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Review Article

Dental Implant Surface Roughness and Topography: A Review of the Literature

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The present review deals with the future perspectives regarding the topography of the implant surface which could be beneficial to implant surgery when implemented in practice. A systematic online review of the main database and a manual search of relevant articles from refereed journals were performed. Thirty articles about surface roughness were found, of which only 22 had information necessary to carry out statistical analysis. The categories were separated into normal bone tissue (15 articles) and augmented bone tissue (7 articles).

The category of normal bone tissue was subdivided into three groups: in vivo animal studies (8 articles), in vivo human studies (3 articles), and in vitro studies (4 articles). All articles that belonged to the augmented bone tissue category were in vivo studies carried out in humans. A total of 423 patients received 1350 implants, of which 725 implants had accurate data.

Since 1991, several average degrees of roughness have been suggested to enhance implant osseointegration as follows: 18-23μm in 1991 and 1995, 6.5μm in 1999, and ≤2.7μm in 2000-2007; however, these averages vary considerably, which might reflect the different types of measurements and techniques used by each author. As a result, there is currently no consensus in the degree of surface roughness that is optimum for bone cell attachment.

Key words: Dental implant, Surface roughness, Surface topography, Osseointegration

INTRODUCTION

Dental implant quality depends on the chemical, physical, mechanical, and topographic characteristics of the surface[1]. These different properties interact and determine the activity of the attached cells that are close against the dental implant surface. Dental implants have been designed to provide textures and shapes that may enhance cellular activity and direct bone apposition (osseointegration)[2]. Osteogenesis at the implant surface is influenced by several mechanisms. A series of coordinated events, including cell proliferation, transformation of osteoblasts and bone tissue formation might be affected by different surface topographies[3]. There is a clinical impression that the amount of bone-to-implant contact (BIC) is an important determinant in the long-term success of dental implants. Consequently, maximizing the BIC and osseointegration has become a goal of treatment, which is enhanced by implant surface roughness[4].

The present literature review aimed to elucidate implant surface topography and to obtain a future perspective regarding the topography of the implant surface which could be beneficial to implant surgery when implemented in practice.

MATERIALS

A systematic online review of the main database and a manual search of relevant articles from refereed journals were performed. Thirty articles about surface roughness were reviewed, of which only 22 had the necessary information to carry out statistical analysis. The categories were classified into normal bone tissue and augmented bone tissue. Of the 22 articles reviewed, 15 belonged to the category of normal bone tissue and 7 to the category of augmented bone tissue.

1. Normal Bone Tissue

The influence of surface roughness on implant osseointegration in normal bone tissue has been studied by various researchers for several years, including several *in vivo* and *in vitro* studies (Tables 1, 2 and 3). Buser et al.[5] evaluated the influence of different surface characteristics on the bone integration of titanium implants and the highest extent of BIC was observed in sandblasted acid-etched surfaces with mean values of 50-60% and with an average roughness of 18-23μm. Wong et al.[6] found an excellent correlation between the average roughness of the implant surface and pushout failure load. In 1999, it was suggested that the interface shear strength of titanium implants is significantly influenced by their surface characteristics[7]. Also, it has been suggested that only a very specific surface topography with a R_a value (arithmetic average of absolute values of all profile points)[1,3] between 1 and 1.5μm provides an optimal surface for bone integration[8].

Studies have shown that cells, including blood monocytes/macrophages, are amongst the first cells to come into contact with the implant surface after its insertion. Monocytes/macrophages have the potential to secrete a range of cytokines and growth factors, which have the capability of initiating both tissue destruction as well as healing or reparative responses. Soskolne et al.[4] examined monocyte adherence to titanium discs with four different degrees of surface roughness and plastic surfaces. The results indicated that the number of monocytes attached to blasted titanium surfaces was significantly greater than to ma-

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Table 1 *In vitro* studies in normal bone tissue

AUTHOR	YEAR	SAMPLE	TYPE OF SAMPLE	OBSERVATION PERIOD	SIGNIFICANT DIFFERENCES	ROUGHNESS (μm)
Martin	1995	48	Ti disks - cell cultures	24–48 hr	YES	Z_m= 18.28
Schwartz	1999	24	Ti disks - cell cultures	24–72 hr	YES	R_a= 6-7
Soskolne	2002	24	Ti disks - cell cultures	7 days	YES	S_a= 1.86
Sammons	2005	7	Pocket culture	2 and 4 weeks	YES	R_a= 2.75
Marinucci	2006	90	Ti disks - cell cultures	24–48 hr	YES	R_a= 3

Z_m＝average profile height（Martin）[26]
R_a＝mean height of roughness（Schwartz[27], Sammons[11], Marinucci[9]）
S_a＝average height deviation（Soskolne[4], Ivanoff[24]）

Table 2 *In vivo* studies in animals

AUTHOR	YEAR	SAMPLE	TYPE OF SAMPLE	PLACED IMPLANTS	HEALING PERIOD	SIGNIFICANT DIFFERENCES	ROUGHNESS (μm)
Buser	1991	6	miniature pigs	72	3–6 weeks	YES	R_a= 18-23
Wong	1995	12	miniature pigs	192	12 weeks	YES	R_a= 6.4
Buser	1999	9	miniature pigs	54	4,8,12 weeks	YES	R_a= 3.1
Huang	2004	8	monkeys	24	16 weeks	YES	NA
Gahlert	2007	13	miniature pigs	78	4,8,12 weeks	YES	S_a= 1.15

NA＝no available data
R_a＝average roughness（Buser[5,7], Wong[6]）
S_a＝mean deviation of the surface（Gahlert[28]）

Table 3 *In vivo* studies in humans

AUTHOR	YEAR	SAMPLE	TYPE OF SAMPLE	PLACED IMPLANTS	HEALING PERIOD	SIGNIFICANT DIFFERENCES	ROUGHNESS (μm)
Ivanoff	2001	27	humans	54	6 and 3 months	YES	S_{cx}= 11.96, S_a= 1.43
Ivanoff	2003	20	humans	40	6 and 3 months	YES	S_{cx}= 11.57, S_a= 1.17
Trisi	2003	11	humans	11	2 months	YES	NA
Grassi	2006	14	humans	28	2 months	YES	R_a= 0.73, R_z= 5.67
Shibli	2007	13	humans	26	2 months	YES	R_a= 0.87, R_z= 5.14

NA＝no available data
S_{cx}＝average wavelength crossing the mean plane（Ivanoff[24]）
S_a＝average height deviation（Ivanoff[24]）
R_a＝arithmetic average of absolute values of all profile points（Grassi[1], Shibli[3]）
R_z＝average value of the absolute heights of the five highest peaks and the depths of the five deepest valleys（Grassi[1], Shibli[3]）

chined titanium surfaces, demonstrating that the characteristics of surfaces with which human blood monocytes interact affect the ability of macrophages to adhere to those surfaces as well as their ability to secrete various inflammatory mediators[9].

On the other hand, Lekholm and Zarb[10] have described four qualities of the jawbone: Type I is composed of homogenous compact bone; Type II exhibits a thick layer of compact bone surrounding a core of dense trabecular bone; Type III exhibits a thin layer of cortical bone surrounding dense trabecular bone of favorable strength; and Type IV exhibits a thin layer of cortical bone surrounding a core of low density trabecular bone. It has been shown that the survival rate of oral implants placed into Type IV bone is markedly decreased compared to other bone qualities. Type IV bone, which is common in the posterior maxilla, presents a considerable challenge to successful implant treatment in this location. In this regard, Huang et al.[2] evaluated local bone formation and osseointegration at titanium porous oxide (TPO)-modified implants in Type IV bone. Bone density reflected the nature of Type IV bone in the posterior maxilla showing limited bone mass with large marrow spaces. The difference in density between bone inside and immediately outside the threads was statistically significant and may be a reflection of remodeling processes in the immediate osteotomy site. The results suggested that the TPO surface possesses considerable osteoconductive potential in promoting a high level of implant osseointegration in Type IV bone of the posterior maxilla. Mean peri-implant bone density ranged from 32% within the threads of the implant to 37% immediately outside the threaded area. Unfortunately, there is no available data about the average roughness of the implants used in this study.

Sammons et al.[11] compared the interaction between rat calvarial bone osteoblasts and titanium dental implants with different microstructured surfaces, which include plasma-sprayed, grit-blasted and/or acid-etched, smooth-machined and anodized titanium. They concluded that a rough surface of the porous microstructure may enhance the rate of cell spreading, although differentiation and calcification occurred on the surface of both rough and smooth microstructures. Furthermore, they found that cell spreading, morphology and alignment were influenced by surface microstructures in both suspensions and pocket cultures. In the latter, osteoblasts migrated from bone fragments onto all surfaces, and cells proliferated to form multicellular layers overlying the microstructures with extracellular matrix both between layers and on implant surfaces.

With regard to bone remodeling around the implant rough surface, a systematic review of this topic has been described by Shalabi et al.[12] who searched the literature from 1953 to 2003 with the following criteria for inclusion: 1) abstracts of animal studies investigating implant surface roughness and bone healing; 2) observations of three-month bone healing, surface topography measurements, and biomechanical tests; and 3) provision of data on surface roughness, BIC, and biomechanical test values. The literature search revealed 5966 abstracts; 470, 23, and 14 articles included the first, second and third selection steps, respectively. Only 14 studies remained for data analysis, all of which investigated the relation between surface roughness and BIC. They concluded that statistical analysis on the available data provided supportive evidence of a positive relationship between BIC and surface roughness. At present, the consensus is that the implant-bone response is influenced by the topographic surface of the implant.

Roughness not only provides better mechanical stability between bone tissue and the implant surface, but is also a configuration that retains blood clots completely and stimulates the bone-healing process[3]. In vitro, cultured osteoblasts from human mandibular bone and three titanium surfaces were studied: machined titanium, micro-sandblasted titanium (average surface roughness of 0.5μm) and macro-sandblasted titanium (average surface roughness of 3μm). Cell morphology was estimated by scanning electron microscope (SEM) analysis and cell proliferation by measuring the amount of 3H-thymidine incorporation into DNA. mRNA expression of osteonectin, osteopontin, bone sialoprotein (BSP) and *Runx2*, which are markers of osteoblastic phenotype, were determined by reverse trasncriptase polymerase chain reaction (RT-PCR) analysis. Compared with a machined titanium surface, micro- and macro-sandblasted surface increased the secretion of TGFβ_2, (growth factor involved in osteoblast proliferation and differentiation), expression of *Runx2* Type II, mRNA (which regulates the expression of osteoblast genes that are key players in mineralized phenotype development), BSP, and osteopontin, but not osteonectin. Osteonectin is mostly expressed late in osteogenesis, and BSP and osteopontin are highly expressed in the early stage of bone maturation, suggesting that osteoblast differentiation on rough surfaces occurs in the early stage. Moreover, the results indicated that the macro-sandblasted (3μm) titanium surface facilitated the increased expression of BSPs and growth factors more than the micro-sandblasted (0.5μm) surface, which favor osteoblast differentiation[9].

Several investigators have demonstrated higher removal torque values and the percentage of bone-to-implant contact (BIC%) for rough dental implant surfaces compared to machined surfaces. Furthermore, histological studies suggest that the sandblasted acid-etched (SLA) surface provides a better human bone tissue response than machined implants under unloaded conditions after a healing period of 2 months. An important feature was that bone density in a 500-μm-wide zone lateral to the implant surface around the SLA implants did not differ between the maxilla and mandible, suggesting that this surface topography may enhance bone quality close to dental implants placed in soft bone[1].

Also, the influence of surface morphology on the osseointegration of zirconia has been studied. Studies suggest that zirconia implants with a sandblasted surface (rough, ZrO_2r) with a roughness value of $S_a = 0.56$μm can achieve higher stability in bone than zirconia implants with a machined surface (ZrO_2m) with a roughness value of $S_a = 0.13$μm. Roughening the surfaces of zirconia implants enhances bone apposition and has a beneficial effect on interfacial shear strength; however, the mean removal torque values were higher for titanium SLA implants ($S_a = 1.15$μm) in comparison with the two zirconia implants[13]. The state of the bone-implant interface at modified zirconia implants was evaluated after removal torque (RTQ) testing and showed a strong bone tissue response to surface-modified zirconia implants after 6 weeks of healing in rabbit bone. The modified zirconia implants showed resistance to torque forces similar to that of oxidized implants and a four to fivefold increase compared with machined zirconia implants[14,15].

2. Augmented Bone Tissue

Roughened implants have been associated with higher survival rates than machined implants in grafted sinuses[13,16]. Only a few controlled longitudinal studies have assessed the impact of rough surfaces versus machined surfaces on long-term implant success in conjunction with the sinus augmentation technique (Table 4). The studies have demonstrated that placement of roughened implants in augmented maxillary sinus has a higher BIC[12,16-19].

Studies have shown that the higher the percentage of BIC, the faster and firmer the bone integration, but the development of BIC is dependent on the implant surface, bone density, and heal-

Table 4 *In vivo* studies in human augmented bone tissue

AUTHOR	YEAR	SAMPLE	IMPLANTS *TOTAL*		*PLACED*	*SUCCESSFUL*	*FAILED*	ROUGHNESS (µm)	STAGE OF IMPLANT PLACEMENT	HEALING PERIOD	SIGNIFICANT DIFFERENCES
Kan	2002	60 humans	228	Rough	163	156	7	NA	Simultaneous and delayed	41 months	YES
				Other	65	49	16	NA	4 months after sinus lift	20-67 months	
Pinholt	2003	25 humans	158	Rough	80	78	2	NA	After 6 months of graft healing	5 years	YES
				Other	78	63	15	NA	8 months after sinus lift	6 months after loading	
Hallman	2005	22 humans	156	Rough	72	68	4	NA	Simultaneous and delayed	1 and 5 years	YES
				Other	84	73	11	NA	After sinus lift	1 year	
Todisco	2006	3 humans	8	Rough	4	3	1	S_a= 3.3	Simultaneous and delayed	3 years	YES
				Other	4	4	0	S_a= 3.6 - 9.9	Simultaneous and delayed	41 months	
Marchetti	2007	30 humans	140	Rough	62	60	2	NA	4 months after sinus lift	20-67 months	NO
				Other	78	73	5	NA	After 6 months of graft healing	5 years	
Stavropoulos	2007	26 humans	35	TR	17	13	4	NA	8 months after sinus lift	6 months after loading	*NO
				PR	18	16	2	NA	Simultaneous and delayed	1 and 5 years	
Yamamichi	2008	257 humans	625	Rough	NA	NA	NA	NA	After sinus lift	1 year	YES
				Other	NA	NA	NA	NA	Simultaneous and delayed	3 years	

NA＝no available data
S_a＝average surface roughness (Todisco[20])
TR＝totally rough
PR＝partially rough
*No significant differences were found between partially rough implants compared with totally rough implants

ing time. Clinical studies have assessed how BIC is influenced by different implant surfaces in augmented bone. In 2006, Todisco and Trisi examined the BIC and osteoconductive capacity (OC) of the surface of 6 different implant surfaces after early loading in humans, which included a microtextured surface with an average surface roughness (S_a) value of 3.30±0.22µm; titanium plasma sprayed (TPS) with a reported S_a value from 3.60 ±0.30µm to 9.90±1.06µm; an oxidized surface with a reported S_a value of 3.14±0.11µm; sandblasted and acid-etched surface with a reported S_a value of 3.32±0.22µm; acid-etched surface with a reported S_a value of 1.82±0.08µm; and hydroxyapatite treatment with an average surface roughness (average peak height) value of 4.9µm. Two implants with different surfaces were placed side-by-side in the grafted (n＝5) and nongrafted (n＝1) sinuses of 3 volunteers, restorations were delivered 60 days later and after 6 months of full occlusal loading the implants were retrieved in block sections. Highest BIC and OC values were exhibited by the microtextured surface, and lowest values were exhibited by the TPS surface. All other surfaces showed excellent BIC (＞50%) but varied widely in surface osteoconductivity (range＝17.55%-28.62%)[20].

In addition, implants with a rough surface in their whole length (FR) have been compared with implants with a 2 mm coronal machined portion (PR) when used in association with the sinus-lift procedure, which yielded no significant differences in terms of the clinical and radiographical characteristics or survival between both groups[21].

RESULTS

The category of normal bone tissue was subdivided into three groups: *in vivo* studies carried out in animals, *in vivo* studies carried out in humans, and *in vitro* studies. According to the sample size, 420 implants were analyzed in *in vivo* studies in animals, 159 implants were analyzed in *in vivo* studies in humans, and 193 samples were analyzed *in vitro* (Fig. 1).

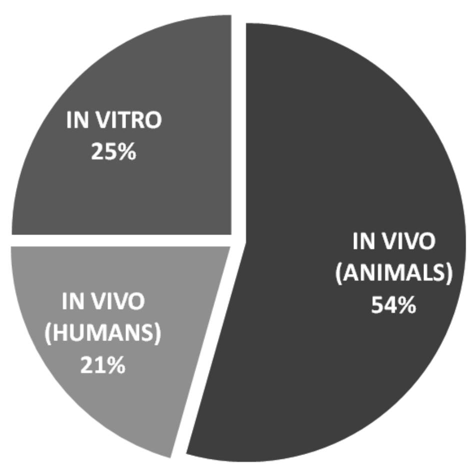

Fig. 1. Samples (in%) divided into *in vivo* studies in animals, *in vivo* studies in humans and *in vitro* studies, which were carried out in normal bone tissue studies by different authors from 1991 to 2007, according with the data obtained from the articles.

The average roughness in normal bone tissue varied widely according to the author and to the unit of measurement used in each study; in general, it was observed that the range has decreased since 1991, when Buser performed one of the first studies on this subject (Fig. 2).

In respect to the second category (augmented bone tissue), all were in vivo studies carried out in humans. A total of 423 patients participated in the studies, underwent surgical procedures for sinus lift, and received 1350 implants (corresponding to 7 different researches), of which 725 implants had accurate data (corresponding to 6 different researches). The seven studies were carried out from 2002 to 2008 and most authors agreed that significant differences exist between rough and machined implants in augmented bone tissue for implant osseointegration (Fig. 3). Some of these studies evaluated differences between implants placed at same time as the sinus lift procedure and implants that were placed in stage 2 (after sinus lift).[7, 19–22]. The average healing period was 40 months, ranging from 6 to 67 months, and during this time the implants remained functional. Only one author specified the average roughness of implants used in his study; thus, we were not able to analyze the average roughness for augmented bone tissue.

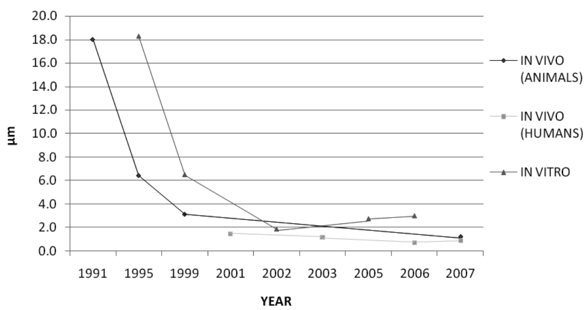

Fig. 2. Average roughness suggested by different authors from 1991 to 2007 in different studies in normal bone tissue, including *in vivo* in animals, *in vivo* in humans and *in vitro* studies.

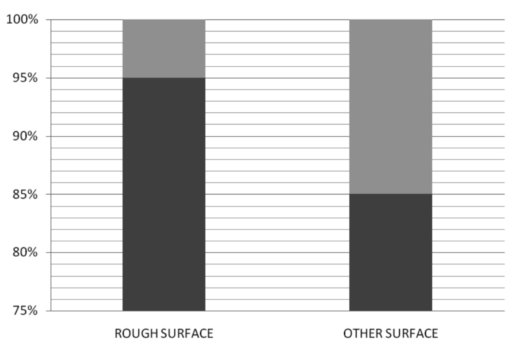

Fig. 3. Percentages of failure and success of rough surface implants and implants with other surfaces, which were used in augmented bone tissue *in vivo* studies in humans from 2002 to 2007.

DISCUSSION

Some studies that have evaluated osseointegration on machined surfaces inserted into human jaws showed that the percentage of BIC ranged between 9% and 13% after a 5-6-month healing period[1, 3, 23, 24]; however, these values were lower than the results presented by Grassi et al.[1], which yielded a mean of 42.83% in SLA-surface implants after a 2-month healing period; and Shibli et al.[3] suggested that the oxidized surface with an R_a value of 0.87±0.14μm had a higher BIC rate (39.04%) than machined surfaces (21.71%) with an R_a value of 0.32±0.03μm under unloaded conditions with a healing period of two months[1, 3, 7]. Consequently, it has been suggested that rough surface implants can be loaded at an earlier time than machined surfaces[3, 25].

Since 1991, several average degrees of roughness have been suggested to enhance implant osseointegration (Fig. 4)[1, 3–5, 8, 9, 11, 24, 26–28]. Wennerberg and Albrektsson[8] suggested that only a very specific surface topography with an R_a value between 1 and 1.5 μm provides an optimal surface for bone integration. In addition, Marinucci et al.[9] demonstrated that an average surface roughness of 3μm is more suitable than 0.5μm for osteoblast differentiation in vitro. Todisco and Trisi[20] compared six different implant surfaces after early loading in humans, in which a microtextured surface with a reported S_a value of 3.30±0.22μm achieved the highest BIC and OC values (94.08% and 34.31%, respectively) in grafted bone; however, these averages varied considerably, which might reflect the different types of measurements and techniques used by each author. As there is currently no consensus on the degree of surface roughness that is optimum for bone cell attachment; further research is needed in this field.

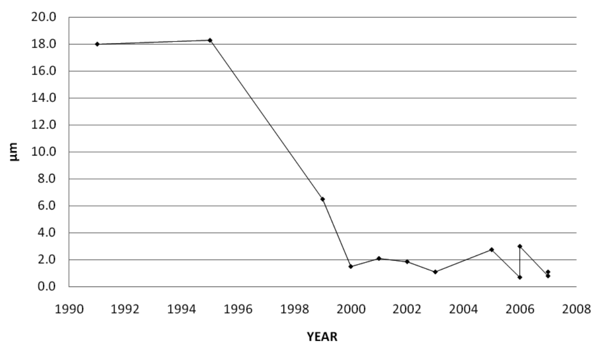

Fig. 4. Average roughness suggested by different authors in *in vivo* and *in vitro* studies in normal bone tissue from 1991 to 2007. A marked decrease of the degree can be seen.

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インプラント体の表面粗さ及び形状：論文的総説

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本総説では，臨床的にインプラント手術において埋入されたインプラント体に対して有利に働くと考えられるインプラント体表面の粗さに関し，どの様な結論が現在得られているのか，また，将来に向けての展望はどうかを追求することを目的としている．

インターネットにて Pub Med 検索において散見し得た文献をもとにインプラント体の表面粗さに関する論文で，本総説の主旨である統計的分析に対応しうる22論文を用いた．

また，通常の骨組織内での検索は15論文，骨造成を行った部位での論文は７であった．さらに，通常の骨組織での論文は，動物実験８，臨床論文３で残りの４論文は in vitro であった．骨造成を行った部位での論文はすべて臨床報告であった．これらすべての論文での患者数は423人，インプラント体数は1350で，その内725本に関してはすべての検索データーが得られた．

1991年からインプラント体の表面性状が骨接合に重要であることが報告され，その粗さは，1991年：18～23μm，1999年：6.5μm，その後2000年から2007年までに2.7μm からそれ以下に変化している．このように年代により表面粗さにかなりの違いがあり，それが論文の著者が用いた測定方法と手技の違いと考えられている．そのため，今日においてもその粗さの詳細な程度には一定の結論がなく，さらなる検索が必要と考える．

キーワード：歯科インプラント治療，表面粗さ，表面形状，骨接合

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