CLINICAL ORAL IMPLANTS RESEARCH

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The Influence of implant geometry and surface composition on bone response

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Date:
Accepted 9 April 2013

To cite this article:
AlFarraj Aldosari A, Anil S, Alasqah M, Al Wazzan KA, Al Jetaily SA, Jansen JA. The Influence of implant geometry and surface composition on bone response.
Clin. Oral Impl. Res. **25**, 2014, 500–505
doi: 10.1111/clr.12190

Key words: calcium phosphate coatings, cylindrical, dental implant, histomorphometry, implant design, osseointegration, surface treatment, tapered

Abstract

Objectives: The implant design and surface modification are independent conditions that can alter the implant bone response. The objective of this study is to compare the bone response to roughened tapered and cylindrical screw–type implants with and without hydroxyapatite (HA) surface coating in the femoral trabecular bone of rabbits.

Material and method: Thirty-two implants (8 × 3.5 mm) consisting of four different types (eight implants in each group), that is, tapered implants, cylindrical implants, HA-coated tapered implants, and HA-coated cylindrical implants were installed in the femoral condyle of 16 rabbits. After 8 weeks of healing, the femoral condyles were retrieved and studied histologically. The bone-to-implant contact percentage was assessed and analyzed statistically.

Results: The histomorphometric analysis revealed that the bone-to-implant contact (BIC) values seemed to be higher for HA-coated tapered implants (65.62 ± 13.02) followed by cylindrical non-coated implants. All four types of implants showed wide distribution of BIC with no statistical significance between different types of implants.

Conclusion: It can be concluded that under the current experimental conditions, implant design and surface composition had little effect on the bone-to-implant interface.

The long-term success of dental implants depends on the interfacial bonding between the implant and surrounding bone. The final outcome of this biological process is determined by various non-implant and implant-related parameters. Non-implant-related factors can be further discerned in: (i) patient-related factors, like host bed condition, health condition and habitual habits, and (ii) dentist-related factors, like surgical skills and experience. Implant-related factors refer mainly to the implant material characteristics, implant design, and implant surface properties (Esposito et al. 1998; Salvi & Lang 2004). Implant-related factors are easier to influence than non-implant-related factors. As a consequence, during the last 20 years, a lot of efforts have been carried out into this direction.

All performed research has proven that factors such as roughness, topography, and chemical composition of the implant surface play an important role to accelerate and to enhance new bone formation at the implant site (Sohn et al. 2006). Studies confirmed that the success of integration of implants into bone tissue correlates positively with the roughness of the implant surface (Anselme & Bigerelle 2006). An increased surface roughness is known to enhance cell adhesion, proliferation, and differentiation (Lee et al. 2008). Another advantage of roughened titanium surfaces is a shorter healing period with good prognosis because of the better bone anchorage (Schenk & Buser 1998). Cooper (2000) concluded that an increase in the surface roughness of titanium implants improved bone integration with respect to the amount of bone formed at the interface, increased osteoconduction and osteogenesis. Also, alteration of the implant surface chemistry, for example, by deposition of a calcium phosphate coating, has been shown to be effective for an additional increase in osteoconductivity (Gan et al. 2004). The use of calcium phosphate–derived coatings, such as hydroxyapatite (HA) surfaces, has been widely documented, and several studies

showed faster bone integration around the implants (Caulier et al. 1995; Gottlander et al. 1997; Mohammadi et al. 2003).

Various approaches can be used to provide an oral implant with a calcium phosphate coating. A current, clinically applied technique is magnetron sputtering, which is based on physical vapor deposition of a thin calcium phosphate film with a uniform thickness without changing the roughness of the carrier material (Jansen et al. 1993; Wolke et al. 2003). Several short- and long-term studies have shown better osseointegration with dental implants modified by this method (Mohammadi et al. 2003; Manders et al. 2006; Ozeki et al. 2006; Fugl et al. 2009).

Besides the direct effect of implant surface properties on bone healing, the dental implant design has been advocated to support final implant success. Implant design is supposed to reduce crestal bone loss, biomechanical load and microdamage to the bone as well as to increase the primary implant stability (Morris et al. 2004; Sakoh et al. 2006). Hence, manufacturers have recently been striving to produce dental implants, which can even achieve a good primary stability in poor bone quality. An example of such a new design is the tapered-screw type implant (Sakoh et al. 2006). The tapered-screw type implants were intended for immediate implantation and resulted in an increased primary stability compared with cylindrical straight-screw types (Garber et al. 2001; Glauser et al. 2004).

However, there are only a few studies that support the theoretical basis of tapered-screw type implants. Irrespective of the fact that implant design and surface modification are independent conditions that can alter implant bone response, till now no study has been performed to investigate the separate added value of these parameters. In the current study, such a comparison was carried out by installing roughened tapered and cylindrical screw–type implants with and without HA surface coating in the femoral trabecular bone of rabbits. It was hypothesized that roughened tapered HA-coated implants would evoke an enhanced bone-to-implant contact after 8 weeks of implantation.

Materials and methods

Sixteen healthy New Zealand White rabbits aged 6–9 months and weighing between 3.5 and 5 kg were used as experimental animals. All rabbits were housed separately in standard cages under laboratory conditions. The study was approved by the Ethical committee of the College of Dentistry, King Saud University. The procedure was based on a well-established bilateral, rabbit, femoral implant model.

Implants

Thirty-two commercially pure titanium (cpTi) implants were used for the study and consisted of four different types (eight implants in each group), for example, tapered implants, cylindrical implants, HA-coated tapered implants and HA-coated cylindrical implants. All implants were provided with a minimally rough surface using a grit blasting and acid etching procedure (Ra = 1.5 μm). Average surface roughness values were analyzed by a universal surface tester (UST; Innowep, Würzburg, Germany) (Tabassum et al. 2010).

Tapered implants

The tapered implants had the following dimensions: length of implant 8 mm, length of crestal part 1.5 mm, diameter at crestal part 3.5 mm, diameter at apex 2.1 mm, thread depth 0.5 mm, distance between threads 0.5 mm (Fig. 1).

Cylindrical implants

The cylindrical implants had the following dimensions: length of implant 8 mm, length of crestal part 1.5 mm, diameter at crestal side 3.5 mm, diameter at apex 2.6 mm, thread depth 0.5 mm, distance between threads 0.5 mm (Fig. 1).

Hydroxyapatite coating procedure

Hydroxyapatite coatings, with a thickness of 1 μm, were deposited on the implants using a commercially available RF sputter deposition system (Edwards ESM 100, HHV Ltd, Crawley, UK) (Wolke et al. 2003). The target material was composed of HA ($Ca_5(PO_4)_5OH$) granules. The titanium implants were mounted on a rotating and water-cooled substrate holder. During deposition, the argon pressure was kept at 5×10^{-3} mbar, and the sputter power was 400 W. After deposition, the coated implants were subjected to an additional infrared heat treatment (HT) for 30 s at 650°C (Quad Ellipse Chamber, Model E4-10-P; Research Inc., Eden Prairie, MN, USA) (Vercaigne et al. 2001). Before implantation, the composition and structure of the coatings were characterized by thin film X-ray diffraction (Philips, PW3710, Almelo, the Netherlands) and Fourier transform infrared spectroscopy. Coating thickness was confirmed by UST.

Before surgical installation, all implants (as-received and coated) were autoclaved.

Surgery

Surgery was performed using aseptic routines and under general anesthesia by intramuscular injections of a combination of a dose of 35 mg/kg ketamine and a dose of 5 mg/kg xylazine. After anesthesia, the hind limbs were shaved, disinfected and isolated with drapes. Infiltration anesthesia was performed at the experimental sites. The left and right knee joints were exposed through a medial parapatellar longitudinal incision. The capsule was incised, and the medial femoral condyle was exposed after lateral dislocation of the patella. With the knee maximally flexed, a hole was created through the articular cartilage into the subchondral bone on the weight-bearing surface of the femoral condyle using a dental drill (type, etc.). Drilling was performed at low rotational speed (600–800 rpm) using extensive external cooling with sterile saline solution. The implant bed was widened in gradient steps with a final drill diameter of 3.3-mm tapered drill for the tapered implant and 3.35-mm twist drill for the cylindrical implants. The implants were installed according a pre-determined randomized sequence (Fig. 2).

Finally, the surgical sites were closed in layers using resorbable sutures (Vicryl, 4-0), and

Fig. 1. Types of Implants used for the study.

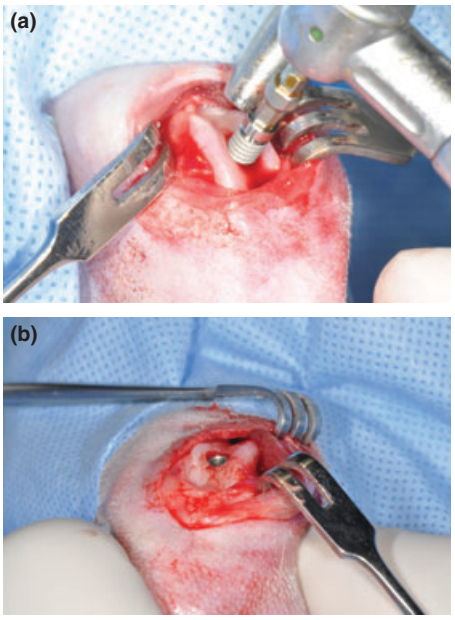

Fig. 2. Implant installation.

animals were returned to their cages. Post-surgery pain was controlled by the administration of Fynadyne® (Fynadine; Schering Plough Animal Health Benelux, Utrecht, the Netherlands) intramuscularly. To reduce the post-operative infection risk, enrofloxacin 5–10 mg/kg (Baytril, Bayvet Division; Chemagro Ltd, Etobicoke, ON, Canada) (5–10 mg/kg) was administered. To ensure randomization of the implants, an installation schedule was used as listed in Table 1. After 8 weeks of implantation, the animals were euthanized, and the femoral condyles were harvested for histological preparation.

Histology

After harvesting, all specimens were cleaned from attaching soft tissues. The femoral condyles including the implants were fixed in 10% formaldehyde. After fixation, the specimens were reduced in size and then dehydrated in increasing ethanol concentrations (70–100%). Finally, they were embedded (non-decalcified) in modified methylmethacrylate (MMA) for 5 days (mixture of 300 ml MMA, 30 ml dibutylphthalate, and 5 g 2,2′azabisisobutyronitrile 98%). After polymerization in MMA, thin sections (approximately 10 μm) were cut in longitudinal direction to the axis of the implant using an inner circular saw microtome (Leica RM 1600, Wetzlar, Germany). These sections were stained with methylene blue and basic fuchsine and were used for light microscopical assessment and histomorphometrical analysis.

Table 1. **Randomization schedule**

Rabbit number	Left condyle	Right condyle
1	A	B
2	C	D
3	B	C
4	D	A
5	C	D
6	A	B
7	D	A
8	B	C
9	A	B
10	C	D
11	B	C
12	D	A
13	C	D
14	A	B
15	D	A
16	B	C

A: tapered Ti; B: tapered HA; C: threaded Ti; D: threaded HA; HA, hydroxyapatite.

Histomorphometry

Histological evaluation was performed using the automated Zeiss Z1 Axio Imager microscope (Carl Zeiss Micro Imaging GmbH, Göttingen, Germany). Histomorphometry was performed using digital image analysis software (Leica® Qwin Pro-image analysis; Leica Microsystems Imaging Solutions Ltd, Cambridge, UK). The quantitative parameter, as assessed, was the percentage of bone-to-implant contact (BIC%). Bone contact was analyzed along the total length of the implant; starting at the first coronal microthread up to the apex of the implant. BIC% was defined as the percentage of the implant surface in direct contact with bone without intervening fibrous tissue layers. All measurements were performed for both sides of the implant on three histological sections per implant (at magnification 25×).

Statistical analysis

Statistical analysis was performed using a random effect multiple regression model in order to correct for clustering of data in one rabbit. The model estimated the effect of implant shape and coating as well as the difference in coating effect for the two implant shapes (i.e. additional interaction term). Differences were always considered significant at P-values < 0.05.

Results

Macroscopic evaluation

All animals survived the experimental period, stayed healthy and showed no sign of infection or discomfort. All implantations sites healed well, and no swelling or redness was observed. Gross examination of the retrieved specimens indicated that all implants were in place without any sign of an inflammatory response. The articulating surface of the knee joint had a smooth appearance, but was not completely covered with cartilage. The implant could easily be recognized.

Histological analysis

Light microscopical examination revealed that no gross difference in bone response to the various implant types were present. All implants were surrounded by trabecular bone, as characterized by the occurrence of bone trabeculae with interspersed areas of bone marrow (Figs 3a and 4). Bone trabeculae were observed to be in direct contact with the implant surface without the presence of an intervening fibrous tissue layer (Fig. 3b,c). No inflammatory cells were seen. The implant bed had completely remodeled, and the original drill hole or loosened bone debris could not be recognized. At the cortical side, no bone resorption was observed, and no overgrowth of cartilage had occurred (Figs 3a and 4).

Histomorphometry

Table 2 and Fig. 4 list depict the bone-to-implant contact data for the various implants. Although, the BIC values seemed to be higher for HA-coated tapered implants (65.62 ± 13.02), the observed difference was not statistically significant (see Table 3). Further, it was noticed that the BIC measurements for the respective implant types showed a wide distribution (Fig. 5).

Discussion

Primary implant stability is considered to play a fundamental role in obtaining successful osseointegration (Albrektsson et al. 1981; Friberg et al. 1991). Primary implant stability lowers the level of implant micromotion, which in turn allows uninhibited healing and osseointegration (Friberg et al. 1991). Factors such as material biocompatibility, implant design and surface, surgical technique, host bed, and the loading conditions have all been shown to influence the implant osseointegration (Albrektsson et al. 1981).

In the present study, osseointegration was studied by installing roughened tapered and cylindrical screw–type implants with and without HA surface coating in the femoral trabecular bone of rabbits. Statistical analysis revealed that no significant differences existed between the bone-to-implant contact measurements for the four implant types. Considering the above-mentioned

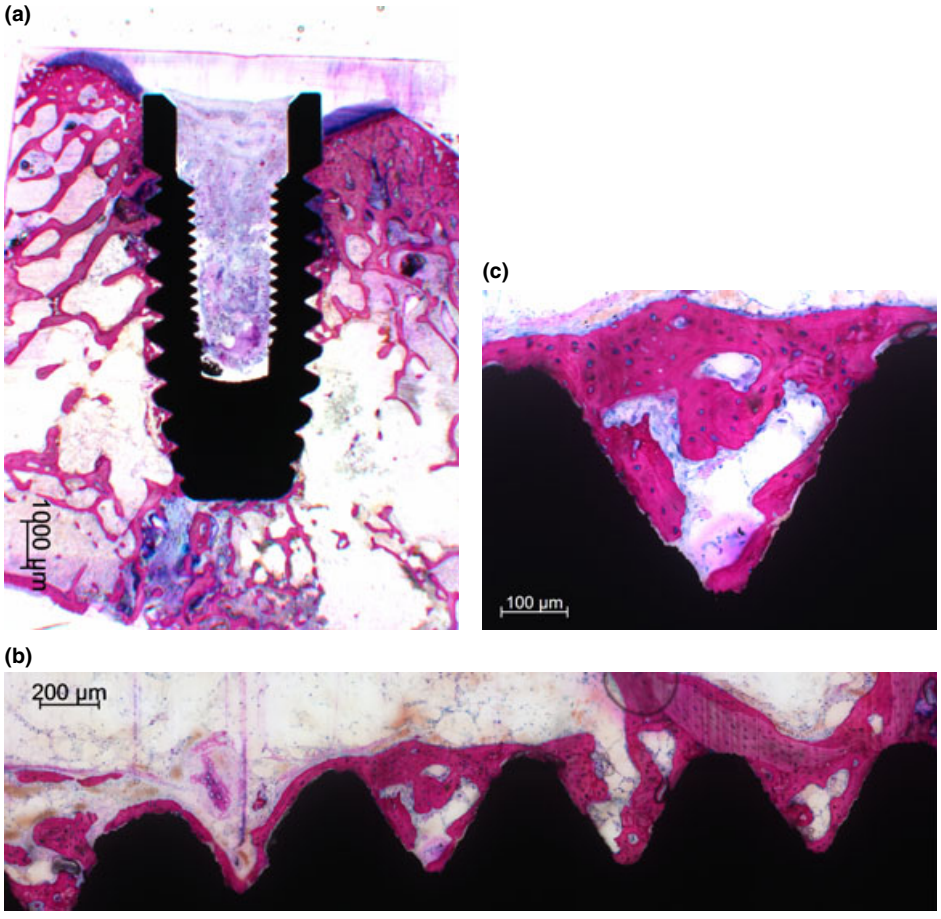

Fig. 3. (a) Histological image of threaded implant provided with hydroxyapatite (HA) coating. Original magnification 1×. (b) Image at higher magnification. The implant surface is covered with bone tissue, which has grown into the screw threads. Original magnification is 20×. (c) High magnification. The bone is in direct contact with the implant. No intervening fibrous tissue layer is present. Bone is characterized by a mineralized matrix including osteocytes. Osteoblasts can be recognized in remodeling lacunae, as well as on the bone surface in contact with the bone marrow. Original magnification 20×.

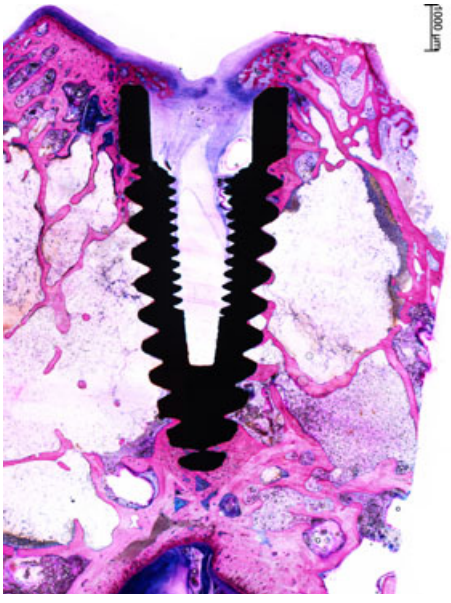

Fig. 4. Light microscopical image of tapered titanium implant showing its positioning into trabecular bone. There is no resorption of the cortical bone. Original magnification 5×.

Table 2. **Showing the bone-to-implant contact percentage (BIC%) in four types of implant used in the study (Ti-Tapered, Ti-Cylindrical, HA-Tapered, and HA-Cylindrical)**

	BIC%		
Type of implant	Median	Mean	SD
Ti-Tapered	49.85	49.07	10.94
Ti-Cylindrical	54.25	55.41	10.72
HA-Tapered	67.10	65.62	13.02
HA-Cylindrical	55.00	55.33	16.89

HA, hydroxyapatite.

justification of our experimental design, it is appropriate to discuss the relevance of our findings.

Originally, endosseous implants were parallel in design and were not suitable in certain situations especially in the maxillary anterior region. Therefore, tapered implants were designed to improve esthetics and to facilitate implant placement between adjacent natural teeth (Shapoff 2002). The rationale behind the use of tapered implants is to provide for a degree of compression of the cortical bone in a poor bone–implant site (O'Sullivan et al. 2004). In an animal experiment, O'Sullivan et al. (2004) installed titanium implants with two different degrees in the femoral condyles of rabbits, and they measured resonance frequency analysis (RFA) values directly after implant insertion, as a measure of primary stability. Their results indicated that 1 degree of taper results in a better primary implant stability compared with standard cylindrical implants. In addition, their data showed that primary stability was increased after 6 weeks of implantation. On the other hand, less positive results about the use of tapered implants were reported by Vandeweghe et al. (2012), who implanted cylindrical and tapered implants in patients. Straight cylindrical implants were clinically found to be more successful than the tapered implant. In addition, more bone loss at the crestal level was seen for the tapered implants. They supposed that this was due to an increased stress in the cortical area as caused by the tapered design. A similar, not favorable effect of the implant tapered design has been reported by Moon et al. (2010). They performed a cadaver study and evaluated the effect of implant shape en preparation of the implant bed on primary implant stability. In agreement with O'Sullivan et al. (2004), they took RFA measurements. However, the RFA data for straight and tapered implants did not differ. On the other hand, overpreparation of the implant bed did have a negative effect on the RFA values. In our histological study, no impact of implant shape on final bone-to-implant contact after 6 weeks of implantation into the trabecular bone of the femoral condyle of rabbits was seen, which fits with the previously mentioned observations. Both cylindrical and tapered implants showed a good primary stability after implantation, which is known to be a determining factor for the osseointegration process. Therefore, it can be hypothesized that bone response after 6 weeks of healing will be similar, as bone bed conditions as well as operator did not differ. In our study, no effect of the implant type on the cortical bone remodeling was observed, which can be due to the fact that the cortical layer at the articulating surface of the rabbit knee is rather thin, which will result in a limited compression of the bone.

Osseointegration can further be improved by modifying the bioinert surface of metallic implants into a bioactive surface, for example, by the use of Ca-P-derived coatings, such as HA. Animal studies have shown faster

Table 3. **Model structure of the random effect multiple regression model**

	Value	*P*-value	Lower	Upper
Intercept	55.17530	0.0000	45.333958	65.016650
Shape	−5.86311	0.3838	−19.909078	8.182862
Coating	−0.02663	0.9967	−13.661454	13.608204
Shape × coating	16.62825	0.0937	−3.235751	36.492252

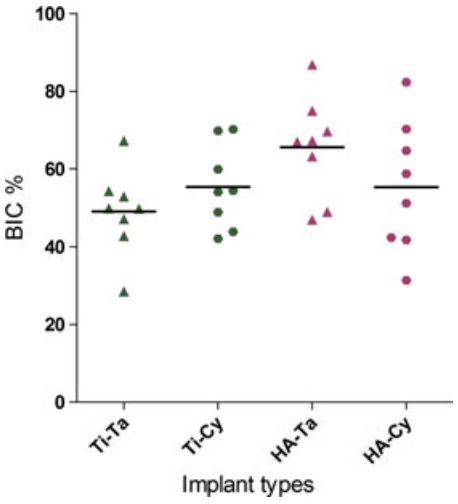

Fig. 5. Bone-to-implant contact percentage (BIC%) in four types of implant used in the study (Ti-Tapered, Ti-Cylindrical, hydroxyapatite [HA]-Tapered, HA-Cylindrical). Graph is showing the distribution of the data.

bone integration around Ca-P-coated implants (Caulier et al. 1995; Gottlander et al. 1997; Mohammadi et al. 2003). Mohammadi et al. (2003) studied bone response to micron- and submicron-thick HA coatings in cortical and trabecular bone in rabbit model. Four types of CaP-coated implants were used (0.1 and 2.0 μm amorphous; 0.1 and 2.0 μm crystalline); uncoated machined commercially pure titanium implants served as controls. Crystalline CaP coatings 100 nm thick on titanium implants elicited an improved early bone response compared with that of uncoated titanium implants. Significantly, more bone-to-implant contact was found in HA-coated implants at 4 and 12 weeks compared with commercially pure titanium threaded implants in a rabbit study (Gottlander et al.1997).

A disadvantage related to the use of Ca-P-coated implants can be the dissolution of the coating or to the detachment at the titanium-coating interface (Biesbrock & Edgerton 1995). Specifically, such observations have been performed for thick, plasma-sprayed Ca-P coatings. However, it has to be noticed that the reported problems can be due to the manufacturing process and that not all manufactures of plasma-sprayed Ca-P coatings deliver coatings with similar quality. On the basis of the outcome of human clinical trials, it has even been suggested that the use of plasma-sprayed Ca-P coatings can results in failure of an implant, due to inflammatory response to released Ca-P particles (Bloebaum et al. 1994) and subsequent osteolysis. Although these problems can be caused by the followed surgical protocol, loading condition or prepared suprastructure, the unfavorable reports have resulted of an almost complete banishment of plasma-sprayed oral implants. In the current study, implants were provided with a Ca-P coating using a magnetron sputtering technique, which is superior compared with plasma spraying and overcomes problems, like coating adhesiveness and dissolution (Jansen et al. 1993; Yang et al. 2005; Ong et al. 2007).

The histomorphometrical measurements indicated no effect of the deposition of a HA coating on the bone-to-implant contact percentage after 6 weeks of implantation. This finding seems to contradict earlier studies about the bone favorable effect of Ca-P sputter–coated implants. However, differences in experimental conditions do not allow a straightforward comparison of the various studies. For example, Hulshoff et al. (1996) installed magnetron sputter Ca-P-coated implants in the femoral condyle of rabbits and left them in place for 3, 6, and 9 weeks. However, in this study, no non-coated titanium implants were included, and plasma-spray-coated implants were used as reference material. In the majority of the other studies, goats were used as experimental animal model, and implants were left in place for 6–12 weeks. In these studies, the Ca-P sputter-coated implants always showed an enhanced bone-to-implant contact compared with as-received titanium implants (Vercaigne et al. 2001; Manders et al. 2006). Further, it has to be noticed that the lack of statistical significance can be due to the small sample size ($n = 8$). However, the number of animals was chosen on the basis of earlier studies in which the same implant location was used. It can be recommended that in future studies, more animals are included.

This discrepancy in bone response can be explained by the used animal model. Rabbits are known to show a faster skeletal change and bone turnover rate than large animal models, like goats and dogs (Castaneda et al. 2006), as well as in humans. Also, the bone formation around implants in rabbits is much faster than in humans. The length of the bone remodeling cycle is 6 weeks in the rabbit compared with about 4 months in humans (Slaets et al. 2007). As CaP coatings are only able to affect the early bone response, it can be hypothesized that an implantation period of 6 weeks in a rabbit is too long to observe any difference in bone behavior. In view of this, it has to be emphasized that researchers have to pay good attention to the research question in their selection of an appropriate animal model.

Finally, some comments have to be made about the insertion of oral implants into the femoral condyle of rabbits. In most studies, implants are installed after surgical exposure of the medial or lateral side of the femoral condyle. However, the dimensions of the femoral condyle are very limited, and a growth plate is present (Bodde et al. 2008). As a consequence, the danger exists that the implants are not completely surrounded by trabecular bone, but are partly inserted into the growth plate. This will have an effect on the final bone formation. This problem can be avoided using the articular approach, as used in the current study design. In rabbits, this is still a very simple procedure, which does not induce serious discomfort for the animals. The histological sections showed clearly that all implants were completely surrounded with trabecular bone and did not interfere with the growth plate.

Conclusion

From the observations of the present study, it can be concluded that within the limitations of the currently used rabbit model, no significant effect of implant design and surface composition on the bone-to-implant bone response was observed after 6 weeks of implantation.

Acknowledgement: The authors acknowledge Dr. E. M. Bronkhorst for his assistance with the statistical analysis.

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