Implant Surface Roughness and Bone Healing: a Systematic Review

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ABSTRACT

A systematic review was performed on studies investigating the effects of implant surface roughness on bone response and implant fixation. We searched the literature using MEDLINE from 1953 to 2003. Inclusion criteria were: (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; (3) provision of data on surface roughness, bone-to-implant contact, and biomechanical test values. The literature search revealed 5966 abstracts. There were 470, 23, and 14 articles included in the first, second, and third selection steps, respectively. Almost all papers showed an enhanced bone-to-implant contact with increasing surface roughness. Six comparisons were significantly positive for the relationship of bone-to-implant contact and surface roughness. Also, a significant relation was found between push-out strength and surface roughness. Unfortunately, the eventually selected studies were too heterogeneous for inference of data. Nevertheless, the statistical analysis on the available data provided supportive evidence for a positive relationship between bone-to-implant contact and surface roughness.

KEY WORDS: implant, surface roughness, bone healing, systematic review.

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INTRODUCTION

A major parameter for the clinical success of endosseous implant therapy is the formation of a direct contact between implant and surrounding bone. The implant-bone response is thought to be influenced by implant surface topography. As a consequence, over the last 20 years, a large number of implant systems with different surface topographies have been introduced. The literature on this topic is extensive and continuously increasing (Table 1). However, the claims made in numerous publications about the effect of implant surface roughness on bone response are not as straightforward as suggested. For example, there is a lack of agreement in findings from *in vivo* animal experiments, where the clinical performance of micro-roughened titanium implants is described on the basis of mechanical failure tests and histological considerations. Some of the studies indicated a tendency for an increase of bone-to-implant contact with increasing roughness of the implant surface (Buser *et al.*, 1991), while other studies either could not confirm this observation (London *et al.*, 2002; Novaes *et al.*, 2002) or could not find any effect at all (Carlsson *et al.*, 1988; Gotfredsen *et al.*, 1992; Vercaigne *et al.*, 1998a, 2000a). Also, it has been suggested that only a very specific surface topography with a Ra value between 1 and 1.5 μm provides an optimal surface for bone integration (Wennerberg and Albrektsson, 2000).

Various explanations can be given to rationalize the above-mentioned discrepancies in the biologic effects of substrate surface roughness, like small but very relevant differences in surface topography, different animal models, and different surgical techniques. Because the utilization of oral implants is increasing, it is essential that clinicians have unequivocal evidence to support claims of alleged benefits of specific morphological characteristics of dental implants (Jokstad *et al.*, 2003). A thorough meta-analysis of the available literature on this topic would be the most appropriate strategy for achieving this goal. Although several meta-analyses have been done so far, none of them addressed animal studies (Cochran, 1999; Lee *et al.*, 2000; Stach and Kohles, 2003; Albrektsson and Wennerberg, 2004a,b). Therefore, the aim of the current study was a systematic analysis of the data regarding implant surface roughness, to determine its relationship, if any, with bone healing and biomechanical tests.

The hypothesis tested in this study was that: (1) higher implant surface roughness leads to a higher bone-to-implant contact (BIC); and (2) higher implant surface roughness results in a higher implant torque resistance.

MATERIALS & METHODS

The major phases in this review were: literature search and selection, inclusion/exclusion of papers, extraction of data, and statistical analysis. The literature was searched in an electronic database (MEDLINE) for dental articles written in English between 1953 and 2003. The Key Word used was "dental implant". Two independent readers carried out a selection of the references found on the basis of abstracts as published in MEDLINE. If no abstract was available in MEDLINE, the original article was used. The emphasis of this first step in the review procedure was on inclusion of references according to the criteria shown in Table 2. Authors' names in the papers included in this step were re-checked in MEDLINE and cross-matched with the original list of references to add references that met the inclusion criteria. Disagreements were resolved by discussion.

The second step of the selection procedure consisted of the reading of the sections "Aim", "Materials and Methods", and "Results" in the articles. The same two readers independently selected the blinded papers to be included in this step on the basis of an additional list of selection criteria (Table 2, step 2).

In step three, papers were included that provided surface roughness values, bone-to-implant contact (BIC), and biomechanical test results of the respective test groups in each study. Finally, the data of these properties were extracted.

For steps one and two, the Cohen's Kappa coefficients were used as a measure of agreement between the readers. The principal author undertook step three.

For analysis of data, slopes of regression lines (and 95% Confidence Intervals) were used to express the relationship with roughness. If only two values for roughness were available, the Student's t test was applied, and the slope (and 95% CI) could easily be calculated. Slopes were considered to be significant if the 95% CI did not include the value of zero.

RESULTS

The MEDLINE literature search resulted in a list of 5966 hits. After the first selection step, 470 articles remained; 5496 were excluded. The inter-reader agreement (κ [kappa] = 0.51 ± 0.03) reflects moderate agreement. To check the validity of this procedure, we subjected a random selection of 100 papers out of the 5378 double-negatives (both readers excluded them) to the criteria of step two. None of the 100 papers was positive.

The second step revealed 23 papers fulfilling all criteria of the selection procedure. The inter-reader agreement for this step was κ = 1. In total, 447 papers were excluded from further analysis for one or more reasons: 324 papers did not describe surface top-

Table 1. Inclusion and Exclusion Criteria for the Selection of Papers in the Three Selection Steps

Step 1	Include	- Animals' studies, *in vivo*
		- Studies dealing with implant surface roughness and bone healing
		- Also, implant surface chemistry and bone healing
		- Control groups from other studies, even if the test group(s) does not fit with other criteria
	Exclude	- Descriptive studies (*i.e.*, preliminary, case reports, pilot studies, reviews and meta-analyses).
Step 2	Include	- Healing period after implant placed, 3 mos or more
		- Surface roughness parameters measured
		- Type of surface mentioned (*i.e.*, machined, etched...)
		- Biomechanical test used
		- Bone-to-implant contact measured in separate groups and expressed in percentage
		- Location of the implantation should be mentioned in the studies
		- Loading or unloading clearly written in the papers
	Exclude	- Studies not meeting all criteria above for inclusion
Step 3	Include	- Three-month healing period after implant placed
		- Surface roughness parameters measured (Ra or Sa)[1]
		- Results of surface examined
		- Biomechanical test used (RTV[2] or equivalent value)
		- Bone-to-implant contact measured in all groups
	Exclude	- Studies not meeting all criteria for inclusion

[1] Ra/Sa = Description of height variation.
[2] RTV = Removal torque values.

Table 2. Papers Chosen after Second Selection (in Alphabetical Order, n = 23); Papers Remaining after Third Selection are in Italics (n = 16) [References not in the print version of the paper are listed in the APPENDIX.]

Reference	Reason(s) for Exclusion
Buser *et al.*, 1999	No bone BIC* % mentioned, and healing period not mentioned in the graph
Dhert et al., 1991	
Dhert et al., 1993	
Giaveresi *et al.*, 2002	No BIC % (only inside screw threads and 3 best threads)
Gotfredsen *et al.*, 1992	Removal torque test without limit and inadequate BIC data
Gotfredsen et al., 1995	
Hallgren et al., 2001a	
Hallgren et al., 2001b	
Hallgren et al., 2003	
Han et al., 1998	
Hulshoff et al., 1997	
Johansson and Albrektsson, 1991	No Ra (only RZ) and no BIC (only 3 best threads)
Johansson *et al.*, 1998	No three-month healing data
Muller-Mai *et al.*, 1989	No Ra, only Rt used for surface roughness
Rupprecht et al., 2002	
Vercaigne et al., 1998b	
Vercaigne et al., 2000a	
Vercaigne et al., 2000b	
Wennerberg et al., 1995	
Wennerberg et al., 1996a	
Wennerberg et al., 1996b	
Wennerberg *et al.*, 1997	No three-month healing data
Wong et al., 1995	

* BIC = bone-to-implant contact; Ra = description of height variation; Rz = average value of absolute heights of 5 highest peaks and 5 deepest valleys; and Rt = maximum peak-to-valley height of profile in assessment length (area).

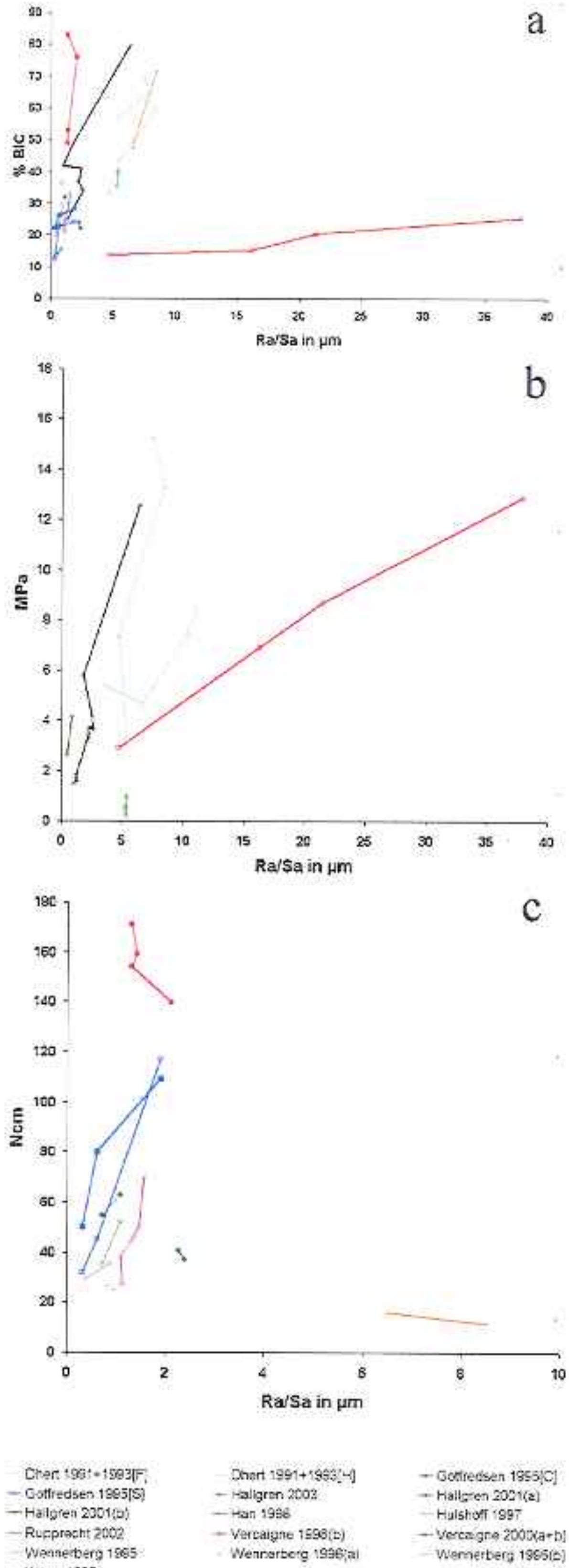

Figure 1. Scatter plots of surface roughness-BIC (a), -push out test (b), and -torque test (c) comparisons. Lines connect data within studies. [C] = Cylindrical implants; [S] = Screw implants; [F] = implant site in femur; [H] = implant site in humerus.

ography, no biomechanical tests were performed in 307 papers, 122 papers did not mention bone-to-implant contact, and 74 papers described studies that did not have the required minimum bone-healing period of 3 mos.

In step three, 7 more papers were excluded for reasons mentioned in Table 1. Of the 16 remaining papers, two sets of papers dealt with the same study (Dhert *et al.*, 1991, 1993; Vercaigne *et al.*, 2000a,b). Consequently, 14 studies (16 papers) remained for inference of data. Three studies divided the implant groups either by implant sites (Dhert *et al.*, 1991, 1993; Hallgren *et al.*, 2003) or presented data based on two different implant designs (Gotfredsen *et al.*, 1995).

As a result, data from 16 groups of implants were available for statistical analysis. All studies investigated the relation between surface roughness and bone-to-implant contact. Although most papers described multiple surface roughness descriptors (*i.e.*, Ra/Sa, Rq/Sq, Rsk/Ssk, etc.), Ra/Sa was the only descriptor common to all papers and therefore was used in the present study as a measure of surface roughness. Ra is the two-dimensional (2D) counterpart of the three-dimensional (3D) descriptor Sa. Both Ra and Sa reflect the arithmetic mean of the absolute values of the surface point departures from the mean plane within the sampling area (Wennerberg, 1996).

Fifteen out of 16 comparisons showed a positive relation between surface roughness and bone-to-implant contact: the higher the surface roughness, the higher the percentage bone-to-implant contact (Figs. 1a, 2). Six comparisons had a statistical significance, since their slopes were significantly different from zero (Fig. 2). The remaining comparisons revealed 9 positive slopes that did not differ significantly from zero, and the negative slope was also not statistically different from zero (Fig. 2). Four studies (Wennerberg *et al.*, 1996a; Vercaigne *et al.*, 2000a,b; Hallgren *et al.*, 2001a; Rupprecht *et al.*, 2002) were not of value, because of extremely large standard errors (SE > 50% BIC/µm), and for this reason they were not included in Fig. 2.

With regard to biomechanical testing, 9 papers used a removal torque test to assess the correlation between biomechanical properties and surface roughness and expressed the results in Ncm. Five papers described push-out tests and expressed the strengths in MPa. Because the results of the two biomechanical tests are not compatible, two subsets were constructed for further analysis (Figs. 1b, 1c). In all studies that presented data on push-out tests, the push-out strength increased with higher surface roughness values (Fig. 1b). All slopes were positive, of which 3 were significantly different from zero (Fig. 2). In contrast, the relation between surface roughness and torque test values is less clear (Fig. 1c). The slopes in 5 studies revealed a positive relationship (the higher the surface roughness, the higher the torque test value), of which 3 were significantly different from zero (Fig. 2). In contrast, 4 studies produced negative slopes that were not significantly different from zero, and 2 of these studies (Wennerberg *et al.*, 1996a; Hallgren *et al.*, 2001a) did not provide reliable information because of the large standard errors (SE > 100 Nm/µm) and were therefore not included in Fig. 2.

The wide variation in slope values indicates substantial heterogeneity (*i.e.*, lack of homogeneity) among the studies. Due to the lack of homogeneity, it is not permissible for the data to be combined for inference. Consequently, the data from the separate studies cannot be combined, and overall slopes cannot be presented.

DISCUSSION

In this study, we attempted, *via* a systematic review, to combine data from animal studies to determine the influence of surface roughness of implants on bone response and implant fixation after 12 wks of implantation. Although implant surface quality can also be a parameter to facilitate the earlier loading of oral implants, the rate of healing was out of the scope of the current review. Unfortunately, the studies that were eventually selected were too heterogeneous for inference of the data. This heterogeneity may have been caused by differences in measurement methods as well as study designs. For example, surface roughness was characterized by different techniques (*i.e.*, 2D/3D). Moreover, various devices, all of which can introduce unknown variability, were used to determine roughness (Macdonald *et al.*, 2004). Another variable is the surgical technique used, which is considered an important factor in successful osteogenesis (Sandborn *et al.*, 1988; Albrektsson, 2001), but which was not fully described in all papers. So far, surgical technique has been given less attention in evidence-based implantology compared with implant surface characteristics.

Furthermore, heterogeneity of data can be caused by variation in the *in vivo* animal model as well as implant location. For example, local bone conditions (quantity and quality) vary significantly between various animal species. This will have a very serious effect on the results of implant bone response studies. It is noteworthy that, of the studies (14) meeting all selection criteria, 9 used rabbits, 9 used goats, and 1 used mini-pigs. Despite the observed heterogeneity, this structured analysis summarizes the best current available information on this topic. We consider the present blinded review as systematic, reproducible, and one that covered the relevant current literature published in the English language.

The selection procedure started with a broad search strategy. This was to avoid the risk of exclusion of any paper that might meet our criteria. The use of only one data source (MEDLINE) carries a chance of selection bias. To overcome this problem, we re-searched by inserting the author's name into MEDLINE. This resulted in the further identification of 103 papers. Inter-reader agreement did not exceed the level of moderate. We consider the result (κ [kappa] = 0.51 ± 0.03) as acceptable and attributable to the step 1 process of reading only the abstracts.

In step 2, where the inter-reader agreement was high (κ [kappa] = 1), the entire paper was accessed. In most of the included studies, the implant surface topography was characterized by more than one surface roughness parameter (*i.e.*, Ra/Sa, Rq/Sq, Rsk/Ssk, etc.). However, Ra/Sa was the only parameter that was used in all 14 studies. By definition, the Ra- or Sa-value is a good general description of the height variation, but is insensitive to wavelength and occasional high peaks and low valleys (Wennerberg, 1996). Morra *et al.* (2003) analyzed the surface composition of 34 different titanium dental implants. They reported that surface topography and surface chemistry are intrinsically intertwined, and they concluded that surface topography is not the only variable controlling the biological response. Yet, despite this shortcoming, we used Ra/Sa as the surface roughness descriptive value to relate bone response with the biomechanical variable.

All selected studies dealt with surface roughness and bone-to-

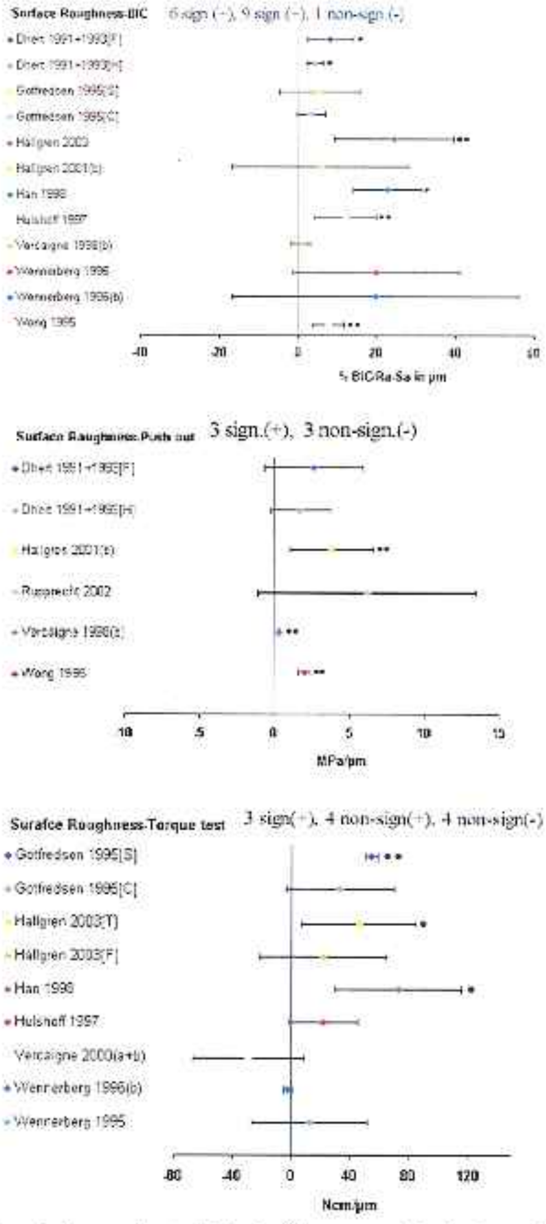

Figure 2. Mean values and 95% Confidence Interval for the slopes of the surface roughness-BIC/torque/push-out test comparisons of the studies evaluated. Asterisks indicate slope-values statistically significant from zero (* = $p < 0.01$; ** = $p < 0.001$).

implant contact. Since about half of the studies showed a significantly increased bone-to-implant contact with a higher surface roughness, the trend for the relationship of surface roughness with bone-to-implant contact is positive. In contrast, it has been claimed that only a very narrow range of surface roughness values (*i.e.*, Ra/Sa value from 1-1.5 μm) positively correlates with increased bone-to-implant contact (Wennerberg and Albrektsson, 2000). However, this was not confirmed by the systematic review, because a positive effect on the bone response was seen from Ra/Sa of ~ 0.5 μm up to ~ 8.5 μm. Although it is difficult to provide a definite explanation for this discrepancy, we know that surface roughness measurements on oral implants are very complex. The different methods used in the various studies can result in different data, which hampers a correct comparison of the results obtained. Therefore, a standardized method for measuring and describing surface roughness must be developed.

Regarding the interpretation of biomechanical tests, push-out testing has been shown in the literature to be uninterpretable for implant materials with different Young's moduli (Dhert *et al.*, 1992). The authors in this study focused on the influence of test conditions on the push-out results. They demonstrated that comparisons of the bone-implant strength would only give rise to more confusion in interpreting and comparing push-out results. Further, the push-out test results showed a stronger relation (Thompson *et al.*, 1999) between surface roughness and bone bonding strength than did the torque test results. This relation was seen in the same range of surface roughness values as for the bone-to-implant contact. This implies that push-out testing indeed reflects the bone-to-implant response. Consequently, removal torque testing might not be the best test for the evaluation of implant fixation or the amount of bone around the implant. This suggestion is enhanced by the knowledge that the underlying biomechanical phenomena in torque testing are very complex, *e.g.*, the shear stress condition at the interface. However, the shape or configuration of the implant system is always an additional issue in the selection of a biomechanical test. Therefore, push-out testing requires the use of cylindrical implants. However, most oral implants have a screw-shaped design. Therefore, when there is no other choice than the use of torque testing, bone-to-implant contact measurements should always be performed, and a thorough analysis conducted of the fracture interface after the torque testing, to determine whether the torque failure is indeed caused by failure of the bone-implant interface.

In conclusion, the number of publications that met all inclusion criteria was found to be very limited. Nevertheless, the statistical analysis on the available data provided supportive evidence for a positive relationship between bone-to-implant contact and surface roughness.

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APPENDIX

Details of Table 2 References Not in the Print Version of the Paper

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