

On Implant Surfaces: A Review of Current Knowledge and Opinions

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The aims of the present review are (1) to identify essential surface parameters; (2) to present an overview of surface characteristics at the micrometer and nanometer levels of resolution relevant for the four most popular oral implant systems; (3) to discuss potential advantages of nanoroughness, hydrophilicity, and biochemical bonding; and (4) to suggest a hypothetical common mechanism behind strong bone responses to novel implant surfaces from different commercial companies. Oral implants from four major companies varied in average surface roughness (Sa) from 0.3 to 1.78 μm and in the developed surface area ratio (Sdr) from 24% to 143%, with the smoothest implants originating from Biomet 3i and the roughest from Institut Straumann. The original Brånemark turned, machined surface had an Sa of 0.9 μm and an Sdr of 34%, making it clearly rougher than the smoothest implants examined. When evaluated for nanometer roughness, there was a substantial variation in Sa in the different implants from the four major companies. Novel implants from Biomet 3i, AstraTech, and Straumann differed from their respective predecessors in microroughness, physicochemical properties, and nanoroughness. When examined with scanning electron microscopy at high magnification, it was noted that these novel implant surfaces all had particular nanoroughness structures that were not present in their respective predecessors; this finding was suggested as a possible common mechanism behind the demonstrated stronger bone responses to these implants compared to adequate controls. INT J ORAL MAXILLOFAC IMPLANTS 2009;24:63–74

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In an earlier publication on oral implant surfaces, the present authors emphasized the importance of using three-dimensional (3D) analysis, ie, not only information about height but also spatial or hybrid data.¹ Furthermore, the importance of using appropriate measurement filters was stressed, and it was emphasized that evaluations should be based on tops, valleys, and flanks of the implant surface if a screw-shaped design was measured. Some examples of surface analyses of then-used implants were presented. Unfortunately, the standards of surface metrology used in published papers today vary so much in quality that any attempt at a systematic review of the importance of surface roughness in bone healing² has inevitable shortcomings; what may be an otherwise

good scientific paper may have unacceptable standards for reporting surface metrology. In other words, what is termed “rough” in one paper may be called “smooth” in another, and conclusions are therefore difficult. This is probably why the Shalabi et al review of 2006² was able to conclude only that there was a positive relationship between surface roughness and bone-to-implant contact, but was unable to document that the bone response peaked above the level of moderate roughness. Increasing surface roughness up to the level of old plasma-sprayed surfaces invokes an impaired bone response, not a reinforced one.^{3–7} Since the present authors published their earlier review,¹ development has been very rapid, and novel surfaces have been introduced clinically, some of them allegedly based on surface characteristics other than micrometer morphology alone, such as hydrophilicity, chemical bonding, and nanofeatures. However, what is fact or fiction with these new surfaces remains difficult to understand; the question is whether a claimed significant bone response attributed to, for instance, hydrophilia or another surface phenomenon may actually be a result of some other characteristic of the same surface.

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The aims of the present review are (1) to identify essential surface parameters as seen by the authors in 2008; (2) to present an overview of surface characteristics at the micrometer and nanometer levels of resolution relevant for the four currently most sold oral implant systems; (3) to discuss potential advantages of nanoroughness, hydrophilicity, and biochemistry; and (4) to suggest a hypothetical common mechanism behind the strong bone responses to novel implant surfaces from different commercial companies.

ESSENTIAL SURFACE ISSUES AS OF 2008

The authors remain convinced that 3D evaluations are preferable, ie, that average roughness over a surface (the Sa value) is more important than average roughness (Ra), a two-dimensional measurement.¹ Like Ra, Sa presents information about average height deviations; however, Ra gives information only from a profile, whereas Sa provides information about a given surface area. Thus the Sa parameter provides a considerably more consistent and reliable value and is not influenced by the measurement direction (ie, whether the profile is measured along or across the dominant direction of the surface irregularities). In general, a positive correlation is found between an increasing Ra or Sa value and stronger bone integration, at least up to a certain level of roughness. In addition to height descriptive parameters, at least one spatial or hybrid parameter is necessary for proper surface analysis; this is even more true currently, with modern implant surfaces that have modifications resulting in small but frequent irregularities. The authors tend to prefer the developed surface area ratio (Sdr), a measurement that provides information regarding surface enlargement if a given surface is flattened out, ie, the subsequent enlargement of the same surface area after this procedure. The density of peaks (Sds) and Sa are relevant for Sdr; Sdr is, in other words, a hybrid parameter that presents information about the number and the height of peaks of a given surface. Naturally, in the authors' laboratories, data are always analyzed from nine or 10 different parameters, but for practical reasons all these data cannot be quoted in the present paper. In animal experiments it seems as though a moderately rough surface with an Sa of about 1.5 μm and an Sdr of about 50% promotes the strongest bone response.³⁻⁷ Of particular interest is the fact that both smoother and rougher surfaces present less robust bone responses than this hypothetical ideal.⁸ Quite another matter is whether the same ideal surface would present any clinical disadvantages over the

long term, eg, as a result of increased corrosion or increased incidence of peri-implantitis. Wennerberg et al analyzed the ionic leakage of moderately roughened surfaces⁹ and found no dangerously elevated levels of corrosion. When performing experiments with the latter potential contraindication, peri-implantitis, Berglundh and coworkers¹⁰ used ligatures in a dog model to elicit an inflammatory response with bone loss; when the ligatures were removed, bone loss largely disappeared spontaneously around polished, smooth surfaces, but not so around moderately rough sandblasted and acid-etched surfaces. The same investigators continued by investigating four commercially available surfaces: the Biomet 3i machined surface, the SLA surface (sandblasted, large-grit, acid-etched; Institut Straumann), the Astra TiOblast surface (Astra Tech), and the TiUnite surface (Nobel Biocare) under similar conditions. Removal of the ligatures resulted in progression of the bone saucerization of all surfaces, but significantly greater bone loss was seen with TiUnite implants.¹¹ Although these data are interesting, one must remember that the results are from animal studies only and ligatures do not represent clinical reality. At this time, it would be premature to conclude that moderately rough surfaces contribute to an increased risk of peri-implantitis in the long term.

The longest followed clinical data of moderately rough surfaces^{12,13} failed to notice any increased incidence of peri-implantitis up to 10 years after placement of Astra TiOblast implants. However, old plasma-sprayed implants that were clearly rougher than modern surfaces did demonstrate increased plaque indices and bone resorption compared to minimally rough controls in two clinical investigations.^{14,15} Recent reports^{16,17} seem to indicate that even old, turned surfaces may cause peri-implantitis with increasing time; figures ranging from 6% to 43% of all implants have been quoted. However, this is clearly dependent on how peri-implantitis is defined; if any bone loss, whatever its magnitude after the passage of the first year, is regarded as peri-implantitis, high frequencies of this disease will be duly reported. But if bone resorption that threatens the implant longevity at 10 to 20 years of follow-up is considered the criterion, a much less frequent incidence is seen, perhaps in the range of 2%.¹⁸⁻²¹ It may further be seriously questioned whether the onset of the major part of reported bone resorption really is related to peri-implantitis at all; instead convincing evidence points to the healing adaptation theory as the explanation for early bone resorption, thereby making peri-implantitis mainly a secondary phenomenon.^{22,23} It seems that the presence of peri-implantitis is judged very differently depending on a

researcher's clinical specialty; some colleagues do not even agree about the acceptable bone loss of < 0.2 mm annually defined in previously published criteria for success.^{24,25}

The opinion of the present authors is that there is no reason to warn about the use of moderately rough surfaces; rather, they seem to be clinically recommendable based on the current knowledge.

CERAMIC IMPLANT SURFACES

Ceramic implants or ceramic implant surfaces have been tried clinically as an alternative to titanium or other metals for a long time. Aluminum oxide implants in polycrystalline (Frialit-1) or in single crystal (Kyocera) form were tried clinically more than 30 years ago. The polycrystalline implants were accompanied by excellently conducted clinical studies (for that time).²⁶ However, the aluminum oxide material (alumina) did not survive the scrutiny of time; the implants fractured in many cases and were withdrawn from the market.

Then followed implants coated with hydroxyapatite (HA) ceramics, of which the first generation did not work very well.²⁷ The second generation of HA-coated implants demonstrated acceptable 5-year results in at least one study.²⁸ Novel application modes of HA have resulted in much thinner HA layers than used previously, when coats were plasma sprayed (then with a minimum coating thickness of some 50 µm). Modern HA applications may be of 1-µm or even nanometer thickness; therefore the risk level can be assumed to be lower should the HA loosen from the substratum.

Today, there is an increasing interest in another ceramic, zirconia (ZrO₂). Zirconia has long been used for abutments in implant dentistry or for gliding surfaces in orthopedics. Loaded zirconia implants were followed in a monkey model for 2 years by Akagawa et al²⁹ with no reports of implant fractures and clear evidence of osseointegration. Similar results were reported in another monkey study by Kohal and coworkers.³⁰ Sennerby et al³¹ compared zirconia implants of different surface roughnesses with TiUnite implants; they found significantly lower removal torques for a control, untreated zirconia implant, which was minimally rough, whereas moderately roughened zirconia implants demonstrated removal torques similar to that seen for the TiUnite implant. Gahlert et al³² presented an experimental study in which the bone responses were compared among two ZrO₂ implants with Sa of 0.13 µm and 0.56 µm, respectively, and sandblasted and acid-etched implants of a similar design with an Sa of 1.15 µm.

The results demonstrated a stronger bone response to the sandblasted/acid-etched surface followed by the rougher of the two ZrO₂ implants. Mellinghoff³³ presented a clinical study of ZrO₂ implants and observed only 93% success at 1 year. Another type of ZrO₂ implant showed 98% clinical success at 1 year.³⁴ The present authors see zirconia surfaces as interesting but would recommend proceeding slowly with this ceramic, so that repetitions of previous clinical problems with other ceramics are not seen.

Sa AND Sdr OF MAJOR IMPLANT SYSTEMS OF 2008

For practical reasons, this overview will be restricted to the four most sold oral implant systems. This in no way implies that less commonly sold implants necessarily show inferior results. In addition to presenting surface data, the authors will briefly present clinical outcomes of the various surfaces; however, since the focus of this paper is on surfaces rather than clinical outcomes, only sparse follow-up data will be presented. The quoted clinical reports have certain characteristics in common: information about success/survival, information about bone loss/level and evidence for acceptable results with respect to bone loss, proper reporting about unaccounted implants, and an acceptable number of dropout patients.^{24,25}

The most commonly sold implant surface today, allegedly with a world market share of close to 30%, is the TiUnite of Nobel Biocare. This surface is anodized, ie, the implant is placed as an anode in a galvanic cell with an electrolyte that contains phosphoric acid (according to the authors' investigations). After current is placed through the galvanic cell, the surface oxide grows from the native state of about 5 nm in thickness to, in this case, some 10,000 nm in thickness. When clinically introduced, the implant had a surface gradient with a thicker oxide in the apical area; since then the gradient has disappeared and the surface has been more hydrophobic than previously (Fig 1), the latter possibly as a result of a new container. The original TiUnite implant has been positively documented clinically for 5 years.³⁵ Whether clinical results of the new surface will in any way be influenced by the introduced alterations is not known. The Sa of TiUnite is 1.1 µm and its Sdr is 37% (Fig 2, Table 1).

The SLA implant (Straumann), allegedly with a world market share of about 25%, has an acid-etched and grit-blasted surface that is similar but not necessarily identical to that used by several other implant producers. According to several authors,³⁶⁻³⁸ the SLA surface is hydrophobic. It was clinically documented with positive results for 5 years in a study by Bornstein



Fig 1a Earlier batch of TiUnite implant (Nobel Biocare) with visible blood filling out the threads of the implant at surgery.



Fig 1b Later batch of TiUnite implants with "dry" implant surface, probably more hydrophobic than earlier batches. Other changes of the TiUnite surface from early to later batches include a modification from a gradient with thicker oxide layers in the apical part of the implant to a uniform oxide thickness in later batches.

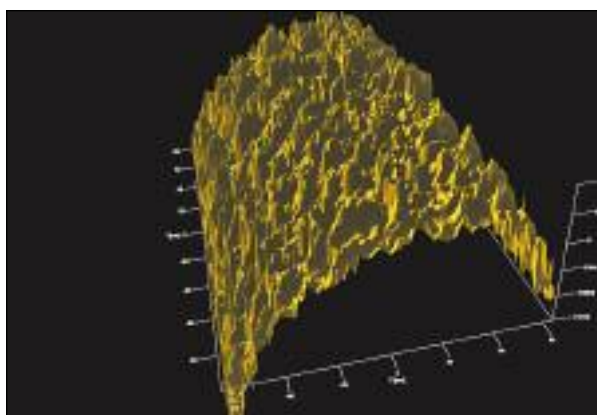


Fig 2a (Left) Top of TiUnite implant with its oxidized surface.

Fig 2b (Below) Valley of TiUnite surface. The Sa of TiUnite is 1.1 μm ; the Sdr is 37%.

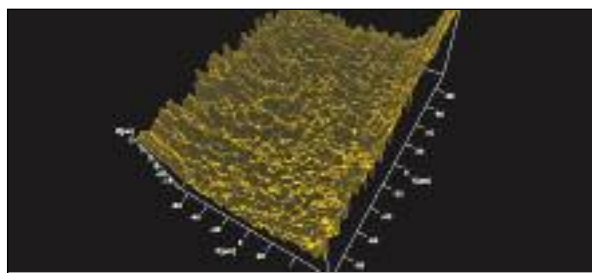


Table 1 Surface Topography of Implants from the Four Major Companies

	Sa (μm)	Sdr (%)
Osseotite	0.68	27
Nanotite	0.5	40
Prevail Ti-6Al-4V	0.3	24
TiOblast	1.1	31
OsseoSpeed	1.4	37
TiUnite	1.1	37
SLA old batch	1.5	34
SLA new batch	1.78	97
SLActive	1.75	143

and coworkers.³⁹ The SLA implant has an Sa of 1.5 μm and an Sdr of 34% (Fig 3, Table 1); however, SLA implants measured again in January of 2008 demonstrated a rougher surface than previous SLA implants: Sa = 1.78 μm and Sdr = 97% (Fig 4). In 2006, a novel hydrophilic surface was introduced, the SLActive, based on animal experiments that this surface shows

a stronger bone response than SLA.^{36,40} One 1-year study showed quite acceptable clinical results of rapidly loaded SLActive implants.⁴¹ The SLActive implant has an Sa of 1.75 μm and Sdr of 143% (Fig 5, Table 1), in this case indicative of a higher density of peaks than on SLA implants.

The Osseotite implant (Biomet 3i) has a turned collar and an acid-etched anchorage portion. The alleged world market share of Biomet 3i implants (all different designs together) is somewhere between 15% and 20%. The Osseotite implant has an Sa of 0.68 μm and an Sdr of 27% in the acid-etched portion (Fig 6, Table 1), whereas the turned, machined part has an Sa of 0.40 μm and an Sdr of 17% (Fig 7). The Osseotite has been documented with good results for 5 years.⁴² Another implant from the same company is the titanium alloy (Ti-6Al-4V) Prevail, which has an Sa of only 0.3 μm and an Sdr of 24% (Fig 8, Table 1). The reason for this implant being clearly smoother than the Osseotite (also true of the huge majority of nearly all other commercially available implants, as far as is

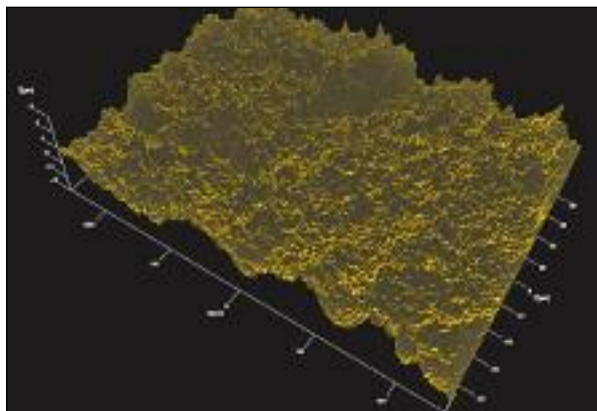


Fig 3 Old batch of Straumann SLA implants with an Sa of 1.5 μm and an Sdr of 34%.

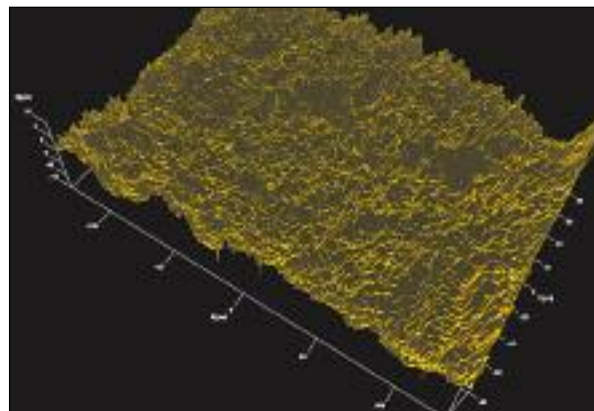


Fig 4 Newer batch of SLA implant with an Sa of 1.78 μm and an Sdr of 97%.

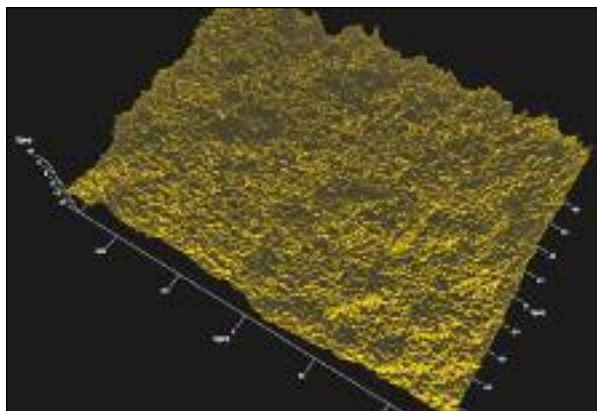


Fig 5 SLActive implant, which differs not only in its physical characteristics (hydrophilia/hydrophobia) from the newer SLA implants, but also in nanoroughness and microroughness, with an Sa of 1.75 μm and an Sdr of 143%.

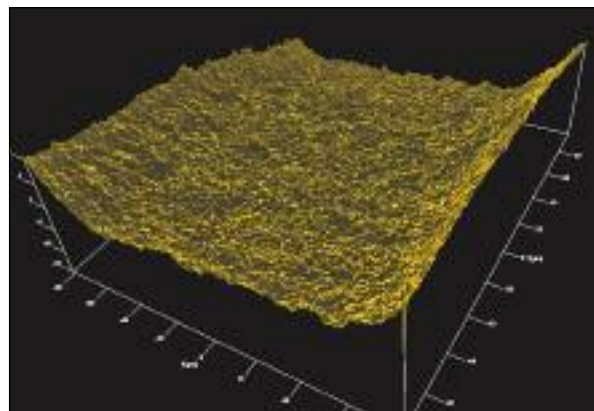


Fig 6 The etched part of the Osseotite surface with an Sa of 0.68 μm and an Sdr of 27%.

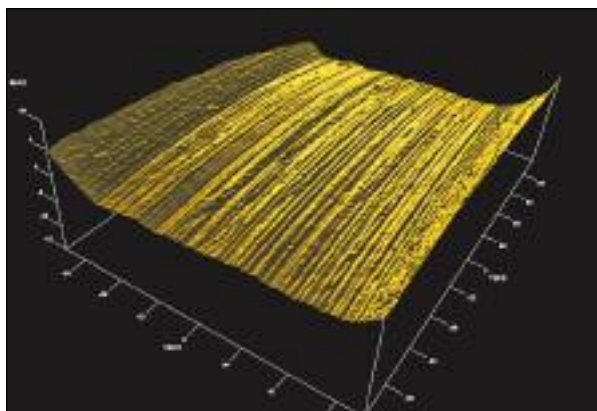


Fig 7a The so-called machined part of the Osseotite surface (Sa 0.40 μm , Sdr 17%) displays a much smoother image than turned, machined Brånemark implants, indicating that machined surfaces are far from uniform with respect to surface roughness.

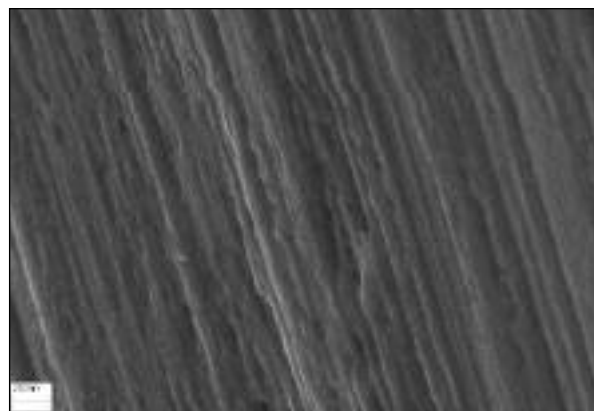


Fig 7b SEM of the polished Osseotite surface (magnification $\times 101,000$).

known by the current authors) is presumably a result of the harder titanium alloy compared to commercially pure titanium. The turning process used to produce these implants, prior to the superficial etching

procedure, will leave less pronounced marks on a harder material. Furthermore, the etching itself may have less of an influence on the surface roughness, although the same acid treatment is used. As a result,

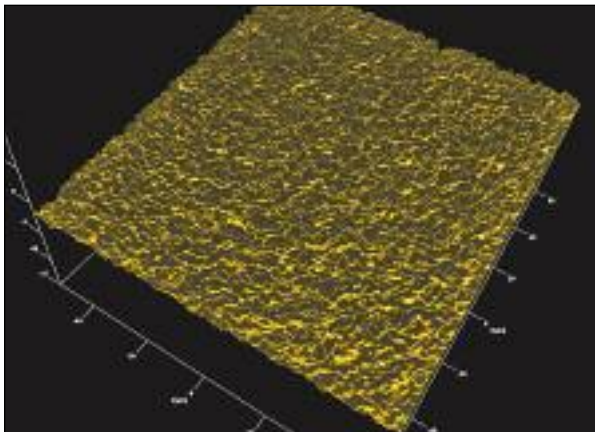


Fig 8a The Prevail Ti-6Al-4V, with an Sa of 0.3 μm and an Sdr of 24%, is the smoothest of all the tested implants; in fact it may be the smoothest implant ever marketed by the four major companies.

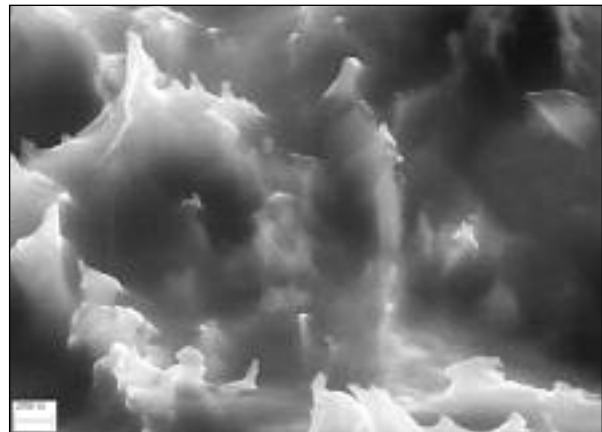


Fig 8b SEM of the Prevail Ti-6Al-4V surface (magnification $\times 100,000$).

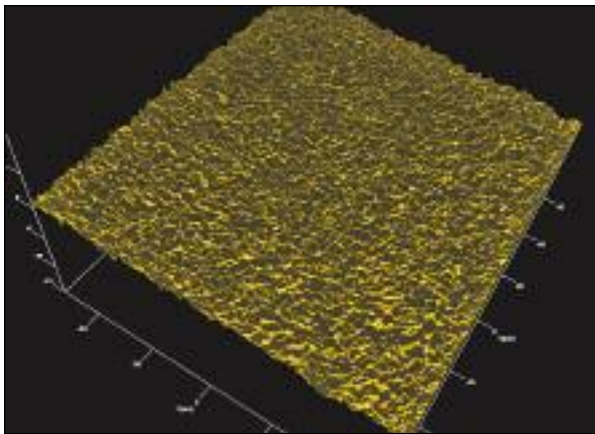


Fig 9 The novel Nanotite surface with an Sa of 0.5 μm and an Sdr of 40%.

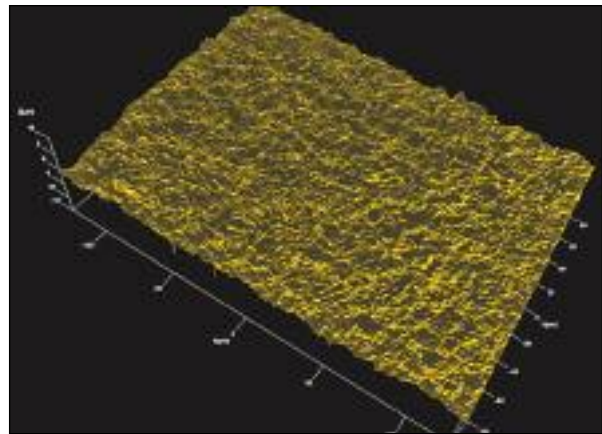


Fig 10 The first clinically introduced moderately rough implant was the TiOblast, with an Sa of 1.1 μm and an Sdr of 31%.

the titanium alloy Prevail implant will have a smoother surface. There is no clinical evidence published on this implant, but one 1-year study with excellent results of the Nanotite implant,⁴³ which has an Sa of 0.5 μm and an Sdr of 40% (Fig 9, Table 1). The Nanotite implant has 20-nm HA compounds attached to its surface; experimental works by Goené et al⁴⁴ and Orsini et al⁴⁵ confirm a stronger bone response to this implant than to Osseotite.

The fourth most common implant is Astra Tech, which allegedly claims about 12% of the world market. Astra Tech implants are blasted with small micron-sized titanium dioxide particles. The TiOblast implant has an Sa of 1.1 μm and an Sdr of 31% (Fig 10, Table 1). Since this was the first moderately rough implant surface, clinically introduced in 1993, 10 years of positive clinical data have been reported.^{12,13} The TiOblast, like

the other Astra Tech implant, the OsseoSpeed, has microthreads, which have been clinically documented to maintain bone levels better than similar implants without microthreads^{46,47} (Fig 11). The OsseoSpeed implant has been treated with fluoride ions, although the remaining fluoride found on its surface is less than 1 atomic % according to the authors' investigations. The OsseoSpeed surface has an Sa of 1.4 μm and an Sdr of 37% (Fig 12, Table 1). This surface has been clinically documented for 1 year with good results in different publications,^{48–50} and one study observed positive results over a 3-year follow-up period.⁵¹

By comparison, the original Brånemark turned, commercially pure titanium grade 1 machined implant had an Sa of 0.9 μm and an Sdr of 34% (Fig 13). This implant has now been documented with good clinical results for up to 20 years.²⁰

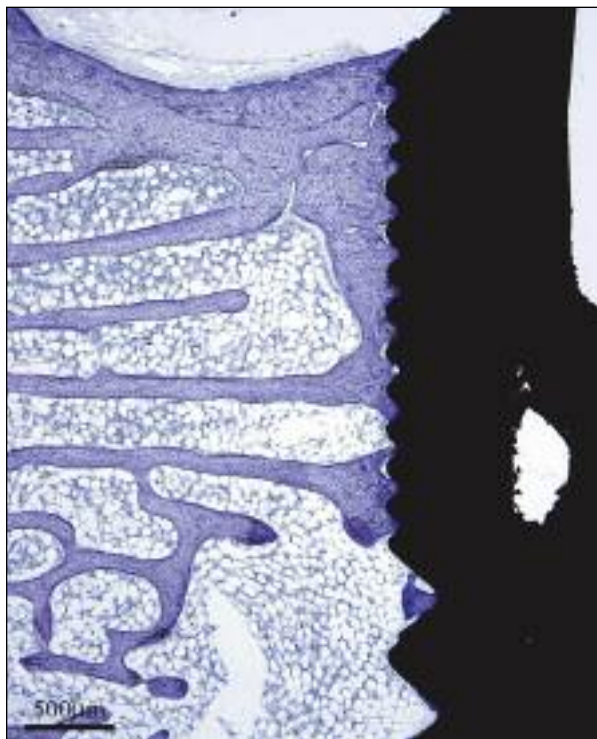


Fig 11 The microthreads of the TiOblast implant have the capacity to maintain bone height according to two different controlled, clinical studies.

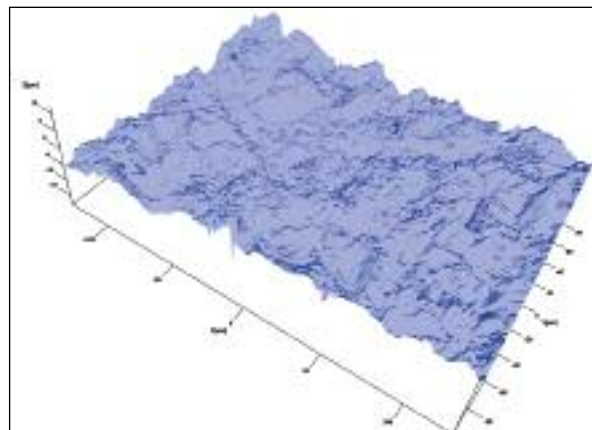
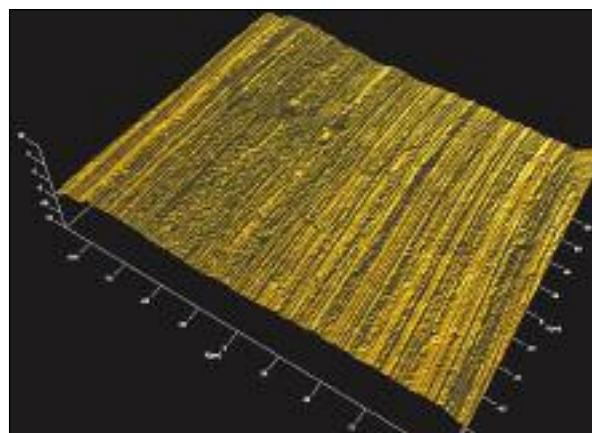


Fig 12 The OsseoSpeed surface from Astra Tech has an Sa of 1.4 µm and an Sdr of 37%. This implant has been clinically documented for 3 years.

Fig 13 (Right) The original Brånemark turned, machined implant was rougher than several marketed implants today (Sa of 0.9 µm and Sdr of 34%).



ON NANOMETER ROUGHNESS OF EXPERIMENTAL AND CLINICAL IMPLANTS

Nanometer roughness has been regarded as an interesting topic, although little is known beyond data from *in vitro* observations. While *in vitro* results are of some scientific interest, they have limited applicability, since they often contrast with *in vivo* observations. The experimental problem is that when surfaces are altered with different techniques, microroughness will change simultaneously with nanoroughness; hence, it is difficult to analyze the individual contribution of the two modes of roughness separately. Furthermore, most techniques used to alter surface roughness, independent of the level of resolution, will also result in unavoidable surface chemical alterations. The ideal experiment would be one in which microroughness was controlled and the bone responses to nanoroughness alone were investigated. Meirelles⁵² did develop such a model recently; by careful electropol-

ishing of a cylindric implant, irregularities at the micron level of resolution were removed, and only nanometer roughness remained, enabling investigations of the possible influence of such fine surface irregularities (Fig 14). The test implant needed external stabilization by an osteosynthesis plate, so that early implant movements would not inhibit bone formation. In a first experiment it was demonstrated that nano-HA-capped (HA particles in the 20-nm range) polished titanium implants showed a stronger bone response than polished controls, a finding that could be explained either by HA chemistry or by the improved nanoroughness of the HA-coated implants.⁵³ In another experiment, a particular nanotitanium surface was introduced; since this showed the strongest bone response, HA chemistry was not the explanatory factor. Nanotitanium implants showed increased feature density and a larger feature coverage area than nano-HA implants, thereby theoretically presenting more binding sites for proteins.⁵⁴

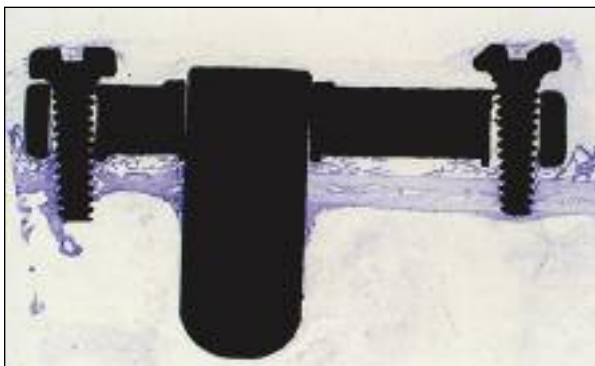


Fig 14a Experimental design of Meirelles et al.⁵³ A nonthreaded, electropolished implant without microroughness was used to investigate the potential importance of nanoroughness in vivo.

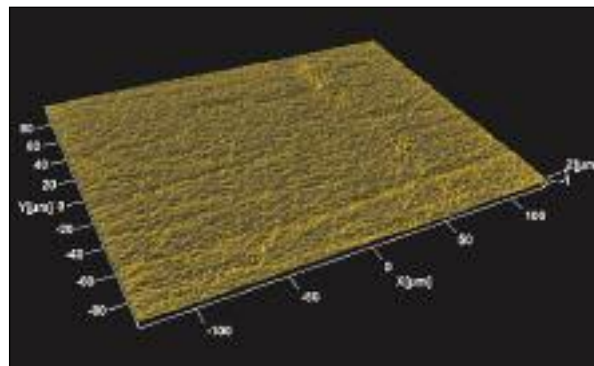


Fig 14b Polished titanium surface that has been supplemented with nanoindentations to analyze the importance of nanoindentations.

IS THERE A COMMON MECHANISM BEHIND THE STRONG BONE RESPONSES REPORTED FOR MANY NOVEL SURFACES?

It seems obvious that osseointegration per se is not linked to certain defined surface characteristics, since a great number of different surfaces achieve osseointegration.⁵⁵ However, stronger or weaker bone responses may be related to surface phenomena. The Nanotite (Biomet 3i), OsseoSpeed (Astra Tech), and SLActive (Straumann) implants, manufactured by three different companies, have one obvious quality in common: they have stronger bone response than their respective predecessors. Different enzymatic reactions for the Astra Tech OsseoSpeed, compared to the TiOblast from the same company, have been documented.^{56,57} It is indeed interesting to observe that the new surfaces from Biomet 3i, Astra Tech, and Straumann companies all differ from their respective predecessors in their changed microtopography, potentially different surface chemistry, and modified nanoroughness. Sul et al⁵⁸ presented a comparative study of an experimental implant with attached magnesium ions and compared the removal torques of this implant, TiUnite, and Osseotite. They found that the magnesium implant elicited a stronger bone response, despite Sa and Sdr of only 0.78 μm and 27%, respectively. This was explained by an assumed chemical bonding of the magnesium implant. There are indeed some data published on allegedly chemically bonded implants (for a review, see Albrektsson and Wennerberg⁵⁹); however, the presence of chemical bonding remains difficult to prove. For instance, titanium may be treated with acid etching followed by sodium hydroxide treatment to achieve bone-bonding ability⁶⁰; in such a case the authors would then prefer not to discuss potential chemical bonding positive chemical effects on bone cells, in general.

Change in Microroughness

Implant microroughness remains an important factor for the bone response; for a review see Albrektsson and Wennerberg.⁵⁹ The fact that altered microroughness, while it is a factor of known importance for strong bone responses, may not be the only relevant factor is important to this discussion, since novel implants such as Nanotite, OsseoSpeed, and SLActive all have microroughness that is different from those of their respective predecessors.

Indeed, the stronger bone response to Nanotite versus Osseotite implants may be dependent solely on the changed microroughness (Nanotite has greater Sdr than Osseotite but smaller Sa). The same may apply for OsseoSpeed compared to TiOblast implants (OsseoSpeed has greater Sa and Sdr than TiOblast) and for SLActive compared to sandblasted and acid-etched implants (SLActive has greater Sdr than sandblasted and acid-etched implants). However, the increased Sdr, which is in this case a greater amount of surface irregularities on the SLActive implants compared to sandblasted and acid-etched implants, has not been documented as "ideal" for strong bone responses; in fact the SLA seems to have a more theoretically ideal Sdr.^{61,62} Of some relevance to the Astra Tech OsseoSpeed surfaces is one experimental study in which a predecessor to the OsseoSpeed implant was deliberately manipulated down to minimal roughness (Sa = 0.9 μm and Sdr = 21%); there was no change to the strong bone response, which was significantly greater than that of TiOblast (Sa = 1.1 μm and Sdr = 31%).⁶³ Taken together and based on the current knowledge of implant surface microroughness, it seems likely that the stronger bone responses reported for these three new commercially available implant systems cannot be explained fully by differences in microroughness.

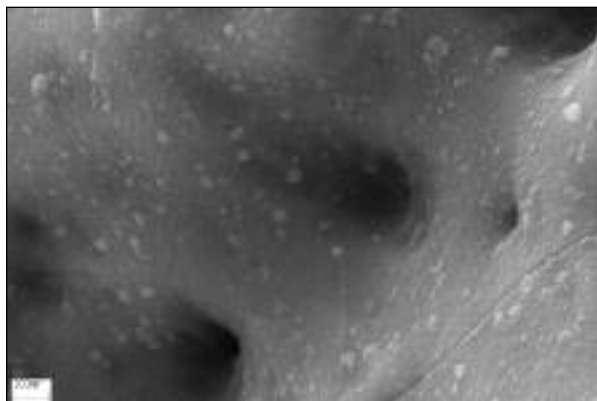


Fig 15 SEM of the TiUnite surface (magnification $\times 101,000$).

Table 2 Surface Roughness at the Nanometer Level of Resolution

	Sa (nm)
Osseotite	19
Nanotite	23
OsseoSpeed	22
TiUnite	33
SLA (old batch)	35
SLActive	97

Physiochemical Effects

One cannot rule out the possibility that Nanotite implants have support from attached HA, ie, a chemical effect. Having said that, a recent experiment conducted by Meirelles et al⁵⁴ found that factors other than chemistry may explain the strong bone responses to nano-HA compounds. With respect to OsseoSpeed implants, one cannot rule out the possibility that the fluoride ions per se support the bone response by acting as some sort of catalyst. However, chemical analyses of OsseoSpeed surfaces clearly demonstrate less than 1 atomic % of fluoride ions attached to the surfaces⁶⁴; the chemical effect of such a small amount is questionable. From a physical point of view, it is interesting to observe that Jimbo et al⁶⁵ have reported that treatment of surfaces with fluoride-containing acids changes those surfaces physically to a hydrophilic state. This would then be a possible common effect with SLActive implants (which do possess hydrophilic characteristics). However, whether hydrophilia has a beneficial effect on implant anchorage (as once suggested by Baier and coworkers⁶⁶) has been questioned.^{67,68} Naturally, it must be considered a possibility that hydrophilia per se need not reinforce the bone response at all but is simply a side effect of no practical significance. But it may also be part of the explanation for the strong bone responses.

Nanoroughness

These observations lead to the third possible mechanism behind the noted strong bone response to these three novel surfaces: nanoroughness. The authors analyzed surface roughness at the nanoscale on implants from the four most popular manufacturers. TiUnite (Fig 15), SLActive, Nanotite, and OsseoSpeed all had nanofeatures on their surfaces, although it is currently unknown which surface, if any,

has the ideal nanoroughness. Sa values at the nanometer level of resolution are presented in Table 2. In these cases the nanoroughness was evaluated with a novel technique⁶⁹ based on first filtering away all microroughness. Hence it was possible to evaluate nanoroughness in the same manner and on the same and equally sized parts of the implants as when micrometer roughness is evaluated, but only height parameters can be evaluated since interferometers have too small a resolution level in spatial directions. However, it is not known whether similar reasoning is applicable as with microsurfaces. A greater degree of nanometer-level roughness may be better, worse, or even irrelevant in the clinical results for an implant. However, what is particularly interesting when discussing nanoroughness of the three novel implants from three different companies is the high-power SEM images. In the case of Nanotite compared to Osseotite, OsseoSpeed compared to TiOblast, and SLActive compared to SLA, there is indeed a common mechanism: that of a noticeable nanoroughness of the novel implants compared to their commercial predecessors (Figs 16a to 16f). To observe these clear differences in nanotopography, high-magnification SEM images are required. The authors suggest that the possibility of a common mechanism behind strong bone responses to many new implants is an altered nanoroughness pattern. It is hypothesized that the different etching procedures used for the three involved surfaces result in a superficial layer of titanium hydride (whether it is TiH_2 , TiH_3 , TiH_4 , or a combination of these remains to be investigated).^{60,70} The hydrogen is gradually replaced by oxide, so a slow transformation of the surface occurs, resulting in nanometer-sized particles of titanium on such surfaces. These small particles may be important in protein adhesion immediately after implant placement.

Figs 16a to 16g High-magnification views of several surfaces. Differences in nanoroughness are apparent when comparing the novel surfaces Nanotite, SLActive, and OsseoSpeed with their respective predecessors (magnification $\times 100,000$).

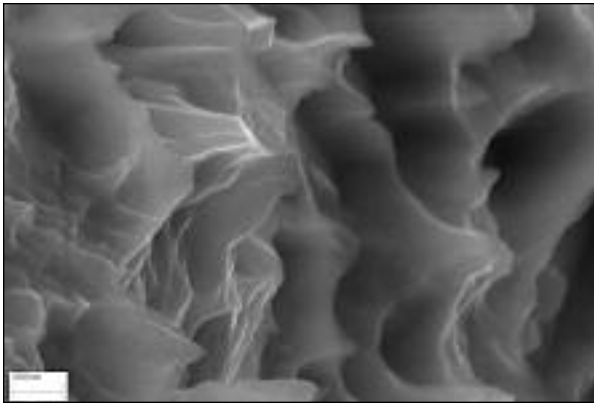


Fig 16a Osseotite surface.

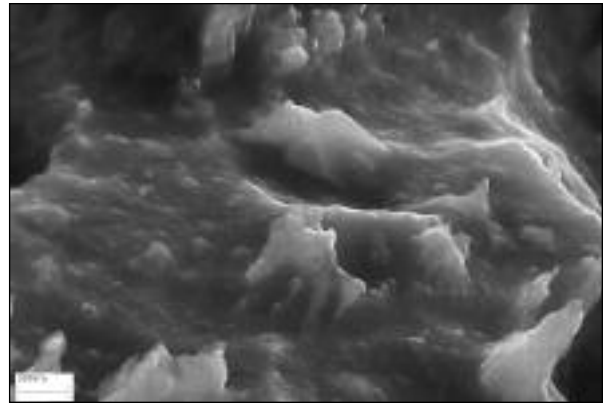


Fig 16b Nanotite surface.

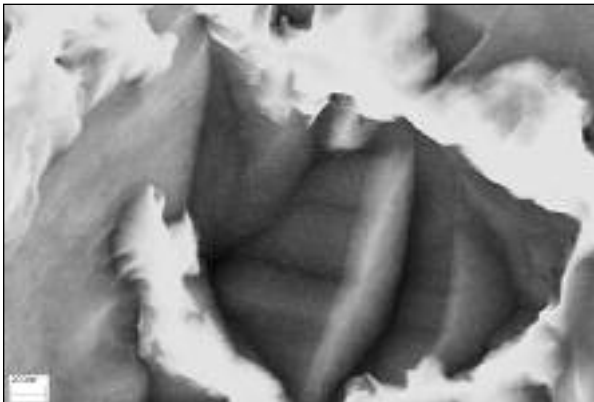


Fig 16c SLA surface.

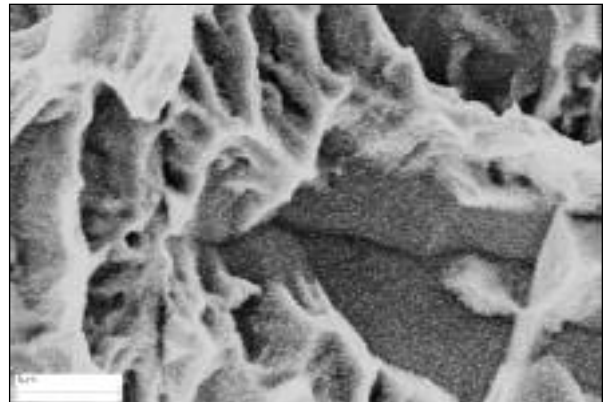


Fig 16d SLActive surface.

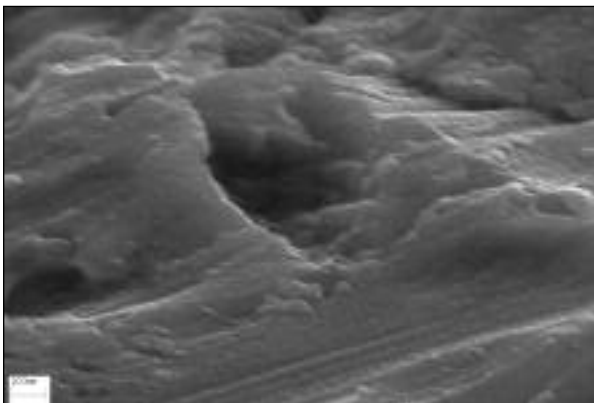


Fig 16e TiOblast surface.

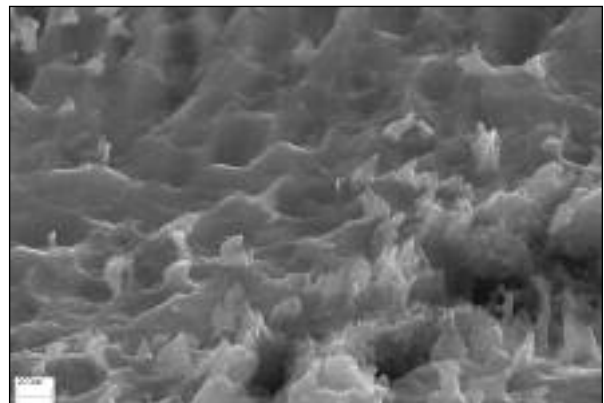


Fig 16f OsseoSpeed surface.

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