Clin Oral Invest (2018) 22:1593–1600
https://doi.org/10.1007/s00784-017-2262-4

ORIGINAL ARTICLE

Dental implant surfaces after insertion in bone: an in vitro study in four commercial implant systems

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Received: 19 June 2017 / Accepted: 17 October 2017 / Published online: 24 October 2017

Abstract

Objectives Primary healing of dental implants is influenced by their surface morphology. However, little is known about any alterations in morphology during their insertion. Therefore, the aim of this study was to evaluate the surface morphology of four different implant systems, following their insertion in porcine jaw bones.

Methods Four fresh porcine mandible specimens were used. Six new implants of four systems (Ankylos® 4.5 × 14 mm, Frialit Synchro® 4.5 × 15 mm, NobelReplace ® Tapered Groovy RP 4.3 × 13 mm, Straumann SLA® Bone Level 3.3 × 14 mm) were inserted, whereas one implant of each system served as a control. After their removal, implants were cleaned in an ultrasonic bath. All 28 implants were examined quantitatively by 3D confocal microscopy for surface characteristics.

Results In the evaluated zones, implants of the Ankylos, Frialit, and Straumann systems showed mostly a reduction of the mean surface roughness Sa, the maximal surface roughness Sz, and the developed surface area ratio Sdr; Nobel implants showed an increase in these parameters. With respect to all three parameters Sa, Sz, and Sdr, statistical analysis revealed that differences between the four systems were highly significant in the apical region of implants. Controls showed no morphologic alterations.

Conclusion The insertion process had an impact on the surface of all four implant systems. Anodized implant surface modification seems to result in more alterations compared with subtractive surface modifications. Therefore, surgical planning should take into consideration the choice of surface treatment because the characteristics of the implants may be modified during the installation process.

Clinical relevance The given information is of value for daily implantation practice and the course of osseointegration.

Keywords Dental implant · Implant surface · Insertion · Surface morphology

Introduction

Dental implants are essential in reconstructive dentistry [1]. One of the prerequisites of this success is the development of implant surface modifications. Osseointegration of implants is characterized by two phases: the primary osseointegration—essentially the physical contact between implant and bone—and the secondary osseointegration, which is the enhancement of this contact during the bone healing process [2].

Implant surface modifications result in a higher degree of roughness intending to increase the osseointegration [3]. Several methods have been described for the modification of titanium implant surfaces including grit blasting, acid etching, and anodization [2]. On the microscopic level, grit-blasted surfaces show peaks and valleys between 4 and 6 μm [4]. Acid etching results in a uniform pattern with a roughness

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between 3 and 6 μm [5]. Anodized implants demonstrate a wide variety of surface features between 0.8 and 7 μm [6].

However, due to the fact that torque moments are needed for primary stability, the question arises as to whether these surface modifications are preserved during the insertion procedure. Recently, deformation of sandblasted and acid-etched (SLA) implants during the insertion process has been shown in a pilot study in human cadaver mandibles [7].

Therefore, the aim of the present study was to examine the surface characteristics of four implant systems after their insertion in porcine mandibles.

Materials and methods

Dental implants For this study, a total of 28 brand new dental implants of the following four commercial systems were available (system, diameter x length): Ankylos® 4.5 × 14 mm (*n* = 7), Frialit Synchro® 4.5 × 15 mm (*n* = 7) (both systems Dentsply, D-Mannheim), NobelReplace ® Tapered Groovy RP 4.3 × 13 mm (*n* = 7) (Nobel Biocare, S-Gothenburg), and Straumann SLA® Bone Level 3.3 × 14 mm (*n* = 7) (Straumann AG, D-Freiburg). These systems differ with respect to their surface modifications, according to information of the manufacturers:

Ankylos® implants were made of commercially pure titanium grade 2. Surface modification was yielded via large grit blasting (Al_2O_3 particles 354–500 μm) and high-temperature acid etching. The latter results in micro-pits of 0.5-1 μm and an average micro-roughness of 1.40–1.75 μm. Frialit Synchro® screws were also made of commercially pure titanium grade 2. The so called Deep Profile Surface (DPS) consisted of two parallel threads and a high temperature acid etched micro structure which results in a micro-roughness of > 2 μm. Nobel Replace ® Tapered Groovy RP implants consisting of commercially pure titanium grade 4. The TiUnite® surface was characterized as a thickened titanium oxide layer which was developed by anodization in a phosphoric electrolyte. This process generated a porous surface with a micro-roughness of 1–2 μm. Straumann implants® were made of pure titanium grade 4. The surface showed a macro-roughness of 20–40 μm peak-to-peak and a micro-roughness of 2–4 μm. Surface modification was performed with the use of large grit (250–500 μm) blasting and acid etching (HCL/H_2SO_4).

In each system, six implants were inserted in porcine bone and one served as control.

Porcine bone samples A total of four fresh porcine mandibles were available. To allow comparison with the human edentulous alveolar process, mandibles were segmented and only the inferior part of the mandibles was used for implant installation (Fig. 1). To guarantee comparability of the four mandible segments, osteodensitometry was performed with use of CT scans (Philips Brilliance iCT 256—slice CT, Philips Healthcare, D-Hamburg) (Fig. 2a, b). Evaluation of bone densities of the four bone samples were performed with use of the software RadiAnt DICOM Viewer (Medixant, PL-Poznan) (Fig. 3). Care was taken to evaluate separately cortical and cancellous bony parts of the mandibles.

Fig. 1 Bovine mandible before implant installation

Implant installation All implants were inserted by the same surgeon and according to standardized protocols of the manufacturers. Six implants of the four systems were inserted into four bone blocks. Surgery was performed with a standard implant surgery device (Implant Center 2, Acteon, D-Mettman) which allowed documentation of torques. Moreover, all mandatory Nobel®, Dentsply® and Straumann® instruments were available. Bony cavities were prepared at 800 rpm with continuous cooling with 0.9% NaCl solution. For pre-tapping of Nobel® implant sites, a guided screw tap-tapered Rp was used at 25 rpm according to the protocol of the company. Similarly, these implants were also inserted at 25 rpm and a maximal torque of 45 Ncm was allowed due to the protocol. In Ankylos® implant cavities, threads were tapped with tapper number B14 at 15 rpm. Similarly, installation of implants was performed at 15 rpm with a maximal torque of 50 Ncm according to the protocol. Furthermore, according to the protocol of the manufacturer, Frialit Synchro® screws were inserted, after additional use of a cortical drill, at 15 rpm without previous thread tapping and a maximal torque of 50 Ncm. Before installation of Straumann SLA® Bone Level implants, threads were tapped with an implant congruent tapper (3.3 mm in diameter) at 15 rpm and a maximal torque of 35 Ncm was allowed due to the protocol.

With the aid of custom made surgical templates, a standardized distance of six millimeters between implants was obtained. To exclude systematic effects on surface morphologies due to different torques during implant installation, all implants were inserted with a standardized torque of 35 Ncm.

Sample preparation To harvest the implants from the bone without further manipulation such as rotation, the mandibles

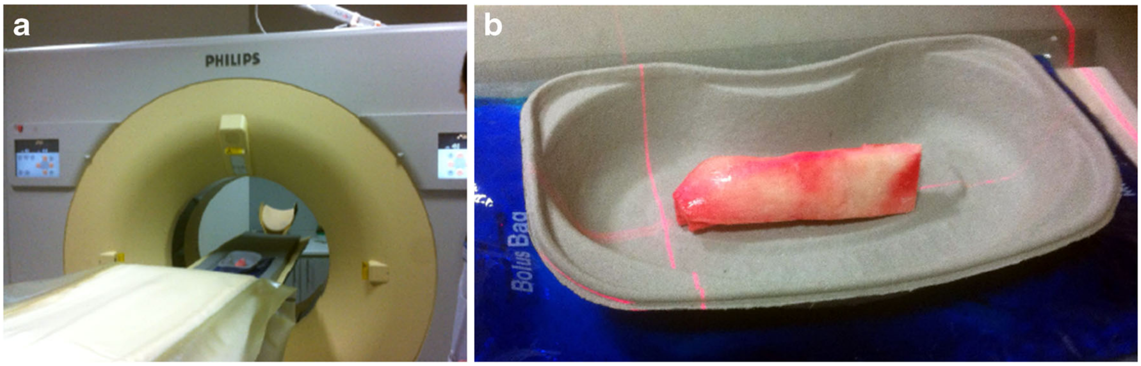

Fig. 2 **a** Philips 256-slice CT scanner with bovine bone sample. **b** Bovine bone sample

were resected into blocks by use of a commercial metal saw (Lux, Obi, D-Wermelskirchen). Care was taken not to harm the implant surfaces. The blocks were cut in a sagittal direction into two halves and carefully separated to gain free access to the implants. These harvested implants were cleaned of existing deposits with distilled water in an ultrasonic bath (Bandelin Sonorex RK100 Transistor Ultraschallbad, D-Berlin). For this purpose and to avoid any contact or damage to the surface, the implants were attached to a fine wire at the insertion abutment. They were allowed to float freely 2 cm below the water surface in the cleaning bath. Each ultrasonic cleaning procedure took 15 min and was repeated until no more deposits on the surface were visible with the naked eye.

3D confocal microscopy For three-dimensional surface analysis, a 3D confocal microscope was used (µsurf expert, NanoFokus AG, D-Oberhausen) which allowed for the quantitative evaluation of the surface roughness of the four different implant systems. Confocal microscopy is an optical imaging technique which enables increased optical resolution and contrast of a micrograph by means of adding a spatial pinhole placed at the confocal plane of the lens to eliminate out-of-focus light [8]. Measurements can be obtained within 5 to 10 s, contactless and without destruction of the surface. The system allowed reconstruction of three-dimensional structures from the obtained images by collecting sets of images at different depths. Accordingly, roughness and surface measurements were performed to a nanometer resolution.

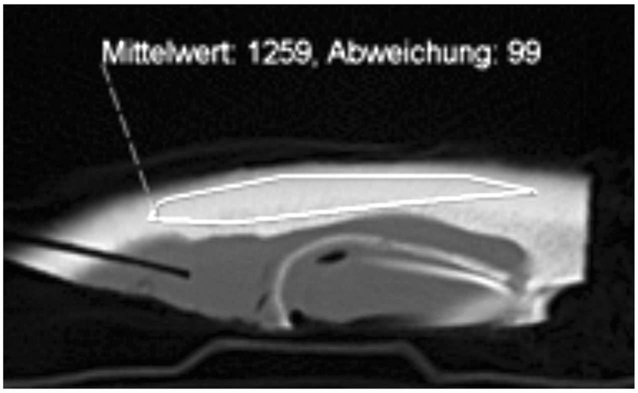

Fig. 3 Evaluation of bone density. Software RadiAnt DICOM Viewer (Medixant, PL-Poznan)

Therefore, harvested implants and controls of all four systems were positioned in the scanner unit (Fig. 4a). The µSoft Analysis Premium software program (NanoFokus AG, D-Oberhausen) was used to calculate 3D roughness parameters (Fig. 4 b). Four standardized areas of interest (AOI) were defined: one in the cervical, two in the middle and one in the apical part of the implant. Each area had a length of 250 µm and a width of 150 µm, i.e., 37,500 μm^2 (Fig. 5).

Surface parameters Implant surface topography was measured as previously recommended [9, 10]. The following surface parameters were measured and/or calculated with the use of customized profile sections (Fig. 6): mean maximum height Sz (average distance between the highest peak and the deepest valley) in micrometers, the mean surface roughness Sa (arithmetic mean deviation of the peak-to-valley height of the surface) in micrometers which provides a good overview of the values of the height of the irregularities on the surface, and the developed surface area ratio Sdr measured in percent (%), a hybrid parameter, given by a combination of amplitude and spatial properties, which indicates the surface area enlargement [9]. The latter describes the ratio of the measured surface compared with a nominal flat area in percent [11, 12] (Fig. 5).

Statistical analysis Statistical analysis of the evaluated values in the regions of interest was performed using a commercial computer program (Microsoft Excel®, version 2010, US-WR-Redmond). Data are presented as counts, mean values or percentages (Tables 1 and 2). Chi square test permitted comparison of the different parameters Sa, Sz, and Sdr between the four implant systems (Table 3). A p value ≤ 0.05 was considered to indicate statistical significance.

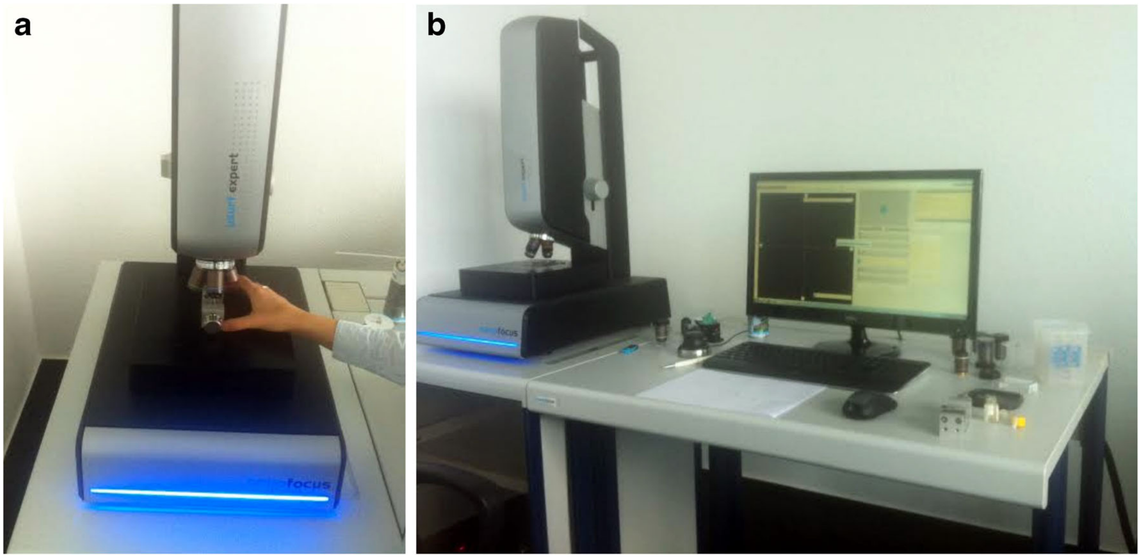

Fig. 4 **a** 3D confocal microscope µsurf expert (NanoFokus AG, D-Oberhausen). **b** Workstation of the µsurf expert system (NanoFocus AG, D-Oberhausen)

Results

Porcine bone samples Hounsfield units of cancellous bone parts of the specimen ranged from 1260 to 1320 HU. Accordingly, all specimens were attributable to bone Class 1 (> 1250 HU) according to the classification of Misch [13] (Fig. 3).

Surface alteration Table 1 provides values of the three parameters Sa, Sz, and Sdr in the four implant systems as compared with controls. It may clearly be seen that all three parameters Sa, Sz, and Sdr demonstrated major differences between tests and controls, especially in the apical region.

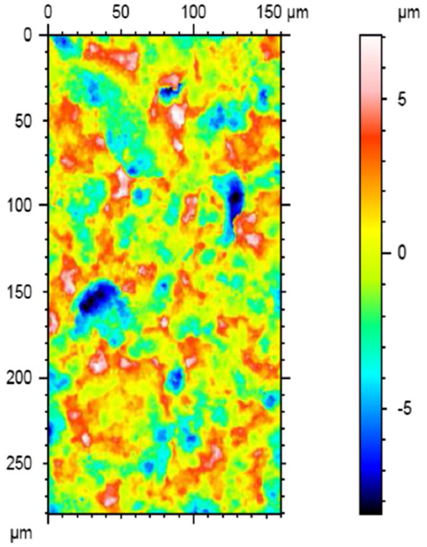

Fig. 5 Scanning of surface areas. Each area had at least a length of 150 µm and a width of 250 µm; i.e., 37,500 µm^2

To allow statistical comparison between the four implant systems, differences were calculated between values of test and control surfaces, in all four measured zones (apex, middle 1, middle 2, and cervical) in all four implant systems. Results are presented in Table 2 as percentage deviation of test values as compared with controls with respect to parameters Sa, Sz, and Sdr in the four implant systems. Accordingly, Table 2 demonstrates that the Sa parameter shows the strongest deviation of tests and controls in the Straumann system (mean, − 10.37%), especially in the apical region (− 27.83%). Moreover, the six tested implants of this system have also shown the highest reduction of the maximal surface roughness Sz (mean, − 15.17%), again in the apical region (− 39.50%). In contrast, installation of implants of the Nobel company resulted in a significant increase of the maximal surface roughness Sz, especially in the apical (+ 70.38%) and cervical (+ 122.53%) region. Finally, an increase of the developed surface area ratio Sdr was obviously seen in the six Nobel implants (mean, + 7.13%), whereas means of all other three systems showed planation of the surfaces (Ankylos, 5.55%; Frialit, 26.10%; and Straumann, 24.19%). Figure 7 shows a graphical summary of the results.

Statistical analysis revealed that differences were highly significant with respect to all three parameters Sa, Sz, and Sdr in the apical region of implants (Table 3).

Discussion

Modification of dental implants has become common in oral rehabilitation in order to increase implant primary stability and, thereby, osseointegration. It has been shown that osteoblasts are attracted by rough surfaces [14]. Accordingly, acid-

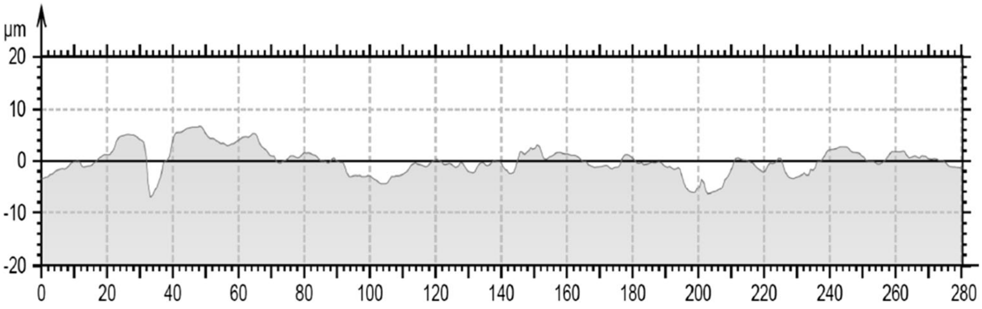

Fig. 6 Customized profile section of scanned surface according to Fig. 5

etched implants demonstrated higher bone-implant contact (BIC) values than machined surfaces after 8 weeks of healing [15]. In addition, anodized implants showed even after 6 weeks better BIC values as compared with machined surfaces [16]. Despite the fact that most modern implant systems offer modified surfaces for the clinician, little is known about any alteration of their morphology during the insertion procedure. Therefore, taking into account the fact that implant supported oral rehabilitation places enormous costs on the public health care system, clinical studies are essential.

In this study, fresh porcine mandibles were used. In a recent pilot study, a human cadaver mandible was used to evaluate surface modifications following insertion of six sandblasted and acid-etched (SLA) dental implants in bone [7]. Accordingly, human bone specimen might have been also desirable in the present study. However, since more than one mandible would have been needed to accommodate all 24 dental implants, comparison of the results might have been compromised due to enormous variations in bone quality and quantity of human mandible [17]. Therefore, in the present study, fresh porcine mandibles were used because dimensions, mechanical properties, and physiology of porcine bone are very similar to that of humans [18]. In addition, comparability of porcine bone samples was evaluated with use of CT diagnosis and thus, the reliability of the present results did not seem to be hampered by the bone model used. In addition, other models like in canines do not reflect a comparative situation like in humans as the chewing behavior of rodents [18]. Porcine models are preferred in this situation [18].

In the literature, surface analysis had often been performed with scanning electron microscopy [2, 7, 10]. However, it was stated that three-dimensional measurements should be included when implant surface morphology is investigated [10]. Accordingly, optical modes of surface characterization (profilometry, interferometry) have been used for more than 20 years [2, 11, 19], including the use of 3D confocal microscopy [9]. Therefore, the use of 3D surface analysis such as 3D confocal microscopy employed in the present study is well

Table 1 Values of Sa, Sz, and Sdr in the four areas of interest (AOI)

Parameter	AOI	Inserted implants (n = 6) vs. control (n = 1)			
		Ankylos	Frialit	Nobel	Straumann
Sa: mean roughness (μm)	Apex	1.735 (1.570)	2.252 (2.260)	1.327 (1.090)	1.660 (2.300)
	Middle 1	1.535 (1.550)	2.393 (2.140)	1.110 (1.250)	1.833 (2.290)
	Middle 2	1.248 (1.470)	1.948 (2.360)	1.115 (1.310)	2.283 (2.230)
	Cervical	1.393 (1.440)	2.152 (2.070)	1.460 (1.090)	2.380 (2.280)
	Mean	1.477 (1.507)	2.186 (2.208)	1.253 (1.185)	2.039 (2.275)
Sz: maximal roughness (μm)	Apex	22.067 (18.300)	18.800 (19.000)	13.222 (7.760)	16.517 (27.300)
	Middle 1	18.675 (14.400)	21.600 (18.800)	8.303 (8.880)	22.317 (23.000)
	Middle 2	14.327 (18.200)	19.700 (21.800)	10.390 (8.040)	31.650 (40.000)
	Cervical	16.167 (18.500)	21.033 (18.000)	18.715 (8.410)	28.517 (26.400)
	Mean	17.804 (17.350)	20.283 (19.400)	12.658 (8.273)	24.750 (29.175)
Sdr: developed surface area ratio (%)	Apex	44.600 (41.500)	51.850 (72.000)	48.033 (33.000)	31.450 (55.300)
	Middle 1	35.450 (31.600)	60.100 (70.500)	38.683 (38.200)	37.000 (55.400)
	Middle 2	25.383 (31.900)	41.700 (66.400)	28.373 (40.300)	48.883 (55.900)
	Cervical	24.533 (32.600)	51.633 (68.900)	40.242 (33.500)	47.017 (50.200)
	Mean	32.492 (34.400)	51.321 (69.450)	38.833 (36.250)	41.088 (54.200)

Major differences between tests and controls can clearly be seen, especially in the apical region

Table 2 Percentage deviation of tests and controls with respect to parameters Sa, Sz, and Sdr

Parameter	AOI	Inserted implants (*n* = 6) vs. control (*n* = 1)			
		Ankylos (%)	Frialit (%)	Nobel (%)	Straumann (%)
Sa: mean roughness (μm)	Apex	+ 10.51	− 0.37	+ 21.71	− 27.83
	Middle 1	− 0.96	+ 11.84	− 11.19	− 19.94
	Middle 2	− 15.11	− 17.44	− 14.86	+ 2.39
	Cervical	− 3.36	+ 3.95	+ 33.90	+ 4.39
	Mean	− 1.99	− 0.96	+ 5.73	− 10.37
Sz: maximal roughness (μm)	Apex	+ 20.58	− 1.05	+ 70.38	− 39.50
	Middle 1	+ 29.56	+ 14.89	− 6.94	− 2.97
	Middle 2	− 21.28	− 9.63	+ 29.23	− 20.88
	Cervical	− 12.61	+ 16.85	+ 122.53	+ 8.02
	Mean	+ 2.62	+ 4.55	+ 53.01	− 15.17
Sdr: developed surface area ratio (%)	Apex	+ 7.47	− 27.99	+ 45.56	− 43.13
	Middle 1	+ 12.18	− 14.75	+ 1.27	− 33.21
	Middle 2	− 20.43	− 37.20	− 29.60	− 12.60
	Cervical	− 24.74	− 25.06	+ 20.12	− 6.34
	Mean	− 5.55	− 26.10	+ 7.13	− 24.19

Sdr increased mostly in the Nobel implants, whereas the other three systems showed planation of the surfaces

established in the literature, allowing calculation of height and spatial parameters such as Sa, Sz, and Sdr on a nano-scale resolution.

Similar to the present study, Mints and coworkers have calculated roughness parameters, including the average height deviation (Sa) [2]. The authors described that turned implant surfaces exhibited similar morphology before and after implant insertion. In contrast, anodized implants demonstrated the most extensive damage associated with insertion: on the crest of the threads and in the apical region, the entire porous oxide layer had been removed. Acid-etched implants showed reduced peak height associated with flattened areas after insertion. In this study, only acid-etched and anodized implants were investigated. Thus, differences of mean values of controls and test implants were calculated and percentage deviation was provided for all three parameters Sa, Sz, and Sdr which is also in accordance with the respective literature [2, 9, 10].

Table 3 Statistical analysis of the four implant systems in the four areas of interest (AOI)

Parameter	AOI	Chi square	*p* value
Sa: mean roughness (μm)	Apex	12.301	0.006**
	Middle 1	7.054	0.070
	Middle 2	2.589	0.459
	Cervical	0.969	0.809
	Mean	4.407	0.221
Sz: maximal roughness (μm)	Apex	16.080	0.001**
	Middle 1	3.220	0.359
	Middle 2	9.582	0.022*
	Cervical	7.620	0.055
	Mean	9.807	0.020*
Sdr: developed surface area ratio (%)	Apex	16.807	0.001**
	Middle 1	9.816	0.020*
	Middle 2	5.987	0.112
	Cervical	6.780	0.079
	Mean	17.780	0.001**

All three parameters Sa, Sz, and Sdr show significant differences in the apical region of implants

A P-value ≤ 0.05* indicated statistical significance, a P-value ≤ 0.01** high statistical significance

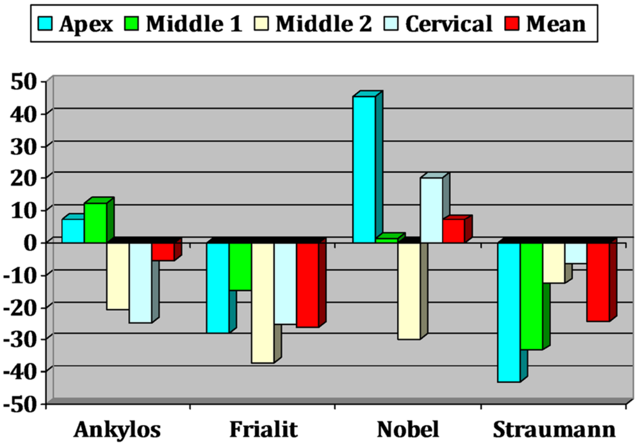

Fig. 7 Developed surface area ratio (Sdr) in percent following implant insertion in porcine bone as compared with controls. Positive values indicate increase in surface area; negative values indicate surface planation

The present results demonstrated that acid etched implants showed a significant reduction of the mean surface roughness Sa, especially in the apical region ($p = 0.006$), and of the mean developed surface area ratio Sdr ($p < 0.001$) (Table 3). These findings were more pronounced in Straumann implants (mean Sa, − 10.37%) as compared with Dentsply implants (mean Sa, − 1.99 and − 0.96%, Table 2; Fig. 7). In contrast, anodized implants of the Nobel company showed a significant destruction of the surface, indicated by a significant increase of the mean surface roughness Sa (mean, + 5.73%) and the developed surface ratio parameter Sdr (mean, + 7.13%) and are in line with recent findings by other groups) [2].

These present results are of clinical interest due to the fact that despite the wide use of osseointegrated titanium implants and the substantially growing research on the development of new titanium surfaces and/or modification of existing surfaces, a detailed understanding of the mechanisms of osseointegration is still lacking [20]. Commercially available implants have been categorized according to the surface roughness value (Sa) into four groups [21]: smooth (Sa < 0.5 μm), minimally rough (Sa = 0.5–1.0 μm), moderately rough (Sa = 1.0–2.0 μm), and rough (Sa > 2.0 μm). The surface roughness increases with the size of the particles used [22]. Twenty-five micron particle-blasted surfaces were rougher than the machined surface (Sa 0.3 to 1.0 μm) while smoother than 75 and 250 μm blasted surfaces. Typical Sa values are 0.5–2.0 μm. Further, implants blasted with 25 and 75 μm particles show higher removal torque compared with a machined implant surface after 12 weeks of healing in either rabbit tibia or femur [19]. Significantly higher bone-implant contact was observed for the 25-μm blasted surface compared with machined surface while the bone area within the threads were significantly higher for the machined surface after 12 weeks [19] and 1 year healing [23]. Interestingly, similar removal torque while significantly higher bone-implant contact and bone area was observed for implants blasted with 25 μm particles compared with 250 μm particles [20, 24].

The biological response to blasted implants show a optimal bone response with regard to removal torque values and bone implant contact to implants when a roughness of 1.5 μm is achieved whereas the blasting particle material, either TiO_2 or Al_2O_3 with a size of 25 μm, did not show any difference in bone response with respect to removal torque, bone implant contact, and bone area after 12 weeks healing [20]. Interestingly, at a level relevant for commercial oral implants, no correlation was found between increasing roughness and ion release, neither in vitro nor in vivo [25]. However, to the knowledge of the authors, surface roughness values provided in the referenced studies were not assessed following implant installation. Therefore, it may be assumed that most of the available data are based on the in vitro surface measurements and not on surface characterization that was performed following the process of insertion. Consequently, it may be anticipated that differences in bone type may affect the results.

These assumptions are corroborated by the new findings previously presented in the literature. It was shown that there was a significant change in the surface concentration of Ti and C following mechanical surface stress [26]. Therefore, it may be anticipated, again, that the insertion process results in different mechanical stress to the surface at different moments [27]. On the other hand, higher stress to the surface may lead to more extensive damage of the surface. Due to the fact that titanium particles were described even in the interface of machined implants [28], it is of interest that these particles can cause chronic inflammation [29], release of pre-inflammatory cytokines such as IL-6, IL-8, and TNF-alpha [30], and thereby compromised implant healing.

Dental implants of the NobelReplace ®, Ankylos®, and Straumann SLA® Bone Level system were installed in this study following bone tapping whereas Frialit Synchro® implants were inserted following use of a cortical drill, as required by the protocol. At first look, one might consider this as a drawback in methodology because literature has pointed out a significant impact of bone tapping on removal torques in the rabbit tibia [31]. However, it was the intention of the present study to use clinical standard protocols of the manufacturers and, thereby, to imitate clinical procedures. Interestingly, Frialit Synchro® implants without pre-tapping have shown very similar surface characteristics like the two systems (Ankylos®, Straumann SLA® Bone Level) with bone tapping. Moreover, maximal torques of 35 Ncm were applied to all four systems although in three systems, significantly higher torque values (and, in consequence, more pronounced surface alterations) might have been possible according to the protocols. Therefore, it may be assumed that the present results were not harmed to any significant extent by bone tapping or not. Nevertheless, this study has some limitations. First, the implants were inserted in vitro in porcine bone with a bone type class I only. Of course, further studies are needed for testing other bone class types, which would be interesting as well. Right now, we addressed the problem in class I bone as this is one of the most frequent situations in clinical implant practice. Second, 3D confocal microscopy does not allow analysis of implant surface chemistry. Therefore, any influence of the insertion process on biocompatibility remains unclear.

Conclusion

Within the limitations of the present study, it may be concluded that the insertion process had an impact on the surface of all four implant systems. In the current study findings, anodized implant surface modification seems to result in severe alterations compared with subtractive surface modifications. Therefore, surgical planning should take into consideration the choice of surface treatment because the characteristics of the implants may be modified during the installation process. According to the findings and study design of the present implants tested, Nobel implants showed least alterations of surfaces. Further studies with respect to implant surface chemistry are required to evaluate potential biological consequences as well as studies with different bone classes.

Funding The work was not funded.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent For this type of study, formal consent is not required.

References

1. Thomason JM et al (2009) Mandibular two implant-supported overdentures as the first choice standard of care for edentulous patients—the York consensus statement. Br Dent J 207(4):185–186
2. Mints D et al (2014) Integrity of implant surface modifications after insertion. Int J Oral Maxillofac Implants 29(1):97–104
3. Albrektsson T et al (1981) Osseointegrated titanium implants. Requirements for ensuring a long-lasting, direct bone-to-implant anchorage in man. Acta Orthop Scand 52(2):155–170
4. Ruger M et al (2010) The removal of Al2O3 particles from grit-blasted titanium implant surfaces: effects on biocompatibility, osseointegration and interface strength in vivo. Acta Biomater 6(7):2852–2861
5. Mata A et al (2003) Osteoblast attachment to a textured surface in the absence of exogenous adhesion proteins. IEEE Trans Nanobioscience 2(4):287–294
6. Choi JW et al (2006) Biological responses of anodized titanium implants under different current voltages. J Oral Rehabil 33(12): 889–897
7. Deppe H et al (2015) Surface morphology analysis of dental implants following insertion into bone using scanning electron microscopy: a pilot study. Clin Oral Implants Res 26(11):1261–1266
8. Pawley J (2006) Handbook of biological confocal microscopy, 3rd edn. Springer, Berlin
9. Sartoretto SC et al (2015) Early osseointegration driven by the surface chemistry and wettability of dental implants. J Appl Oral Sci 23(3):279–287
10. Wennerberg A, Albrektsson T (2000) Suggested guidelines for the topographic evaluation of implant surfaces. Int J Oral Maxillofac Implants 15(3):331–344
11. Arvidsson A, Sater BA, Wennerberg A (2006) The role of functional parameters for topographical characterization of bone-anchored implants. Clin Implant Dent Relat Res 8(2):70–76
12. Brown CA, Johnsen WA, Hult KM (1998) Scale-sensitivity, fractual analysis and simulations. Int J Mach Tools Manufact 38: 633–637
13. Misch CE (1999) Bone density: a key determinant for clinical success. In: Misch CE (ed) Contemporary implant dentistry, 2nd edn. CV Mosby Company, St Louis
14. Cooper LF (2000) A role for surface topography in creating and maintaining bone at titanium endosseous implants. J Prosthet Dent 84(5):522–534
15. Trisi P et al (2003) Bone-implant contact on machined and dual acid-etched surfaces after 2 months of healing in the human maxilla. J Periodontol 74(7):945–956
16. Pak HS, Yeo IS, Yang JH (2010) A histomorphometric study of dental implants with different surface characteristics. J Adv Prosthodont 2(4):142–147
17. Bouwman JP, Tuinzing DB, Kostense PJ (1994) A comparative in vitro study on fixation of sagittal split osteotomies with Wurzburg screws, Champy miniplates, and biofix (biodegradable) rods. Int J Oral Maxillofac Surg 23(1):46–48
18. Mosekilde L (1995) Assessing bone quality—animal models in preclinical osteoporosis research. Bone 17(4 Suppl):343S–352S
19. Wennerberg A et al (1995) A histomorphometric and removal torque study of screw-shaped titanium implants with three different surface topographies. Clin Oral Implants Res 6(1):24–30
20. Ballo AM et al (2011) Dental implant surfaces—physicochemical properties, biological performance, and trends. In: Turkyilmaz PI (ed) Implant dentistry—a rapidly evolving practice. InTech
21. Albrektsson T, Wennerberg A (2004) Oral implant surfaces: part 1—review focusing on topographic and chemical properties of different surfaces and in vivo responses to them. Int J Prosthodont 17(5):536–543
22. Wennerberg A et al (1992) An optical three-dimensional technique for topographical descriptions of surgical implants. J Biomed Eng 14(5):412–418
23. Wennerberg A et al (1997) A 1-year follow-up of implants of differing surface roughness placed in rabbit bone. Int J Oral Maxillofac Implants 12(4):486–494
24. Wennerberg A, Albrektsson T, Andersson B (1996) Bone tissue response to commercially pure titanium implants blasted with fine and coarse particles of aluminum oxide. Int J Oral Maxillofac Implants 11(1):38–45
25. Wennerberg A et al (2004) Titanium release from implants prepared with different surface roughness. Clin Oral Implants Res 15(5): 505–512
26. Valente ML, Lepri CP, dos Reis AC (2014) In vitro microstructural analysis of dental implants subjected to insertion torque and pullout test. Braz Dent J 25(4):343–345
27. Guan H et al (2009) Influence of bone and dental implant parameters on stress distribution in the mandible: a finite element study. Int J Oral Maxillofac Implants 24(5):866–876
28. Schliephake H et al (1993) Metal release from titanium fixtures during placement in the mandible: an experimental study. Int J Oral Maxillofac Implants 8(5):502–511
29. Goodman SB, Ma T (2010) Cellular chemotaxis induced by wear particles from joint replacements. Biomaterials 31(19):5045–5050
30. Bukata SV et al (2004) PGE2 and IL-6 production by fibroblasts in response to titanium wear debris particles is mediated through a Cox-2 dependent pathway. J Orthop Res 22(1):6–12
31. Tanaka M et al (1994) Effects of bone tapping on osseointegration of screw dental implants. Int J Oral Maxillofac Implants 9:541–547