Oral Implant Surfaces: Part 1—Review Focusing on Topographic and Chemical Properties of Different Surfaces and In Vivo Responses to them

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Purpose: This article reviews the topographic and chemical properties of different oral implant surfaces and in vivo responses to them. ***Materials and Methods:*** The article considers detailed mechanical, topographic, and physical characteristics of implant surfaces. Anchorage mechanisms such as biomechanical and biochemical bonding are examined. Osteoattraction and doped surfaces are discussed. ***Results:*** Surface quality of an oral implant may be subdivided into mechanical, topographic, and physicochemical properties. Topographic properties are evaluated at the micrometer level of resolution. Moderately rough surfaces (S_a between 1.0 and 2.0 μm) show stronger bone responses than smoother or rougher surfaces. The majority of currently marketed implants are moderately rough. Oral implants permit bone ingrowth into minor surface irregularities—biomechanical bonding or osseointegration. Additional biochemical bonding seems possible with certain surfaces. Osteoattraction is a commercial term without precise biologic correspondence. Surfaces doped with biochemical agents such as bone growth factors have been developed. ***Conclusion:*** Moderately roughened surfaces seem to have some clinical advantages over smoother or rougher surfaces, but the differences are small and often not statistically significant. Bioactive implants may offer some promise. *Int J Prosthodont 2004;17:536–543.*

The surface quality will determine tissue reactions to an oral implant. Surface quality may be divided into three categories: *(1)* mechanical properties, *(2)* topographic properties, and *(3)* physicochemical properties. This article treats those aspects of surface quality separately, although it is known that changing one aspect may lead to changes in the others. For instance, Sul et al[1] observe that anodizing an implant leads to changes in surface roughness as well as alterations of oxide crystallinity and embedding of ions in the surface. Morra et al[2] found that machined implants display a lower concentration of titanium on the surface and a higher concentration of carbon than sandblasted, acid-etched, or plasma-sprayed surfaces.

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Aspects of Surface Quality

Mechanical Properties

Mechanical properties of implant surfaces relate to potential stresses in the surface that may result in increased corrosion rate and wear relating to the hardness of the material. Decreased fatigue strength of implant surfaces has been described with porous coatings.[3] Wear is related to the strength of the material, but also to surface roughness. One technique to minimize wear is ion implantation.[4] Mechanical properties of oral implant systems have been insufficiently investigated.

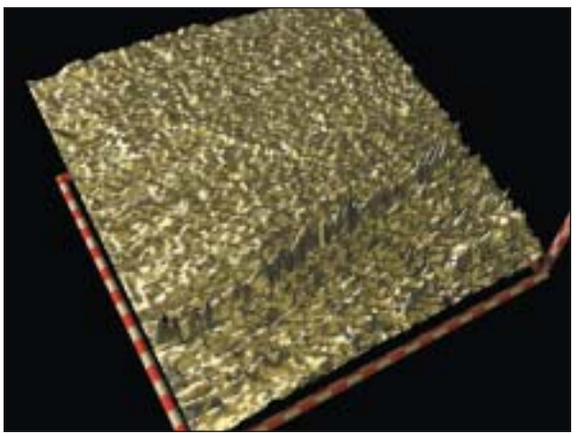
Topographic Properties

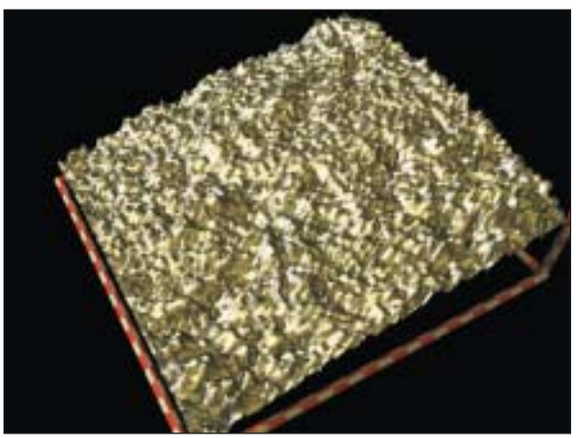
Topographic properties of implant surfaces are important. The surface topography relates to the degree of roughness of the surface and the orientation of the surface irregularities. Surface roughness has been the main focus on oral implants for more than a decade. The original Brånemark implant (Nobel Biocare) was a turned screw of minimal surface roughness, ie, between 0.5 and 1.0 μm in S_a value (Fig 1). For a long time, this implant

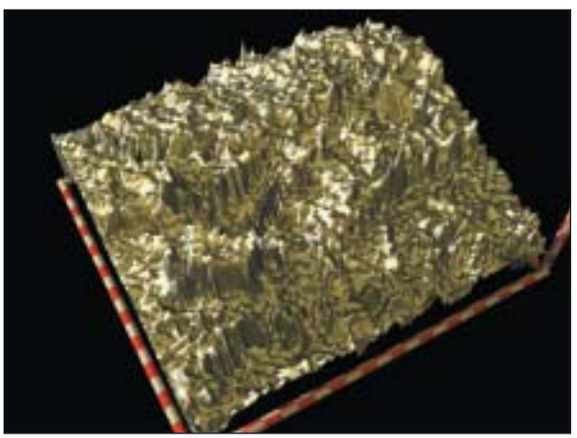
Fig 1 *(right)* Turned surface is not at all smooth. This remains the best documented of all implant surfaces (each red and white section of the bars = 10 μm).

Fig 2 *(below)* Moderately roughened surface, with roughness in the range of 1 to 2 μm S_a, displays stronger bone response than smoother or rougher surfaces (each red and white section of the bars = 10 μm).

Fig 3 *(below right)* Plasma-sprayed implant is roughest and has demonstrated a weaker bone response than moderately roughened implants (each red and white section of the bars = 10 μm).







was the gold standard, based mainly on a good clinical record.[5,6] However, by the mid-1990s, the bulk of experimental evidence pointed in the same direction: Implants of a roughness of about 1.5 μm (S_a) show stronger bone response (Fig 2) than turned (smoother) and plasma-sprayed (rougher) implants[7] (Fig 3 and Table 1).

However, more interfacial bone (stronger bone response) in experimental animals need not imply greater clinical success (Fig 4). Furthermore, potential drawbacks of roughening the implant surface include greater problems with peri-implantitis and a greater risk of ionic leakage. The risk of increased peri-implantitis with rougher surfaces had some clinical support from independent investigation,[8,9] albeit related to very rough (> 2.0 μm S_a) plasma-sprayed implants. On the other hand, clinical documentation of moderately roughened surfaces, such as the Tioblast screw (Astra Tech), shows no increased incidence of peri-implantitis and, in fact, maintained bone height levels at 5 years of follow-up.[10–13]

The other potential drawback of roughened surfaces, increased risk of ionic leakage, was based on the physical knowledge that greater surface roughness gives greater tissue-implant contact and hence ionic leakage. However, risk levels were not identified, and it seems probable that the increase in ionic leakage with slight roughening of an oral implant is negligible.[14] In fact, the majority of commercially available oral implants are currently moderately roughened, which may be their major benefit. However, some moderately roughened implants will be discussed under the chemical heading, as they combine a moderate surface roughness with a chemical surface modification described as unique by the manufacturer.

In basic science, there is currently considerable interest in nanostructures. With respect to surface roughness, it is unknown whether nanometer-sized irregularities will affect the bone response. Changes in implant roughness at the micrometer level of resolution may simultaneously result in changes at the nanometer level. It is therefore diffcult to reliably exclude the possibility that nanometer-sized surface irregularities may influence the bone response to an implant. To the knowledge of the present authors, the proof is limited to in vitro data from various nanosurfaces. One study showed that

Table 1 Characteristics of Different Implant Surfaces

Roughness (S_a)	Clinical usage	Potential benefits	Potential risks
0.0–0.4 µm ("smooth")	Abutments, certain "machined" experimental implants	None, if used for bone anchorage	Too smooth for proper osseointegration
0.5–1.0 µm ("minimally rough")	Turned implants, Osseotite, most implants used before 1995	Longest clinical documentation of all implants	Less forgiving for untrained surgeons?
1.0–2.0 µm ("moderately rough")	Tioblast, SLA, TiUnite, Frialit-2, most implants of today	Stronger bone response, tendency to better clinical results than turned implants	Many, but not all, designs have only short clinical follow-up
> 2.0 µm ("rough")	Plasma-sprayed titanium, hydroxyapatite-coated implants	Positive 5-year documentation reported	Increased incidence of peri-implantitis reported in two studies

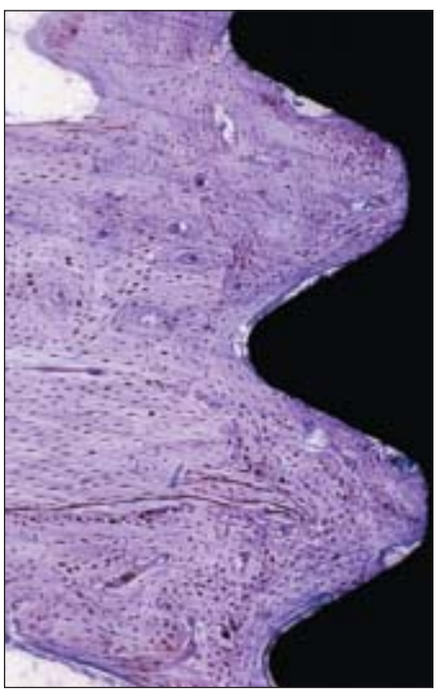


Fig 4a Implant with a high proportion of bone-to-implant contact. A greater amount of interfacial bone need not imply improved clinical function (hematoxylin-eosin stain; distance between two thread tips = 600 µm).

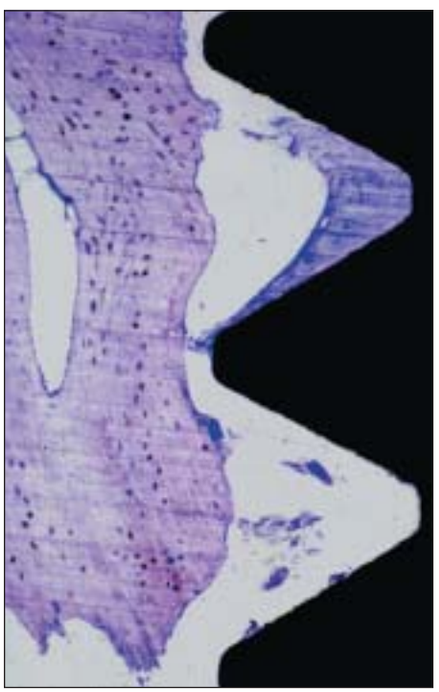


Fig 4b Implant with a low proportion of bone-to-implant contact. Controlled clinical testing is necessary to reveal whether a defined surface alteration is beneficial (hematoxylin-eosin stain; distance between two thread tips = 600 µm).

macrophage cell lines react to microgrooves at the nanometer level,[15] whereas another investigation saw no significant effects in cell adhesion to different nanotopographies.[16] There is a need for more in vitro, and of course in vivo, data to decide on the potential importance of nanostructures. Nevertheless, for clinical purposes, the relevant way to describe an oral implant surface is by referring to its micrometer-sized irregularities.[17]

Physical Characteristics

Physical characteristics refer to factors such as surface energy and charge. According to Hench and Ethridge,[18] surface energy is a measure of the extent to which bonds are unsatisfied at the surface. A surface with a high energy has a high affinity for adsorption. In other words, an oral implant with high surface energy may, at least theoretically, show stronger ossseointegration than implants with a low surface energy. Glow discharge treatment results in high surface energy as well as implant sterilization.[19] Baier[20] claims that high surface energy influences proteins to form an advantageous primary coat on the implant.

A practical way to measure surface energy is contact angle measurements,[18] a method also used to determine whether a surface is hydrophobic or hydrophilic, ie, the wettability of a surface.[21] However, the hypothesis that implants with a high surface energy result in

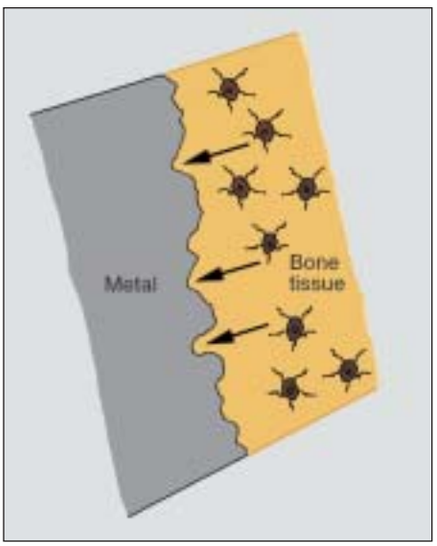


Fig 5 Biomechanical bonding means bone ingrowth into micrometer-sized surface irregularities. This is the same as "osseointegration" in the orginal meaning of the term.

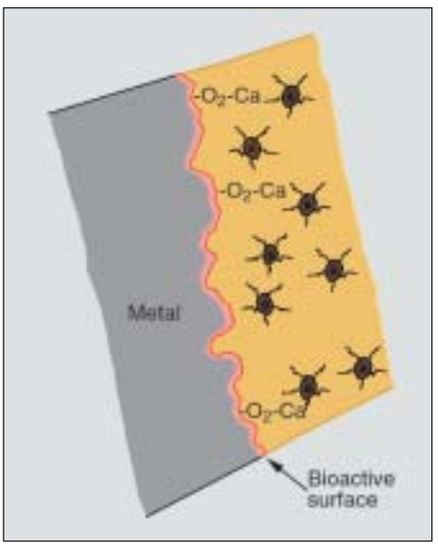


Fig 6 Biochemical bonding may occur with certain bioactive implant surfaces.

stronger osseointegration has not been verified by in vivo studies.[22,23] It is possible that an initially high surface energy will be immediately changed when the implant is moved from the glow discharge container through the air toward the patient.

Chemical properties seem to be the main focus for the future in oral implantology. The chemical composition of the surface will provoke different reactions from the surrounding media. The chemical composition of the surface often differs from that of the bulk material because of preparation methods and impurities trapped in the surface.[24,25] The surface layer may contain reactive bonds, and a continuous exchange of water and various ions influences the binding of proteins to the surface and the subsequent cell reactions.[26,27]

Anchorage Mechanisms of Oral Implants

Many oral implant companies have recently launched new products with claimed unique, and sometimes bioactive, surfaces; the focus has shifted from surface roughness to surface chemistry. To properly explain the claims for new surfaces, it is essential to summarize current opinions on bone anchorage, with emphasis on the potentials for biochemical bonding.

Biomechanical Bonding

A turned titanium implant, such as the original Brånemark screw, is anchored to bone through ingrowth into small irregularities of the implant surface—biomechanical bonding (Fig 5). Thus, osseointegration depends on biomechanical bonding. Blasted, acid-etched, and other moderately roughened implants show a stronger bone response than turned devices. However, they are also dependent on biomechanical bonding. This type of anchorage may follow the placement of relatively inert titanium (and some other metals and ceramics) implants of at least minimal surface roughness. The potentially negative aspect with biomechanical bonding is that it is time consuming. There are weeks of delay before bone has started to grow into surface irregularities of the implant. Before bone interlocking, the implant is dependent on its macrodesign (eg, threaded screw) for retention. Scientific papers published into the 1980s generally indicated that bone needs a minimum of 50- to 100-μm cavities or pores for proper ingrowth. Today, we have sufficient knowledge that irregularities at least down to 1 μm may be invaded by bone, although complete Haversian systems need a larger space.[17]

Electropolished titanium surfaces of roughness similar to abutments (ie, about 0.2 μm S_a) do not become properly osseointegrated.[28–30] The strongest biomechanical bonds are seen to surfaces of a roughness of about 1.5 μm, whereas rougher, plasma-sprayed implants show weaker bone ingrowth.[7]

Biochemical Bonding

According to Osborn and Newesly,[31] titanium (and similar metals and certain ceramics) are bioinert, in contrast to bioactive materials, such as various calcium phosphates and bioglasses, to mention but a few examples.

The best definition of the biochemical bonding mode of implant anchorage (Fig 6) is: "Bioactivity is the characteristic of an implant material which allows it to form a bond with living tissues."[32] Potential chemical bonding between implant and host tissues was first suggested by Hench et al[33] and referred then to a certain glass-ceramic composition and its reaction to the host tissues. Although of substantial interest to experimentalists, bioglass ceramics never became commonly used for oral implants, presumably for biomechanical reasons. Instead, calcium phosphate ceramics (eg, hydroxyapatite [HA]) were launched as potentially bioactive surface coatings for titanium implants (for review, see Hulbert[34]).

It is important to understand that bioactive implants may, in addition to chemical bonding, show biomechanical anchorage; hence, a given implant may be anchored through both mechanisms. The theoretic advantage with bioactive implants is that the biochemical attachment is rapid, ie, it functions at a time when proper biomechanical bonding has not yet been developed.

Although commercially pure (cp) titanium in its native form is only capable of biomechanical bonding, chemical modifications of cp titanium may lead to a bioactive material. Surface modifications have consisted of NaOH and heat treatment,[35,36] ion implantation with calcium,[37] or anodizing with electrolytes containing phosphorus, sulphur, calcium, or magnesium ions.[38–40] Such modified titanium surfaces are interesting, but, to the knowledge of the present authors, have not been clinically introduced.

To the authors' knowledge, two types of implant surfaces are potentially bioactive and presently marketed as oral implants: One such surface is represented by calcium phosphate–coated implants marketed by several companies; the other is the fluoridated Osseospeed implant (Astra Tech). Because oxidized implants may also be bioactive,[40] whether there is any evidence of the oxidized TiUnite surface (Nobel Biocare) being bioactive has been particularly investigated.[38] That experimental study failed to indicate any bioactivity of an oxidized surface with embedded phosphorus ions, one characteristic of the TiUnite implant.

Calcium phosphate–coated implants. As summarized by Legeros,[41] calcium phosphate biomaterials have similarities to bone mineral: They may form bone apatite like mineral or carbonate HA on their surfaces (bioactivity); they are able to promote cellular function, leading to formation of a strong bone–calcium phosphate interface; and they are osteoconductive and may bind bone morphogenetic proteins (BMP) to become osteoinductive. Jarcho et al[42] were the first to present indications of direct bone bonding to HA. It is today generally believed that calcium phosphates may have bioactive capacity,[43,44] although this may not apply to all types of calcium phosphates.

The mechanisms of the potential bioactive capacity of calcium phosphate are not known, but it has been hypothesized that an interfacial bone mineral–like carbonated apatite layer is formed by ion dissolution from the bioceramic material.[45] Other potential mechanisms include a direct effect from high calcium and phosphate concentrations and high affinity for growth factors (for review, see Jansen et al[46]).

Fluoridated implants. Fluoride treatment of titanium was introduced by Ellingsen.[47] He performed push-out tests of fluoridated and control titanium implants placed in rabbits for up to 8 weeks. The fluoridated implants sustained greater push-out forces than controls, and substantial bone adhesion was observed to fluoridated implants, whereas controls always failed in the interface between bone and foreign material. The latter finding is an indication of bioactivity of the fluoridated implants. Johansson et al[48] report significantly greater bone contact to fluoride-modified titanium implants at 1 and 3 months of follow-up, despite the fact that the fluoridated implants were minimally rough and the blasted controls moderately roughened. Ellingsen[49] describes another rabbit experiment with turned titanium implants compared to blasted, intermediately rough implants with and without fluoridating of the surface. Not surprisingly, removal torque tests verified significantly stronger removal torque for the blasted implants. However, the fluoridated, blasted implants showed a significantly higher removal torque than the blasted test implant, again indicative of a bioactive reaction of fluoridated titanium implants.

Evidence for a Bioactive Implant Surface

It has so far been impossible to prove the existence of bioactivity. However, several indications for biochemical bonding have been presented in the scientific literature. Each one links to a plausible explanation for biochemical bonding:

- Tissue coalescence. This theory is based on high-power transelectron micrography (TEM) demonstrating that the tissue "floats into" the surface of the biomaterial. The distances are so small that biochemical bonding seems probable.[50] However, Davies[51] points out the similar interfacial morphology between high-power images of potentially bioactive HA and cp titanium, not regarded as bioactive.
- When an implant is removed, eg, with a push-out test, the rupture occurs not at the interface, but in

the bone tissue.[47] This may be important, as ionic bonds act over a short distance (nanometers), whereas recorded movements of osseointegrated implants occur at the micrometer level of resolution. Ionic bonds would not be possible if these movements occurred in the interface between bone and material; hence, they must occur in the bone tissue, at least for bonded implants. However, finding bone tissue on implant surfaces after push-out tests may not serve as conclusive evidence of bioactivity, as, at least in theory, biomechanical interlocking may result in fractured-off portions of bone tissue trapped in three-dimensionally oriented irregularities of the implant.

- Chemical evidence, such as the formation of carbonate apatite layers on calcium phosphate ceramic implants.[41,52] The chemical evidence reported in the literature is quite interesting, but more knowledge is needed before the chemical evidence can be regarded as conclusive.
- A finding of significantly stronger bone attachment to a surface-treated implant compared to an identical, but not surface treated, control, where no known factors (eg, potential differences in surface roughness because of surface treatment) can explain the stronger bone attachment.[40] Naturally, future research may identify other factors (not necessarily associated with bioactivity) that can explain the observed differences.

One problem, of course, is the fact that several techniques for surface modification of oral implants simultaneously lead to a rougher surface. Hence, when the bone response to the new, potentially bioactive, surface is evaluated, the positive effects on the bone response may be explained by an increase in surface roughness.

Oral Implant Surfaces Suggested To Be "Osteoattractive"

In some cases, manufacturers claim that they have a particularly osteoattractive surface but do not use the term "bioactive." One reason for the reluctance to claim bioactivity (apart from a lack of direct evidence) is that the 510(k) designation "substantial equivalence" may be denied, and then prospective, randomized controlled studies must be performed before any sales of the device in the US. This article classes implants not known to meet any of the indications for bioactivity under this heading.

From a scientific point of view, it is difficult to define particular osteoattractiveness and differentiate such surfaces from moderately roughened surfaces that are quite attractive for bone formation. Major oral implant companies lacking proper 5-year clinical documentation of their new surfaces have been particularly prone to suggest that these have some special attractiveness for bone tissue. Osseotite acid-etched implants (3i) have been claimed to give rise to a particular fibrin retention that allows osteogenic cells to migrate to the implant surface, enabling what Davies[53] calls "de novo bone formation." This type of fibrin retention is indeed seen on many different implant surface topographies.[54] Therefore, it is not surprising that other surfaces, such as the novel Cellplus implant (Dentsply/Friadent), are claimed to demonstrate similar fibrin retentive capacity.[55]

Other surfaces claimed to be unique with respect to the bone response include the SLA surface (Straumann) and TiUnite. The SLA surface is blasted and acid etched; as such, it is not really unique, since the DPS implant surface (Dentsply/Friadent) is also blasted and acid etched. Both surfaces are moderately roughened. Whether one is more osteoattractive than the other must be considered unproven. TiUnite implants are anodized, ie, the oxide thickness has been considerably increased to more than 1,000 nm (the actual oxide thickness varies along the implant length). When titanium surfaces are placed in a galvanic cell with phosphoric acid as an electrolyte (the precise contents of the electrolyte are not known to the public, but the authors have found it to contain phosphorus ions), over time surface breakdown will occur. Naturally, it is more appealing to refer to the surface becoming "porous" (there are, in fact, more indentations than true pores) and claim that these pores have some unique characteristics. There is little scientific evidence of this.

All implant types described as "osteoattractive" may, in fact, share the characteristic of being moderately roughened and thereby more attractive for new bone formation than smoother turned or rougher plasma-sprayed implants.

Doped Surfaces

Under this heading are implant surfaces that have been doped with a potentially bone-stimulating agent, such as BMP or other bone growth factors (Fig 7). Although long discussed, the present authors are unaware of whether doped surfaces really have been tried and documented as oral implants. Presumably, they are still hypothetic solutions for the future. It is suggested to proceed with caution, not the least since it is doubtful if external administration of growth factors has any effect in the case of an ordinarily placed oral implant.[56] This observation does not contradict evidence of positive effects of BMPs in cases with lack of bone support, eg, resorbed alveolar ridges.[57]

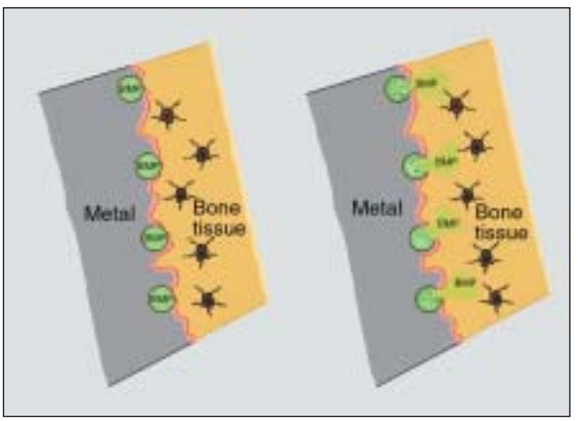


Fig 7 Doped surfaces that contain various types of bone growth factors or other bone-stimulating agents may prove advantageous in compromised bone beds. However, at present clinical documentation of the efficacy of such surfaces is lacking; *BMP* = bone morphogenetic protein.

Conclusion

Moderately roughened surfaces may have some clinical advantages compared to smoother turned and rougher plasma-sprayed surfaces. Bioactive implants may present some promise for the future. However, the authors concur with Jokstad et al[58] that, "A substantial number of claims made by different manufacturers on alleged superiority due to design characteristics are not based on sound and long-term clinical scientific research." In fact, it seems probable that improvements in surgical technique will present good prospects for improving clinical results.[59,60] Some surgeons simply have fewer good clinical results than others working with the same implant. This is an important observation to avoid being misled by the commercial side of oral implantology, where allegedly osteoattractive surface modifications are claimed as the only way to improve clinical success.

References

1. Sul YT, Johansson CB, Petronis S, et al. Characteristics of the surface oxides on turned and electrochemically oxidized pure titanium implants up to dielectric breakdown: The oxide thickness, micropore configuration, surface roughness, crystal structure and chemical composition. Biomaterials 2002;23:491–501.
2. Morra M, Asinelli C, Bruzzone G, et al. Surface chemistry effects of topographic modification of titanium dental implant surfaces. 1. Surface analysis. Int J Oral Maxillofac Implants 2003;18:40–45.
3. Kohn DH, Ducheyne P. A parametric study of the factors affecting the fatigue strength of porous-coated Ti6Al4V implant alloy. J Biomed Mater Res 1990;24:1483–1501.
4. McKellop HA, Röstlund T, Ebramzadeh E, Sarmiento A. Wear of titanium 6-4 alloy in laboratory tests and in retrieved human joint replacements. In: Brown SA, Lemons JE (eds). Medical Applications of Titanium and Its Alloys: The Material and Biological Issues. Philadelphia: American Society for Testing and Materials, 1995.
5. Albrektsson T, Dahl E, Enbom L, et al. Osseointegrated oral implants. A Swedish multicenter study of 8139 consecutively inserted Nobelpharma implants. J Periodontol 1988;59:287–296.
6. Eckert SE, Parein A, Myshin HL, Padilla JL. Validation of dental implant systems through a review of literature supplied by system manufacturers. J Prosthet Dent 1997;77:271–279.
7. Wennerberg A. On Surface Roughness and Implant Incorporation [thesis]. Göteborg, Sweden: Department of Biomaterials, University of Goteborg, 1996:1–196.
8. Becker W, Becker B, Ricci A, et al. A prospective, multicenter trial comparing one- and two-stage titanium screw shaped fixtures with one-stage plasma-sprayed solid-screw fixtures. Clin Implant Dent Relat Res 2000;2:159–165.
9. Åstrand P, Anzén B, Karlsson U, Saltholm S, Svärdström P, Hellem S. Nonsubmerged implants in the treatment of the edentulous upper jaw: A prospective clinical and radiographic study of ITI implants—Results after 1 year. Clin Implant Dent Relat Res 2000;2:166–174.
10. Norton M. Marginal bone levels at single tooth implants with a conical fixture design. The influence of surface macro- and microstructure. Clin Oral Implants Res 1998;9:91–99.
11. Palmer R, Palmer P, Smith B. A 5-year prospective study of Astra single tooth implants. Clin Oral Implants Res 2000;11:179–182.
12. Gotfredsen K, Karlsson U. A prospective 5-year study of fixed partial prostheses supported by implants with a machined and TiO_2 blasted surface. J Prosthodont 2001;10:2–7.
13. Steveling H, Roos J, Rasmusson L. Maxillary implants loaded at 3 months after insertion: Results with Astra Tech implants after up to 5 years. Clin Implant Dent Relat Res 2001;3:120–124.
14. Wennerberg A, Ide-Ektessabi A, Shino H, et al. Titanium release from implants prepared with different surface roughness. An in vitro and ex vivo study. Clin Oral Implants Res (forthcoming).
15. Wojciak-Stothard B, Curtis A, Monaghan W, Macdonald K, Wilkinson C. Guidance and activation of murine macrophages by nanometric scale topography. Exp Cell Res 1998;223:426–435.
16. Rice JM, Hunt JA, Gallagher JA, Hanarp P, Sutherland AS, Gold J. Quantitative assessment of the response of primary derived human osteoblasts and macrophages to a range of nanotopography surfaces in a single culture model in vitro. Biomaterials 2003;24:4799–4818.
17. Wennerberg A, Albrektsson T. Suggested guidelines for the topographic evaluation of implant surfaces. Int J Oral Maxillofac Implants 2000;15:331–344.
18. Hench LL, Ethridge EC. Biomaterials. An Interfacial Approach. New York: Academic, 1982.
19. Baier RE. Conditioning surfaces to suit the biomedical environment: Recent progress. J Biomed Eng 1982;104:257–271.
20. Baier RE. Surface preparation. J Oral Implantol 1986;12:387–395.
21. Baier RE, Meyer A. Surface analysis. In: von Recum AF (ed). Handbook of Biomaterials Evaluation. Scientific, Technical and Clinical Testing of Implant Materials. New York: MacMillan, 1986:97–108.
22. Carlsson L, Albrektsson T, Berman C. Bone response to plasma-cleaned titanium implants. Int J Oral Maxillofac Implants 1989;4:199–204.
23. Wennerberg A, Bolind P, Albrektsson T. Glow discharge pretreated implants combined with temporary bone ischaemia. Swed Dent J 1991;15:95–101.
24. Kasemo B, Lausmaa J. The biomaterial-tissue interface and its analogues in surface science and technology. In: Davies JE (ed). The Bone-Biomaterials Interface. Toronto: University of Toronto Press, 1991:19–31.

25. Smith DC, Pilliar RM, Chernecky R. Dental implant materials. 2. Preparative procedures and surface spectroscopic studies. J Biomed Mater Res 1992;25:1069–1084.
26. Williams RL, Higgins SJ, Hamnett A, Williams DF. The characteristics of protein adsorption onto metallic biomaterials. In: Heimke G, Soltész U, Lee AJC (eds). Clinical Implant Materials. Advances in Biomatenals. Vol 9. Amsterdam: Elsevier Science, 1990:327–332.
27. Smith DC. Dental implants: Materials and design considerations. Int J Prosthodont 1993;6:106–117.
28. Carlsson L, Röstlund T, Albrektsson B, Albrektsson T. Removal torques for polished and rough titanium implants. Int J Oral Maxillofac Implants 1988;3:21–24.
29. Buser D, Schenk RK, Steinemann S, Fiorellini JP, Fox CH, Stich H. Influence of surface characteristics on bone integration of titanium implants. A histomorphometric study in miniature pigs. J Biomed Mater Res 1991;25:889–902.
30. Carlsson L, Regner L, Johansson C, Gottlander M, Herberts P. Bone response to hydroxyapatite coated and commercially pure titanium implants in the human arthritic knee. J Orthop Res 1994;12:274–285.
31. Osborn JF, Newesly H. Dynamic aspects of the implant-bone-interface. In: Heimke G (ed). Dental Implants, Materials and Systems. Munich: Hanser, 1980:111–123.
32. Hench LL. Bioactive glasses and glass ceramics: A perspective. In: Yamamuro T, Hench L, Wilson J (eds). Handbook of Bioactive Ceramics. Vol I. Boca Raton, FL: CRC, 1990:7–23.
33. Hench LL, Greenlee TK Jr, Allen WC, Piotrowski G. An Investigation of Bonding Mechanisms at the Interface of a Prosthetic Material, Report No. 1, Contract No. DADA 17-70-C-0001. Washington, DC: US Army Research and Development Command, Clearinghouse for Federal Scientific and Technical Information, 1970.
34. Hulbert SC. Bioactive ceramic-bone interface. In: Yamamuro T, Hench L, Wilson J (eds). Handbook of Bioactive Ceramics. Vol I. Boca Raton, FL: CRC, 1990:3–6.
35. Kim HM, Miyaji F, Kokubo T, Nakamura T. Preparation of bioactive Ti and its alloy via simple chemical surface treatment. J Biomed Mater Res 1996;32:409–417.
36. Skripitz R, Aspenberg P. Tensile bond between bone and titanium—A reappraisal of osseointegration. Acta Orthop Scand 1998;69:2–6.
37. Hanawa T. Titanium and its oxide film: A substrate for formation of apatite. In: Davies JE (ed). The Bone-Biomaterials Interface. Toronto: University of Toronto Press, 1991:49–61.
38. Sul YT, Johansson CB, Kang Y, Jeon D-G, Albrektsson T. Bone reactions to oxidized titanium implants with electrochemical anion sulphuric acid and phosphoric acid incorporation. Clin Implant Dent Relat Res 2002;4:78–87.
39. Sul YT, Johansson CB, Röser K, Albrektsson T. Qualitative and quantitative observations of bone tissue reactions to anodised implants. Biomaterials 2002;23:1809–1817.
40. Sul YT, Johansson CB, Albrektsson T. Oxidized titanium screws coated with calcium ions and their performance in rabbit bone. Int J Oral Maxillofac Implants 2002;17:625–634.
41. Legeros RZ. Properties of osteoconductive biomaterials: Calcium phosphates. Clin Orthop 2002;395:81–98.
42. Jarcho M, Kay JF, Kenneth I, Gumaer K, Doremus R, Drobeck H. Tissue cellular and subcellular events at the bone-ceramic hydroxyl apatite interface. J Bioeng 1977;1:259–278.
43. Ogiso M, Tabata T, Ichijo T, Borgese D. Examination of human bone surrounded by a dense hydroxyapatite dental implant after long-term use. J Long Term Eff Med Implants 1992;2:235–247.
44. Neo M, Kotani S, Nakamura T, et al. A comparative study of ultrastructures of the interfaces between four kinds of surface-active ceramic and bone. J Biomed Mater Res 1992;26:1419–1432.
45. Ducheyne P, Qui Q. Bioactive ceramics: The effect of surface reactivity on bone formation and bone cell function. Biomaterials 1999;20:2287–2296.
46. Jansen JA, ter Brugge P, van der Waal E, Vredenberg A, Wolke J. Osteocapacities of calcium phosphate ceramics. In: Ellingsen JE, Lyngstadaas SP (eds). Bioimplant Interface. Boca Raton, FL: CRC, 2003:305–322.
47. Ellingsen JE. Pre-treatment of titanium implants with fluoride improves their retention in bone. J Mater Sci Mater Med 1995;6:749–758.
48. Johansson C, Wennerberg A, Holmén A, Ellingsen JE. Enhanced fixation of bone to fluoride-modified implants. In: Transactions of the Sixth World Biomaterials Congress. Sydney: Society for Biomaterials, 2002:601.
49. Ellingsen JE. Increasing biocompatibility by chemical modification of titanium surfaces. In: Ellingsen JE, Lyngstadaas SP (eds). Bioimplant Interface. Boca Raton, FL: CRC, 2003:323–340.
50. Hench LL, Splinter RJ, Allen WC, Greenlee TK Jr. Bonding mechanisms at the interface of ceramic prosthetic materials. J Biomed Mater Res Symp 1971;2:117–126.
51. Davies JE. The use of cell and tissue culture to investigate bone cell reactions to bioactive materials. In: Yamamuro T, Hench L, Wilson J (eds). Handbook of Bioactive Ceramics. Vol I. Boca Raton, FL: CRC, 1990:195–225.
52. Daculsi G, LeGeros RZ, Heughebaert M, Barbieux I. Formation of carbonate-apatite crystals after implantation of calcium phosphate ceramics. Calcif Tissue Int 1990;46:20–27.
53. Davies JED. Mechanisms of endosseous integration. Int J Prosthodont 1998;11:391–401.
54. Davies JED. Critical issues in endosseous peri-implant wound healing. In: Ellingsen JE, Lyngstadaas SP (eds). Bioimplant Interface. Boca Raton, FL: CRC, 2003:219–228.
55. Geis-Gerstorfer J, Lindemann W, Rupp F, Scheider L. In vitro screening of microstructured titanium implant surfaces. Presented at the 10th International Friadent Symposium, 16–17 May 2003, Mannheim, Germany. Mannheim: Dentsply/Friadent, 2003:21–22.
56. Franke-Stenport V. On Growth Factors and Titanium Implant Integration in Bone [thesis]. Göteborg, Sweden: Department of Biomaterials/Handicap Research, University of Göteborg, Sweden, 2002:1–160.
57. Wikesjö U, Sorensen RG, Kinoshita A, Wozney JM. rhBMP-2/αBSM induces significant vertical alveolar ridge augmentation and dental implant osseointegration. Clin Implant Dent Relat Res 2002;4:174–182.
58. Jokstad A, Brägger U, Brunski J, Carr AB, Naert I, Wennerberg A. Quality of dental implants. Int Dent J 2003;53:409–443.
59. Albrektsson T. Is surgical skill more important for clinical success than changes in implant hardware? [editorial]. Clin Oral Implants Res 2001;3:6–7.
60. Bryant SR. Oral Implant Outcomes Predicted by Age- and Site-Specific Aspects of Bone Condition [thesis]. Toronto: University of Toronto, 2001.