A Histometric Comparison of Smooth and Rough Titanium Implants in Human Low-Density Jawbone

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The aim of this investigation was to conduct a comparative histometric analysis of bone-implant interface between a rough titanium surface and smooth implants in low-density human jawbone after 3, 6, and 12 months of submerged, undisturbed healing. Six adult volunteer patients undergoing standard implant placement were enrolled in this project. Each patient received 1 smooth and 1 rough implant. After 3, 6, and 12 months, the implants were harvested for histometric analysis. The values of bone-implant contact were the following: 3 months smooth 6.2%, 3 months rough 58.9%, 6 months smooth 3.55%, 6 months rough 72.9%, 12 months smooth 6.7%, and 12 months rough 76.75%. The results showed that in low-density bone the rough surface dramatically enhanced the amount of bone-to-implant contact. Because of the small number of implants examined, definite conclusions cannot be drawn, even though the statistical analysis showed significant differences between the smooth and rough groups (P = .0129; F = 76.065). Nevertheless, a trend was evident in these observations: while a rough implant surface may enhance the rate of osseointegration, it is not able to significantly change the bone density, and an implant placed in low-density bone is at a higher risk of failure when occlusal loading begins.
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Key words: histometry, human histology, implant surface, rough implants

Osseointegrated implants made of commercially pure (cp) titanium are used for the fixation of dental prostheses with good long-term clinical results.[1,2] Even though osseointegration is a biologic concept clinically functioning, many aspects of this "living bone in direct contact with an implant surface at the light microscopic level" phenomenon need clarification.[3,4] The design of implants must suit the desired application, and in implant dentistry, screw and cylindric implants are the preferred shapes because they are relatively easy to place and to remove.[5,6] Primary stability is essential to achieve ideal osseointegration and it depends on both macroscopic and microscopic implant characteristics, as well as bone structure.[7]

The intimate mechanisms by which titanium implants are anchored to bone are not completely understood. The percentage of bone-to-implant contact (BIC) at the interface level seems to be a crucial factor. Implants with roughened surfaces demonstrate better early anchorage in bone tissue than implants with smooth surfaces.[6,8] Resistance to unscrewing up to 12 months following placement for screw-shaped titanium implants increases with time in proportion to the increase in bone-to-implant contact.[9,10]

Traditionally, histometric measurements of BIC have been made in animal studies. Some studies have shown that machined-prepared smooth titanium surfaces allow a good percentage of bone contact.[9,11,12] On the other hand, implants with a rough surface have demonstrated a higher percentage of bone-to-implant contact.[6,8] A rougher surface has been shown to result in faster[13] as well as firmer bone integration.[14] Results of the animal experiments were then extrapolated to humans, but no histologic data, to the authors' knowledge, has been reported to confirm these findings in human beings, although many commercially available implants do have a rough surface.

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Fig 1a Experimental mini-implant, 5 mm × 3.3 mm, used for the histologic evaluation.
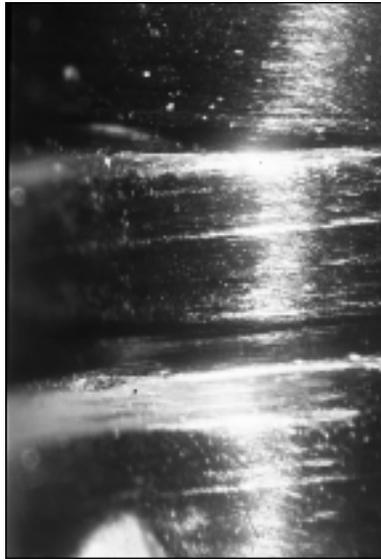

Fig 1b Reflected light micrograph of the titanium surface of the smooth implant (original magnification ×50).

Fig 1c Reflected light micrograph of the titanium surface of the rough implant (original magnification ×50).

Long-term success rates seem better when implants are placed in areas with denser bone (Types 1 and 2) and lowest in areas with low bone density (Types 3 and 4).[15,16] This reduction in the success rate in low-density bone seems to be the result of lower biomechanical anchorage of the implants in trabecular bone. If rough implants are able to enhance the amount of bone-implant contact, they should be able to enhance anchorage of the implant in bone, particularly in areas where bone density is lower, thus improving the success rate.

The aim of this report was to histometrically compare the percentage of BIC of a rough titanium surface and a smooth implant in low-density human jawbone, after 3, 6, and 12 months of submerged, undisturbed healing.

Materials and Methods

Test Device. Twelve experimental implants were manufactured by Exacta (Biaggini Ormco Italia, La Spezia, Italy). The test device was a conical screw-shaped implant, 3.3 mm wide and 5 mm long (Fig 1a). The implants were made of cp titanium grade 3 (Uni 9763/2) with 2 different implant surfaces. In the control group the implant surface was polished to obtain a smooth texture (Fig 1b). In the test group, the implant surface was roughened using a corundum-blasting procedure (Fig 1c). The blasted surface showed a mean Ra of 1.329 (Rt = 21.557; Rmax = 20.847). The

implants were surgically placed and retrieved after 3, 6, and 12 months, so that 3 test and 3 control groups were analyzed.

Surgical Procedure. Nine adult volunteers (5 males and 4 females) undergoing standard implant procedure for implant placement were provisionally enrolled in this report. All the experimentation was done in accordance with the Helsinki Declaration of 1975, as revised in 1983. Exhaustive medical histories were collected. All the patients were healthy and did not present any contraindication to oral surgical procedures.

The patients underwent standard implant placement in the posterior jaws (both arches). A periapical radiograph was obtained before surgery to provide a general assessment of bone density. If the radiographic analysis showed low density, then the patients were provisionally enrolled in the study. The bone density, as determined by surgical hand drilling resistance, had to be Type 3 or 4 according to Misch[17] and Trisi and Rao.[18] If during drilling the registered drilling resistance yielded a value of 3 or 4, then the patient was definitively enrolled in the study. At the end of the selection process, 6 patients met the prerequisite for enrollment.

During stage 1 surgery, 2 mini-implants were placed distally to the most distal standard implant, in sites where the bone height was insufficient for the placement of a standard implant. Each patient received 1 smooth and 1 rough implant. The patients were informed that the surgical proce-

Table 1 Bone-Implant Contact in Implants Examined

Time/implant type	Count	Mean contact	SD	SE
3 months smooth	2	6.200	1.556	1.100
6 months smooth	2	3.550	5.020	3.550
12 months smooth	2	6.700	2.121	1.500
3 months rough	2	58.900	5.091	3.600
6 months rough	2	72.900	12.162	8.600
12 months rough	2	76.750	12.657	8.950

SD = standard deviation; SE = standard error.

dures used to position the mini-implants presented the same risks as standard dental implant procedures and gave their informed consent to participate in the project. The minimal distance between the standard implants and the mini-implants was 6 mm to avoid any risk for the standard implants. Prior to surgery, the patients were given a single dose of 2 grams of amoxicillin.

Following local anesthesia, a mucoperiosteal flap was elevated with a crestal incision utilizing a #15 blade. The flap was wide enough to allow for positioning of the therapeutic implants and the 2 mini-implants. Using low-speed calibrated burs, under copious irrigation with cooled sterile saline solution, the implant sites were prepared, taking care to always obtain primary stability. The mini-implants were placed at a crestal level to allow submerged healing. Following implant placement, the flap was adapted and sutured with 4.0 silk suture, thus obtaining primary wound closure. Postoperative therapy included 2 g of amoxicillin per day and 3 daily rinses with 0.12% chlorhexidine for 7 days after surgery. Weekly examinations in the first month and a monthly control in the following months were scheduled to evaluate possible complications. After 3, 6, and 12 months, the implants were uncovered and the mini-implants were harvested. Under local anesthesia, the experimental implants were carefully retrieved, along with a small portion of surrounding bone. The area of surgery was thoroughly rinsed with sterile saline solution, and a regenerative procedure involved placement of a collagen barrier membrane to obtain healing of the residual defect.

Histologic and Histometric Procedure. All bone biopsies were immediately rinsed in saline, fixed in 10% neutral buffered formalin, and processed to obtain thin ground sections. The specimens were dehydrated in an ascending series of alcohol rinses and then embedded in Remacryl resin (an experimental resin created by Mr Cesare Scala, Istituto di Microscopia Elettronica Clinica, Ospedale Sant'Orsola, Bologna, Italy). After polymerization, the specimens were sectioned at 200 to 250 μm by a Micromet high-speed rotating blade microtome (Remet, Bologna, Italy), and ground to about 40 to 50 μm by an LS2 (Remet) grinding machine, according to Donath and Breuner.[19] The histologic slides were routinely stained with toluidine blue, Masson-Goldner, or von Kossa staining solutions.

After the sectioning process was completed, each slide was histometrically analyzed to quantify the percentage of BIC around each implant. The histometric analysis was performed by counting, in a rectangular integrating grid eyepiece with horizontal and vertical lines, the length of the surface of the implant covered by bony trabeculae over the total length of the implant surface. These measurements were made using a 10× objective in all specimen fields, by counting the intersections over the implant surface. For each implant 3 sections were analyzed. Finally, the results were expressed as a percentage of the implant surface covered by bone. These measurements were made on each specimen and the results were recorded in the corresponding groups. Thereafter, a repeated-measures analysis of variance (ANOVA) test was applied to obtain some estimate of the probability that the results could be explained by chance.

Results

All patients healed without complication after stage I and stage II surgery. Six months after implant retrieval, radiographic examination showed complete filling of the bony defects at the site of the mini-implant removal. The patients were dismissed from the study but they are still examined 3 times a year to evaluate the long-term stability of the implants and to ensure oral hygiene compliance. Histometric results may be found in Table 1.

Smooth Implants at 3 Months. The bone density was Type 3. The mean percentage of BIC was 6.2% (Fig 2a). Although bone trabeculae surrounded almost all of the implants, few areas of BIC were visible. The titanium was separated from
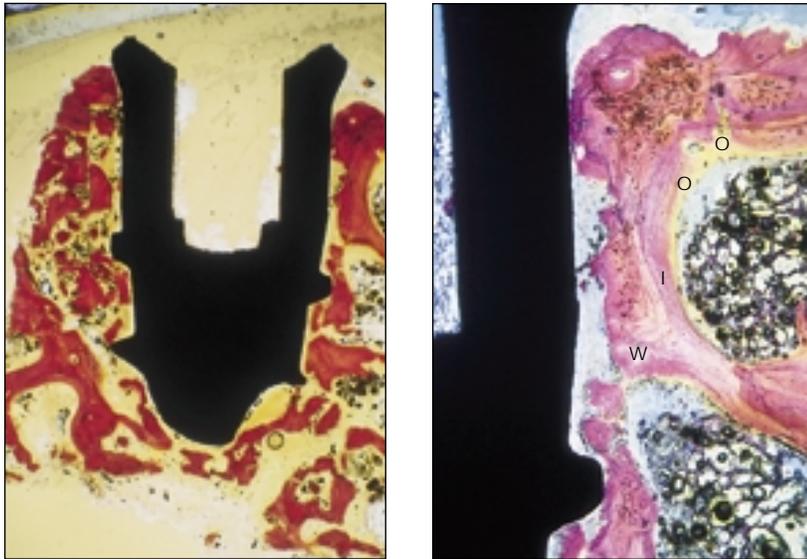
Fig 2a *(Left)* Histologic section of a 3-month smooth specimen. The density of the bone is nearly 50%, but very few areas of bone-to-implant contact are present (original magnification ×10, Masson-Goldner staining).

Fig 2b *(Right)* Magnified view of the smooth implant surface at 3 months. The bone facing the implant surface is a composite bone made of areas of woven bone (W) and layers of lamellar (L) bone. Also some osteoid (O) seams are visible. It is possible to observe a few contact points between the implant and bone (original magnification ×50, Masson-Goldner staining).

the bone by a layer of loose marrow tissue without inflammatory cells. The bone trabeculae showed many layers of newly formed bone with osteoid seams that occasionally made contact with the implant (Fig 2b). At this stage most bone formation was of the lamellar type, even if areas of woven bone were visible (Fig 2b). The bone surface facing the implant did not match the implant profile, thus demonstrating that this gap was not an artifact caused by the retrieval surgery or specimen processing. Moreover, this gap was filled with cells and fibers that were well organized and preserved.

Rough Implants at 3 Months. The mean percentage of BIC was 58.9% (Fig 3a). The bone density was Type 3. New bone grew from the wall of the pre-existing drilled bone and, in many areas, filled the space up to the implant surface, thus providing the opportunity for osseointegration. This newly formed bone had the appearance of woven bone, with many thin trabeculae surrounding a network of capillaries (Figs 3a and 3b). Most of the marrow spaces at the level of the implant surface were closed by the newly formed bone (Fig 3a). Areas of lamellar bone apposition, with osteoid layers and osteoblast cells, were also visible on the implant surface and between the trabeculae of the woven bone. Bone remodeling was also present, with the coupling activity of the osteoclasts and the osteoblasts near the implant surfaces.

Smooth Implants at 6 Months. The mean percentage of BIC was 3.5%. The implants were also placed in low-density Type 3 or 4 bone (Fig 4a). Very few and thin bony trabeculae surrounded the implant, and only very small areas of bone-to-implant contact were visible (Fig 4a). A layer of

sound marrow tissue, without signs of inflammatory cells, was interposed between the titanium and bone (Fig 4b). The trabeculae were composed of cores of woven bone surrounded by few layers of lamellar bone (Fig 4b). Few signs of osteoid tissue and remodeling activity were visible.

Rough Implants at 6 Months. The mean percentage of BIC was 72.9%, and the bone density was Type 3 or 4. The blasted implants were surrounded by a network of thin bony trabeculae (Fig 5a). This thin layer of newly formed bony trabeculae was in direct contact with a large portion of the implant surface and was mineralized, as shown by von Kossa staining (Fig 5b). The bone contact stopped suddenly at the level of the cover screw, which was not blasted (Fig 5a). This layer of bone was composed of 2 or 3 bone lamellae. Few signs of bone-forming activity or remodeling activity were present. In some areas, where medullary spaces came into contact with the implant surface, loose bone marrow tissue was present. The bone surrounding the implants seemed to form a basket of thin trabecular bone, similar to a very thin alveolar cortex.

Smooth Implants at 12 Months. The mean percentage of BIC was 6.7% (Fig 6a). The bone quality was low and there was little BIC contact. A thin layer of trabecular bone surrounded almost all the implant surface, but it was separated from the titanium surface by a layer of marrow tissue (Fig 6b). This bone formed a thin capsule around all of the implant surface, but only in small limited areas did the bone face the implant surface, implying there might be osseointegration. The bone had the appearance of very thin and brittle bony
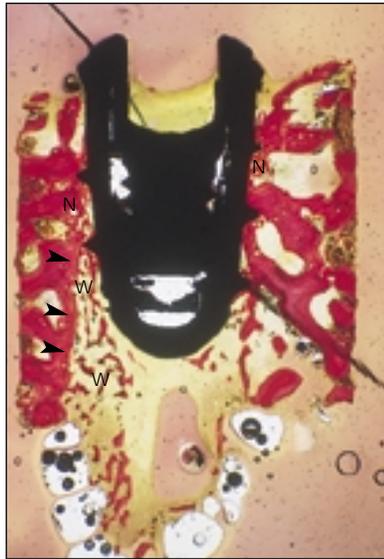
Fig 3a Histologic section of a 3-month blasted specimen. The implant was placed in bone with almost the same density as the bone surrounding the smooth implant. The gap (*arrowheads*) between the prepared bone bed and the implant is still visible at the apex of the implant. A layer of woven bone (W) is closing this gap and enhancing the percentage of osseointegration. In the other areas of the implant surface, the marrow spaces in contact with the blasted titanium are being closed by newly formed bone (N) (original magnification ×8, Masson-Goldner staining).
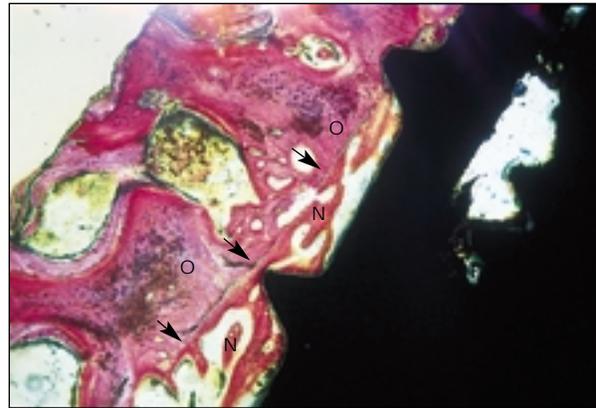

Fig 3b Magnified light micrograph of the blasted 3-month specimen showing the woven aspect of the new bone (N) formed over the implant surface. This new bone is close to the medullary spaces at the level of the implant surface and fills the gap (*arrows*) between the old pre-existing bone (O) and the implant surface (original magnification ×50, Masson-Goldner staining).
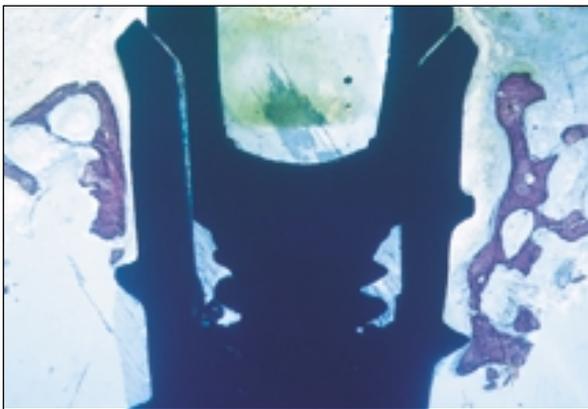

Fig 4a Histologic section of a 6-month smooth implant showing the very low density of bone and an almost complete absence of bone-to-implant contact. The bone trabeculae around the implant surface are very thin and brittle (original magnification ×25, toluidine blue staining).
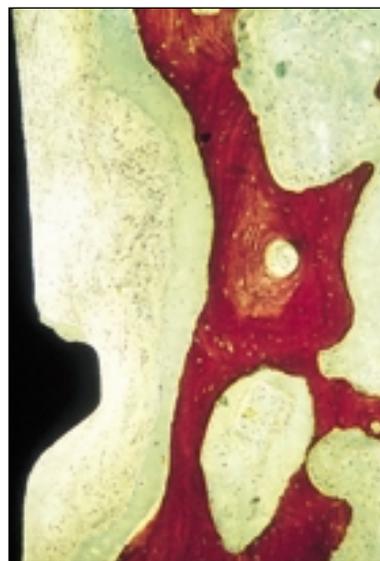

Fig 4b High-power view of the section in Fig 4a. The connective tissue layer interposed between the bone and the implant demonstrates that the implant is not osseointegrated. Few fibrous cells are visible (original magnification ×100, Masson-Goldner staining).
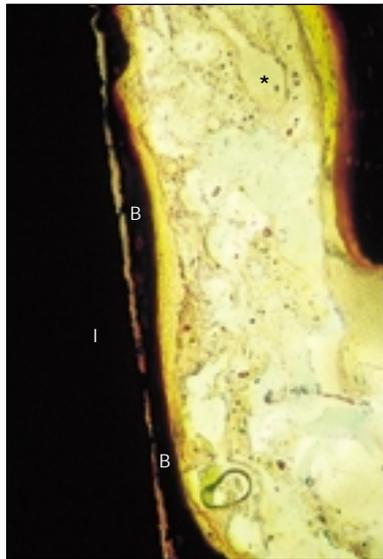
Fig 5a *(Left)* Histologic section of a 6-month blasted implant showing very low bone quality. A very thin layer of bone (*arrowheads*) is in contact with the implant surface, despite the very low bone quality and the almost complete absence of bony trabeculae around the implant. Note that the bone contact reaches the neck of the implant (*arrow*), but stops at the level of the cover screw, which is not blasted (original magnification ×12, toluidine blue staining).

Fig 5b *(Right)* Magnified view of the 6-month blasted implant. A very thin layer of bone (B) is present directly attached to the implant (I) surface. Few cells and some capillaries (*asterisk*) are present in the surrounding soft tissue. The layer of bone attached to the titanium is so thin that high-power magnification was needed to observe it clearly (original magnification ×200, von Kossa staining).
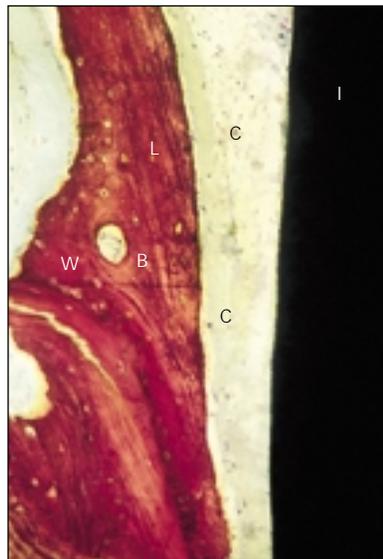
Fig 6a *(Left)* Histologic section of a 12-month smooth implant. The bone density is very low and the implant is not in contact with the surrounding bone trabeculae. Only at the apex of the threads was a limited area of bone contact visible. Nevertheless, a thin basket of new bone surrounded the entire implant (original magnification ×8, toluidine blue staining).

Fig 6b *(Right)* Soft tissue encapsulation of the 12-month smooth implant. A layer of loose marrow tissue (C) is interposed between the implant (I) and the shield of bone (B). Few fibroblasts and no inflammatory cells are visible in this space. The bone surface facing the implant shows a resting appearance without osteoid or bone resorption. The bone is composed mainly of areas of woven (W) bone surrounded by layers of lamellar (L) bone (original magnification ×200, Masson-Goldner staining).

trabeculae, mainly composed of woven bone with small spots of lamellar bone (Fig 6b). The scaffold of bone surrounding the implant seemed to be a little bit more mature than at 6 months. The peri-implant bone trabeculae were organized in a layer parallel to the implant surface but were mostly separated from the titanium. Loose marrow tissue without signs of inflammatory cells outlined the trabeculae around the implant.
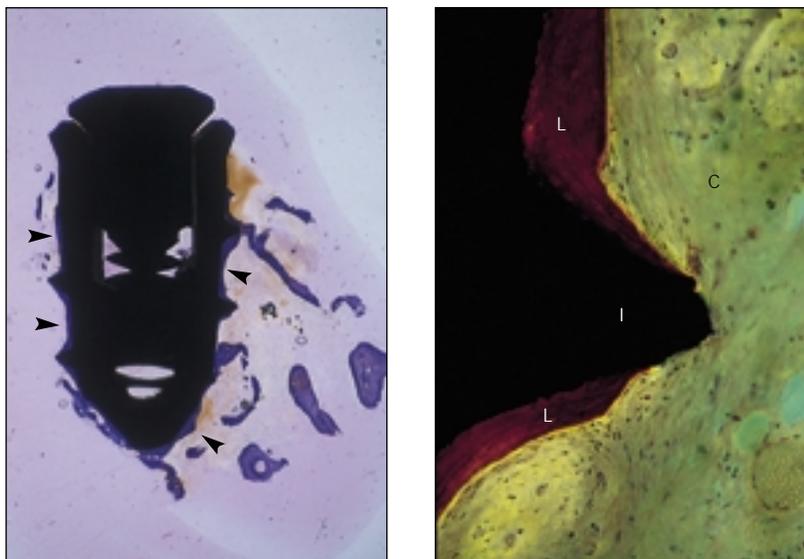
Rough Implants at 12 Months. The mean percentage of BIC was 76.7% (Fig 7a). Implants placed in low-density bone showed a high percentage of bone-to-implant contact. In this case, the implants were surrounded only by a thin layer of

mature lamellar bone composed of few bone lamellae (Fig 7b). Also in this case, the new bone was organized to form a basket or thin shell, similar to the alveolar cortex, that seemed to be isolated in the bone marrow soft tissue, since very few trabeculae were present around this basket. Layers of osteoid tissue were visible, as were areas of bone corticalization (Fig 7c). Primary osteons were present in the vicinity of the implant surface (Fig 7c). Loose connective tissue without signs of inflammatory cells outlined the trabeculae around the implant.

Statistical Results. Repeated-measures ANOVA showed that a significant difference ($P = .0129$; $F = 76.065$) existed between the mean percentage of

Fig 7a *(Left)* Twelve-month blasted implant. The bone density is very low, but the implant is surrounded by a thin layer of bony trabeculae perfectly adherent to the titanium surface (*arrowheads*) (original magnification ×8, toluidine blue staining).

Fig 7b *(Right)* Magnified photomicrograph of the previous section. The thread and the body of the implant (I) are covered by a very thin layer of bone (L) composed mainly of few bone lamellae. Outside the capsule of bone, connective tissue (C) lines the peri-implant bone (original magnification ×200, Masson-Goldner staining).

contact of the smooth titanium surface and the mean percentage of contact of the rough titanium surface. The BIC of the rough implants was significantly higher than the BIC of the smooth implants. Despite the very small number of the analyzed specimens, the power of the statistical analysis, ie, the probability of rejecting the null hypothesis, appeared to be high (97.7%).

Discussion

Results from the present investigation in human jaws showed that the rough titanium-blasted surface achieved a high rate of BIC, even in low-density bone. The percentage of BIC on the rough surfaces was high after 3 months of healing, improved at 6 months, and did not improve after the initial 6 months of healing; but it remained stable after 12 months of healing without functional loading. On the other hand, the BIC rate for the smooth implants was low at 3 months and remained low at 12 months. Because of the small number of specimens in each group, it was not possible to draw definite conclusions from the present investigation.

A number of experiments have been performed to increase the anchorage of bone to the implants by modifying the surface structure of the implants.[8–14,20] The process whereby some cells, such as macrophages, prefer rough surfaces was established by Rich and Harris[21] and described as "rugophilia." Other studies have been published elucidating the mechanisms behind the behavior of cells on rough surfaces.[22–29] Osteogenic cells either find the roughened surface better for attachment,
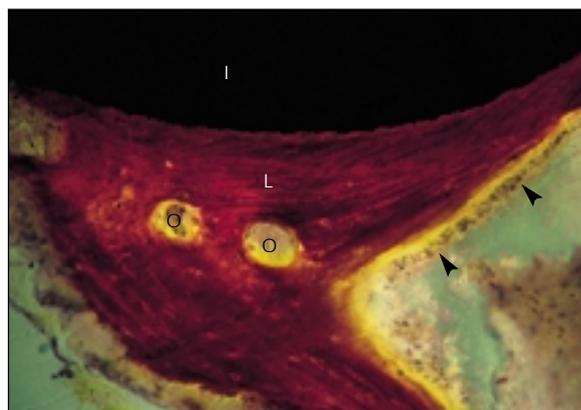

Fig 7c Magnified view of the previous implant, showing the lamellar bone (L) at the apex. Primary osteons (O) and a layer of osteoid tissue are present near the implant surface (I). A seam of osteoblasts is forming new bone (*arrowheads*) (original magnification ×200, Masson-Goldner staining).

or the environment provided by the surface somehow enhances osteogenesis. In vivo research has shown that a smooth titanium surface may favor fibrous tissue encapsulation, preventing direct bone-implant contact in the transcortical model.[14,30] A series of investigations showed that grit-blasted titanium implants achieve a higher level of removal torque and bone-implant contact than smooth machined titanium surfaces.[6,31–36]

Several commercial implant systems are machined with a turning process. The roughness of a turned surface, as measured by Wennerberg et al,[36] has a S(a) equal to 0.77 µm, compared to the roughness of a blasted surface, which exhibits a mean surface roughness ranging from 1.16 to 1.94

μm. Other studies have shown that a surface roughness ranging between 1 and 1.5 μm has a better bone fixation than standard machined cp titanium implants, which have a mean surface roughness of 0.6 to 0.7 μm.[31–34] Implant surfaces that were sandblasted and acid-etched achieved greater bone-implant contact than the rougher titanium plasma-sprayed (TPS) surfaces.[8] Implant surfaces that were sandblasted or acid-etched consistently performed better (ie, resisted push-out/torque forces) than implant surfaces that were either corundum-blasted,[37] sandblasted and acid-pickled, or plasma-spray–coated.[38] From these studies it is interesting to note that topographically rougher TPS surfaces, as well as corundum-blasted and sandblasted surfaces, appear to be inferior to surfaces that were treated with a combination of sandblasting and acid-etching. Several investigators have demonstrated that implant surface roughness enhances the biomechanical anchorage (osseointegration) of implants to bone, as determined by torque removal tests.[7,37–39]

The degree of surface roughness may not be the only aspect of surface topography that affects osseointegration. Intimacy of bone contact with the implant surface may also be important, as may the ionic charge, surface energy, surface tension, and other still undefined properties of the surface. Some of these characteristics could explain the ability of the cells to form bone directly on the titanium surface.

Results of the present work showed that smooth titanium barely achieved osseointegration in low-density bone. The low level of bone-to-implant contact seen around the smooth implants placed in low-density bone could be explained by considering that at the initial placement, the implant surface achieved only a limited amount of primary contact with the bony trabeculae. For this reason, this implant may be considered similar to an implant placed in an improperly prepared implant bed.

In a clinical study of osseointegration, the failures of direct bone bonding were attributed to inadequate primary contact of the implant with bone.[40] As stated by Brånemark et al,[41] one of the prerequisites for osseointegration is perfect adaptation between the implant and the prepared bone bed. However, the blasted surface, because of its roughness or other unidentified properties, is able to enhance cell attachment and to initiate bone formation directly over the implant surface. Present results showed that a rough titanium surface induced the formation of a layer of bone over the entire implant surface in areas where the bone would not otherwise be found. Moreover, this bone was completely attached to the titanium surface after 3 months of healing.

One disadvantage of rough surfaces could be their enhanced ability to attach bacteria of the plaque, thus enhancing the risk of infection of the peri-implant gingiva. Tillmanns et al[42] clinically evaluated, monitored, and compared the progression of ligature-induced peri-implantitis around different types of endosseous implants with 3 different surfaces in the canine mandible, namely smooth, blasted, and HA-coated. The results of Tillmanns's study revealed that all implants tested showed plaque accumulation and typical signs of peri-implant lesions. After 3 and 6 months of evaluation, all the implants showed the same level of bone loss. No statistically significant differences were noted among the 3 experimental implant types. The clinical parameters of the experimental implants were equally susceptible to ligature-induced peri-implantitis.

To date, no study, to the authors' knowledge, has compared the effect of different titanium surfaces in low-density bone, where the rough surfaces may have an effective advantage. Even though a high rate of bone-implant contact was found on rough surfaces, the biomechanical ability of this thin bony layer to withstand occlusal load is questionable because bone density did not improve with implant placement. Although the results of the mechanical tests published have shown a higher resistance of roughened implants, these tests were not performed in low-density bone.

In areas of low bone density, the long-term implant survival rate is lower than in areas with good bone quality.[15,16] Even though rough implants, as well as HA-coated implants, achieve a higher rate of bone-implant contact, caution should be used when placing any type of implant in soft bone. When analyzing the bone-implant interface, researchers should thus take into account not only the percentage of bone-to-implant contact, but also the density of the bone around the implant, since clinical studies have revealed that bone density is an important factor in long-term implant survival. The present analysis in humans confirms results from animal studies, but also suggests an important additional factor. Bone density does not change or improve by modifying the implant surface. The biomechanical effectiveness of rough surfaces in soft bone should be evaluated in an experimental model that duplicates the low-density bone found in critical areas of human jaws. It is questionable whether or not this bone is able to withstand a functional occlusal

load at the end of the healing period. The use of an active surface is certainly an advantage but does not modify the density of the bone, and one should expect a higher rate of failure with any type of implant placed in very low-density bone.

It has been shown that functional loading stimulates bone corticalization,[41,43,44] but this process involves a mechanism of bone modeling and remodeling that requires at least 1 year of adaptation to the occlusal load.[41,44] A heavy occlusal load on implants placed in very low-density bone may induce microfractures of the thin bony trabeculae that provide the osseointegration, thus leading, ultimately, to implant failure. In these cases, progressive bone loading could stimulate remodeling activity, inducing the corticalization of the bone and enhancing bone density[17] without overcoming bone biomechanical limits.

Conclusion

With all the limitations of the present investigation, it may be concluded that even though a rough implant surface may enhance the rate of osseointegration, it is not able to improve bone density. For this reason, more biomechanical studies should be performed to evaluate the biomechanical advantages of rough implants when placed in low-density bone, where they seem to have the highest benefits, and to clarify bone resistance in these settings to occlusal load.

Acknowledgments

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