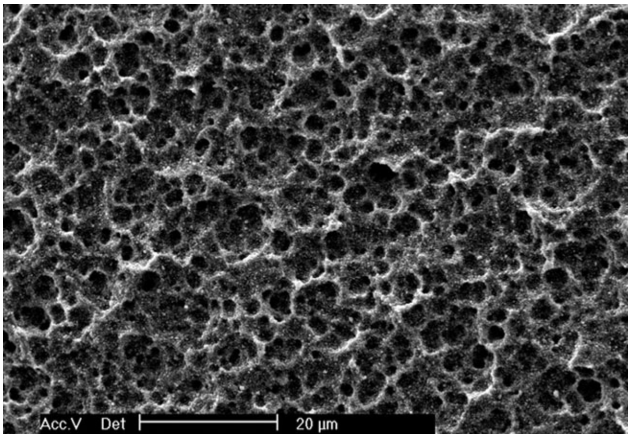

Figure 4 Representative scanning electron micrograph of the zirconia surface (scale bars: 20 µm).

(Figure 4), which is similar to the Ti-SLA surface. However, zirconia seemed to have a flatter profile with less porosity in comparison with the Ti-SLA surface.

Macroscopic observations showed dehiscences after a healing period of 4 weeks (Figure 5). Figure 6 shows a representative case of bone resorption around Ti-SLA and zirconia implants after 4 weeks within the same animal. The descriptive analysis of all implants shows more bone resorption around Ti-SLA implants compared with the zirconia implants at any investigated time point. In particular, after 4 weeks more than 80% of all Ti-SLA implants showed bone resorption of three threads or more whereas on 25% of all zirconia implants no bone resorption was noticed (Figure 7).

Because of these dehiscences only a total of 59 implants could be used for the RTQ measurements (4-week group: $n = 10$ for Ti-SLA, $n = 10$ for zirconia; 8-week group: $n = 12$ for Ti-SLA, $n = 11$ for zirconia; 12-week group: $n = 8$ for Ti-SLA, $n = 8$ for zirconia). Before the failure of the osseointegrated implant-bone interface, torque increased steadily with increasing rotation angle. The average RTQ value was lowest at 4 weeks of integration for both Ti-SLA and zirconia implants. The RTQ value increased between 4 and 8 weeks, but no further increase could be observed between week 8 and 12 (Table 2).

Figure 5 Clinical observation of a dehiscence defect after a healing time of 4 weeks.

The statistical analysis was the intra-animal comparison of the RTQ mean values between Ti-SLA and rough zirconia implants (Figure 8). The confidence intervals for the 4- and 12-week groups are very broad and therefore no conclusion could be made in terms of differences or equivalence in those groups. There was no difference in RTQ value between the Ti-SLA and zirconia implants at 8 weeks (Table 3).

DISCUSSION

Roughening the titanium implant surfaces has been reported to be an effective way to improve bone integration. It has been shown in different animal studies that microrough surfaces lead to significantly higher bone-to-implant contact as well as higher RTQ values compared with machined surfaces.[15–18]

However, biomechanical and histomorphometrical investigations on zirconia implants are very rare in the literature. Sennerby and colleagues developed a surface coating method using a slurry containing zirconia powder and a pore former.[7] The result after sintering was a zirconia implant with a porous surface structure that was similar to the TiUnite™ surface (Nobel Biocare, Goteborg, Sweden). Zirconia implants with either a machined or two different porous surfaces were placed in the tibia and femur of 12 rabbits using a rotational scheme. Titanium implants with an oxidized surface served as a control. The implants in six rabbits were subjected to RTQ tests after a healing period of 6 weeks. The implants in the remaining six animals were removed en bloc for histomorphometrical analysis. RTQ results showed higher values for the zirconia implants with the two different porous structures than for the titanium implants. However, the results were not significant. The lowest values were found for the machined zirconia implants. No significant differences regarding bone-to-implant contact and bone area filling could be observed between the different treatment groups. In a second study, Gahlert and colleagues investigated zirconia implants with either a machined or a sandblasted surface in the maxilla of mini pigs.[6] Ti-SLA implants served as a control. A total of 78 implants were placed

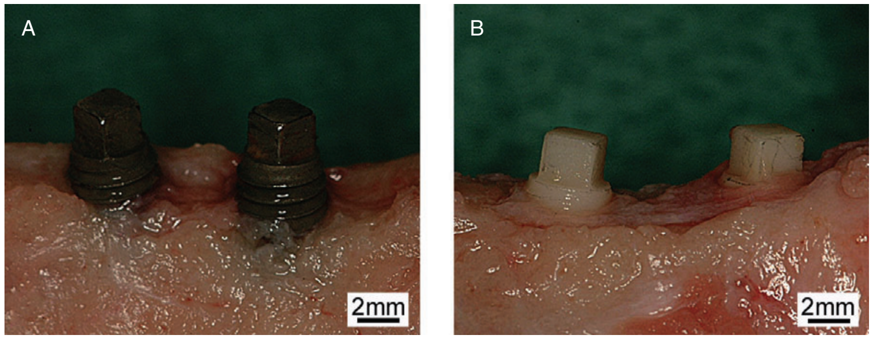

Figure 6 Representative picture of (A) sandblasted and acid-etched titanium and (B) zirconia implants with bone resorption.

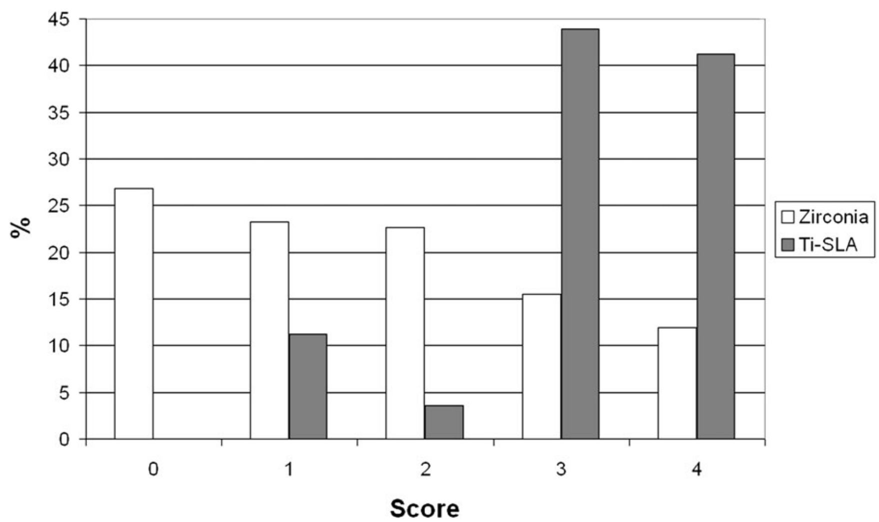

Figure 7 Grade of bone resorption after 4 weeks for sandblasted and acid-etched titanium and zirconia implants given in scores from 0 to 4. 0 means no bone resorption, 1 means bone resorption to the first thread, 2 means bone resorption to the second thread, 3 means bone resorption to the third thread, and 4 means bone resorption to more than three threads.

using a randomized scheme. After healing periods of 4, 8, and 12 weeks, 20, 24, and 25 implants, respectively, were subjected to RTQ analysis; fewer were processed for histomorphometrical analysis. The machined zirconia implants showed statistically significantly lower RTQ values than the sandblasted zirconia implants and the Ti-SLA implants after 8 and 12 weeks. The RTQ values of sandblasted zirconia surfaces showed significantly lower RTQ values than Ti-SLA implants after 8 weeks. The authors concluded that roughening the machined zirconia implants enhances bone apposition and has a beneficial effect on the interfacial shear strength. Further histological investigations demonstrated high degrees of bone–implant contact.[8,10,12–14]

To directly compare the interfacial biomechanical properties of a zirconia surface with a Ti-SLA surface in the current study, a well-established animal model was used.[21,22] The characterization of the zirconia surface and the Ti-SLA surface was performed with SEM and confocal three-dimensional white light microscopy.

TABLE 2 Removal Torque Values (Ncm) for Both Implant Types after 4, 8, and 12 Weeks of Healing Time

Implant	4 Weeks (Mean ± SD)	8 Weeks (Mean ± SD)	12 Weeks (Mean ± SD)
Sandblasted and acid-etched titanium	42.1 ± 21.6	75.0 ± 28.1	73.1 ± 41.8
Zirconia	42.4 ± 15.1	69.6 ± 25.1	69.3 ± 24.2

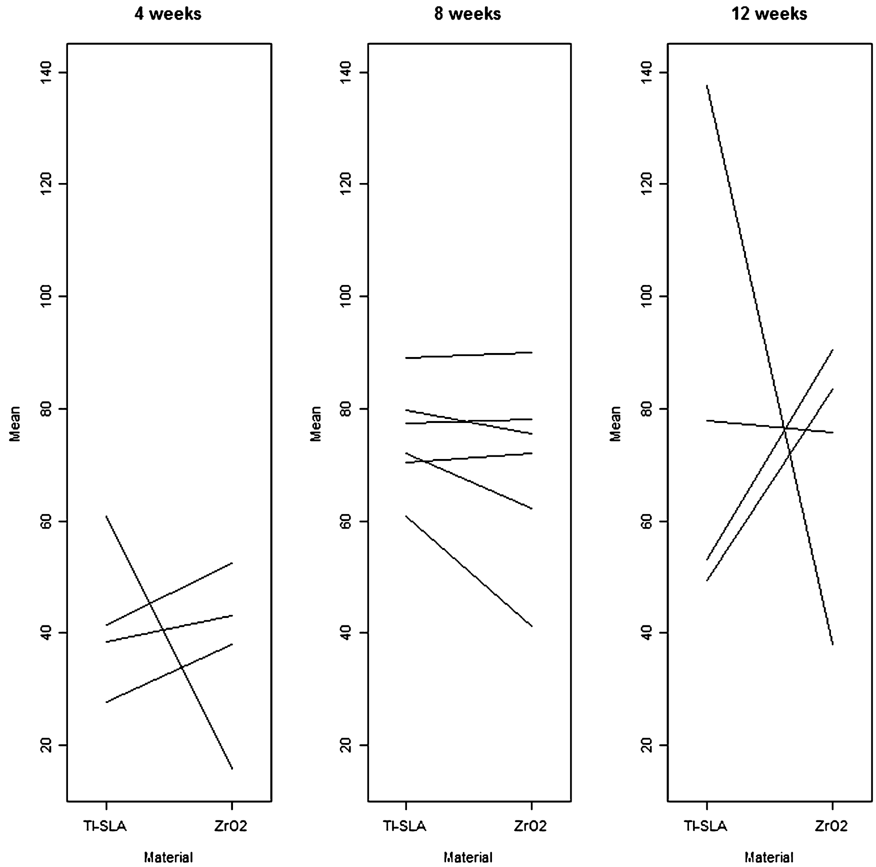

Figure 8 Comparison of removal torque means for sandblasted and acid-etched titanium and rough zirconia. Each point represents the mean torque value for all implants on one animal having the same material. The lines indicate corresponding values for each animal.

Both surfaces showed a similar rough microstructure. However, Ti-SLA is even rougher with an S_a value of 1.23 ± 0.04 µm and a maximum peak-to-valley height S_t of 7.59 ± 0.60 µm compared with the zirconia surface with an S_a value of 0.59 ± 0.01 µm and a maximum peak-to-valley height S_t of 3.84 ± 0.14 µm.

The results of the RTQ measurements showed an increase in RTQ values of the zirconia implants and Ti-SLA implants between 4 and 8 weeks, but there was no further increase between 8 and 12 weeks because of remodeling effects. Similar results could be observed for Ti-SLA implants.[21] In comparison with the published RTQ values in the previous study on sandblasted zirconia implants (32.4 ± 17.0 after 4 weeks; 43.1 ± 19.0 after 8 weeks; 31.3 ± 12.8 after 12 weeks),[6] the current study shows higher RTQ values for zirconia implants (42.4 ± 15.1 after 4 weeks; 69.6 ± 25.1 after 8 weeks; 69.3 ± 24.2 after 12 weeks). This result is even more important because the dehiscences could affect the RTQ values for both the Ti-SLA and zirconia implants. There was no difference in RTQ between the Ti-SLA and zirconia implants after 8 weeks, even though the Ti-SLA surface roughness is 100% higher than the zirconia surface. One reason could be the observed bone resorption after 4 weeks. Eighty percent of all Ti-SLA implants showed a bone resorption of three threads or more whereas 25% of all zirconia implants did not show any bone resorption. In the remaining 4 weeks after the removal of the PEEK caps and the performance of the RTQ test, bone on Ti-SLA implants was not able to fully regenerate, and therefore the RTQ values on Ti-SLA were lower than expected and reported elsewhere. Therefore,

TABLE 3 Ninety-Five Percent Confidence Intervals for the Intra-Animal Removal Torque Mean (Ncm, Zirconia – Sandblasted and Acid-Etched Titanium)

	4 Weeks	8 Weeks	12 Weeks
Upper border	38.16	3.66	94.05
Mean	−4.82	−5.1	−7.61
Lower border	−47.79	−13.86	−109.28

no conclusion can be made between the surface roughness that is 100% higher for Ti-SLA and the outcome from the RTQ test after 8 weeks. In addition, because of very high confidence intervals in the 4- and 12-week groups, no conclusions in terms of any difference or equivalence between the Ti-SLA and rough zirconia implants at these time points could be made. One reason for the high confidence interval in the 4- and 12-week groups could be the observed large bone resorption in certain cases. The origin of these bone resorptions could be found in the presence of microgaps between the implants and the PEEK caps in combination with the septic environment and anatomical situation. The PEEK caps were removed after 4 weeks, when dehiscences were observed for the first time. Another reason could be the different materials used in the study because not only the surface topography but also surface chemistry, surface charge, and wettability have an impact on the physiologic reaction to the implant surface. Therefore, further studies need to be performed to investigate the influence of the surface composition, surface charge, and wettability of zirconia on the bone apposition.

One advantage of zirconia is the significantly reduced plaque affinity, which reduces the risk of inflammatory changes in the adjacent soft tissue.[10] In our study, we observed more Ti-SLA implants with higher bone resorption compared with zirconia implants at any time point.

In conclusion, the osseointegration of zirconia implants is promising. This surface could offer an enhanced in vivo interaction between the implant surface and the tissue similar to the interaction known for well-documented Ti-SLA implant surface.

ACKNOWLEDGMENTS

The assistance in the statistical analysis by Mr. André Klima is gratefully acknowledged (Statistical Consulting Unit, Ludwig-Maximilians University, Munich, Germany). We would also like to thank Sandro Matter, Michael de Wild, Jost Lussi, and Michel Dard (Institut Straumann AG, Basel, Switzerland) for their support in manufacturing the implants and discussing the study design.

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