Suggested Guidelines for the Topographic Evaluation of Implant Surfaces

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The bone anchorage components of commercially available oral implant systems differ in surface roughness by at least sixfold. Correct reporting of the surface roughness of implant systems is important, since one cannot exclude the possibility that surface roughness will influence clinical results. However, many confusing statements are found in the literature when the surface topography of implants is described. Different measuring instruments and techniques strongly influence the outcome of a topographic characterization. Furthermore, a screw-type design introduces problems for most measuring instruments. Without a standard procedure, it is generally impossible to compare values from one study with another. The aim of the present study was to suggest standards for topographic evaluation of oral implants in terms of measuring equipment, filtering process, and selection of parameters. It is suggested that the measuring instrument be able to measure all parts of a threaded implant if the investigation relates to such a design. Preferably, 3-dimensional measurements should be performed. On screw-type implants, tops, valleys, and flanks should be evaluated. At least 3 samples in a batch should be evaluated, filter size must be specified, and at least one of each height, spatial, and hybrid parameter should be presented. (INT J ORAL MAXILLOFAC IMPLANTS 2000;15:331–344)

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So-called rough dental implant surfaces have become an important issue. This is mainly because numerous experimental reports from animal studies have pointed to a more rapid bone response to roughened surfaces than to smoother polished or turned surfaces.[1–7] Furthermore, experimental studies have demonstrated an optimal surface roughness for intermediately rough implants,[6,8–12] ie, a roughness, in terms of height deviation, in the range of 1 to 1.5 µm. Many clinicians seem to have drawn direct conclusions from such reported experimental findings, ignoring several reports of poor correlation between animal findings and clinical results.[13,14] Furthermore, some authors have presented comparisons between machined implants and novel types of rougher surfaces without mentioning that machined surfaces span a wide range of surface textures.[15]

In implant research the term "machined surface" is often used as a description of turned, milled, or sometimes polished surfaces. Thus, the comparison between such surfaces and rougher surfaces may not always be relevant for commercially available oral implants. To further add to the confusion, clinical support for implants with an intermediate surface is lacking. Thus far, the only controlled study comparing 3-year outcomes of TiO_2-blasted implants and (presumably smoother) turned implants found no difference with respect to success rates or bone height levels around the 2 types of implants.[16] The latter study compared 199 turned or blasted implants placed in posterior segments of a matched patient series. With so little clinical support, caution would seem advisable with respect to routine clinical usage of intermediately roughened implants to avoid a repetition of the hitherto poor results of hydroxyapatite-coated implants,[17] another product launched clinically and solely on the findings of more rapid bone formation in animals.

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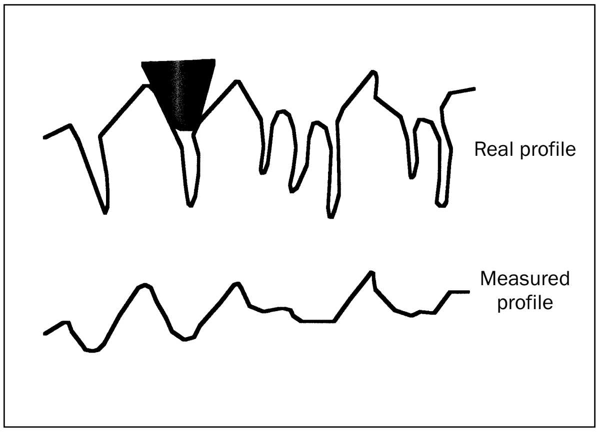


Fig 1 Diagram of the influence of tip radius on the measured profile. A radius that is too large will result in a loss of information.

Irrespective of the poor level of current clinical support for new rough surfaces, any change in implant hardware that results in a documented rapid bone response in animals is of interest to the scientific community. However, reliable, quantitative surface evaluations are mandatory before any conclusions can be drawn as to which surface roughness results in the strongest bone response. Industrial standards for surface evaluations do exist but unfortunately are not specifically applicable to oral implants. In addition, early reports on implants with supposedly enlarged surfaces for the most part did not include quantitative surface evaluations; a surface one author termed rough, the next author called smooth. At best, surfaces were documented with scanning electron microscopy (SEM) photographs.[18–23] Although SEM provides high-quality images, the method is more suitable for morphologic than topographic description. For topographic characterization, SEM is almost exclusively used as a comparative method and is therefore prone to subjective interpretations. Some height information can currently be achieved with a stereo pair of SEM images, but this technique may result in loss of the high resolution that is otherwise the major advantage of this method.[24]

Problems remain with respect to proper evaluation of the surface roughness of oral implants. First, many investigators continue to use inappropriate instruments capable of measuring only flat or cylindric surfaces, which is not at all relevant for the most common oral implant design (a screw-type implant). Second, there is no consensus on which parameters should be evaluated—whether 2- or 3-dimensional evaluations should be performed, or what is the preferred level of resolution for surface evaluations. Third, the concepts of form, waviness, and roughness have not been properly understood by many authors, so wide ranges of roughness are reported for apparently very similar surfaces.

The aim of the present report was to suggest standards for the evaluation of implant surfaces and offer advice on how to avoid some of the pitfalls when reporting data on "rough" and "smooth" implants.

METHODS FOR EVALUATION OF SURFACE ROUGHNESS OF ORAL IMPLANTS

There are 3 major groups of instruments that can supply quantitative and qualitative data for surface topographic evaluations: mechanical contact profilometers, optical profiling instruments, and scanning probe microscopes.

Mechanical Contact Profilometers

The principle of mechanical contact profilometers (contact stylus instruments) is that a pick-up with a stylus is traversed over the surface at a constant velocity. Most mechanical contact profilometers use a diamond tip as a stylus. The tip, attached to a cantilever, is drawn across the surface in the X direction. Vertical movements of the cantilever are registered in an analog or digital signal, and a profile of the surface is recorded. Standard tips for mechanical profilometers are often produced with a radius of 2 or 10 µm and an angle of 60 or 90 degrees. Naturally, this will determine the smallest pits the tip can enter and the steepest slopes that may be measured (Fig 1). The tip is always in contact with the sample and is therefore exposed to wear and contamination. Inspection in a light microscope before measurement is recommended. For 3-dimensional (3-D) images, after one scan is performed, the tip moves back to its starting point, and the cantilever is indexed in the Y direction before another scan is made. The step in the Y direction can be set from 1 to several µm. In implant research, contact profilometers have been used almost exclusively for cylinder and flat sample investigations in dental related research[2,25–30] and for roughness evaluations of experimental and retrieved orthopedic implants.[31–34] Pure titanium plates with different surface modifications were measured in a study of Ungersböck and Rahn.[35] They suggested that using a mechanical profilometer with SEM was the best method for investigating metallic implants, and for anodized implants, the authors found that interference microscopy was a valuable method. However, the design of the implant can determine which instrument can be used and where the measurements can be performed. Discs and cylinders can be measured with a mechanical contact profilometer, while only selected parts of a screw design can be measured with this method. When screw-type dental implants have been evaluated with a contact profilometer,[36–38] there is generally no information given about precisely which regions of the screws were actually measured. However, the measurements must refer to some areas without threads, since a mechanical contact profilometer cannot evaluate threaded regions, which is a serious shortcoming with that method in implant evaluations.

The hardness of the implant material is another factor that needs to be considered. If the material is too soft, the surface will be damaged from the load applied on the tip. This is a drawback for all contact systems. Typically applied loads for mechanical contact instruments are in the milligram range, while for atomic force microscopy (AFM), the typical load is in the microgram range. However, considering the different tip sizes of these 2 systems, the actual pressure on the sample surface will be similar.

Advantages in Implant Research. These instruments generally have a large horizontal measuring range (typical 100 × 100 mm) and a vertical range up to 8 mm. They are suitable for evaluating large, rough areas, eg, blade-type implants, and for measurements of deviation in form, for example, in relation to wear.

Disadvantages in Implant Research. Mechanical contact profilometers cannot be used for nondestructive evaluations of screw-type dental implants, since the tip cannot evaluate threaded parts. (Surface roughness may differ significantly at different locations of an implant [Table 1]).

Table 1 Surface Roughness Measured at 5 Different Sites on Commercially Produced Screw-Type Implants with Optical Profilometry

Implant/manufacturer	S_a (SD)	S_{cx} (SD)	S_{dr} (SD)
Nobel Biocare (Göteborg, Sweden)			
Top	0.99 (0.5)	10.0 (1.7)	1.29 (0.2)
Valley	0.60 (0.3)	8.60 (1.0)	1.17 (0.1)
Flank	0.65 (0.1)	7.27 (0.4)	1.26 (0.1)
TiOblast (Astra Tech AB, Mölndal, Sweden)			
Top	1.27 (0.2)	10.79 (1.1)	1.32 (0.1)
Valley	1.15 (0.2)	10.27 (1)	1.31 (0.1)
Flank	0.84 (0.1)	9.26 (0.5)	1.25 (0.0)
Osseotite (3i, Palm Beach Gardens, FL)			
Top	1.97 (1.0)	14.12 (3.0)	1.42 (0.2)
Valley	0.69 (0.1)	10.35 (0.6)	1.12 (0.0)
Flank	0.54 (0.1)	9.34 (0.5)	1.13 (0.0)
SLA (Institut Straumann AG, Waldenburg, Switzerland)			
Top	1.79 (0.2)	17.51 (2.4)	1.42 (0.1)
Valley	1.32 (0.1)	17.85 (0.7)	1.27 (0.0)
Flank	1.23 (0.1)	14.68 (1.9)	1.30 (0.1)
Bonefit (Institut Straumann AG)			
Top	2.08 (0.1)	12.35 (0.5)	1.79 (0.0)
Valley	2.12 (0.7)	13.01 (1.9)	1.91 (0.4)
Flank	2.09 (0.2)	12.91 (0.9)	1.88 (1.1)

Gaussian filter size 50 × 50 µm. Values are averages based on 9 measurements. Measured area 245 × 245 µm.
S_a = Arithmetic mean of the departures of the roughness area from the mean plane (corresponds to 2-D R_a); S_{cx} = average spacing between the irregularities crossing the mean plane (S_m in 2-D); S_{dr} = developed surface area ratio, ie, a ratio between the 3-D measurement and a 2-D reference plane (no corresponding 2-D measurement).

Optical Profiling Instruments

There is a wide range of different optical instruments, a thorough description of which can be found elsewhere.[24,39,40] Because they are non-contacting, these methods are attractive in biomaterial research since many biomaterials have soft and vulnerable surfaces. Optical instruments are generally faster and have better resolution than mechanical contact instruments. As was the case for mechanical contact profilometers, optical instruments have been used mainly in experimental studies evaluating discs or cylinders.[3,4,41] For topographic characterization of oral implants, the most applicable methods are the following three.

Focus Detection Systems. These systems use a light beam as an optical stylus about 1 µm in diameter. The light beam is scanned over the surface by moving the sample, the light beam, or the objective. The focus is determined by detecting the light intensity. The beam size, the numerical aperture, and the wavelength of the illuminating light determine the lateral resolution, which is normally 1 to 1.5 µm, while maximum vertical resolution is about 5 nm. The maximum vertical measuring range is approximately 500 µm, and the maximum lateral measuring range could be as high as 300 × 300 mm. Surface irregularities with slopes exceeding 15 degrees are difficult to measure because of scattering of the reflected light.

Advantages in Implant Research. The large vertical measuring range is an advantage for rough surfaces, such as plasma-sprayed and some hydroxyapatite-coated surfaces.

Disadvantages in Implant Research. The high reflectance from, for example, polished surfaces may be too good and result in spikes, ie, the auto-focus detection systems have difficulty finding the real focus. An overestimation of the surface roughness generally results.[42] On the other hand, the reflected light must be at least 4% of the incident light,[39] if measurements are to be possible. Furthermore, the systems have difficulties finding the focus when measuring surfaces with a range of different reflecting coefficients,[39] which are often found among commercially available implants.

Confocal Laser Scanning Microscopy. The present authors have extensively used a specially designed focus detection system (TopScan 3D, Heidelberg Instruments GmbH, Heidelberg, Germany) that employs confocal laser scanning microscopy (CLSM). The reflected light and the XYZ position of the laser spot (He-Ne) are measured simultaneously. The system adjusts the focus point by point, independently of previous measures, which reduces integration errors.

Two pinholes reduce the light entering the detector from out-of-focus details, resulting in fine vertical resolution. Furthermore, the CLSM technique is also less prone to overevaluation of surface roughness. TopScan 3D has a maximal measuring area of 2 × 2 mm and maximal vertical range of 108 µm. The vertical resolution is 6 nm and the lateral resolution is 0.6 µm. Maximal slopes of surface irregularities that can be measured are 30 degrees. A more detailed evaluation of the system has been published.[43] The accuracy and reliability of this instrument were evaluated, and it was found to be well suited to topographic characterization of oral implants and other biomaterials.[44] A study of the surface roughness of retrieved femoral heads was published by Wennerberg et al.[45] Optical investigations of screw-type oral implants have been reported only with the TopScan 3D.[6,8–12,46–48]

Advantages in Implant Research. A high numerical aperture can be used, which is important when measuring porous and/or tilted surfaces. Flank measurements of oral implants are possible.

Disadvantages in Implant Research. The maximum lateral measuring range of 2 × 2 mm may be too small for investigations related to wear of orthopedic implants. Likewise, some fiber mesh surfaces have a peak-to-valley height exceeding the vertical measuring range. However, for oral implants the lateral and vertical measuring range is adequate.

White Light Interferometer. A light beam is separated into 2 beams; one is reflected from a reference plane and the other is reflected from the surface of the sample to be measured. Surface irregularities will cause phase changes in the reflected light; some waves cancel each other out, while others augment each other. The dark and light fringes are then no longer straight and equally spaced (as they are for optically flat surfaces). The degree of fringe modulation is proportional to the surface height. Each point of the surface is measured independently of the previous measure, reducing integration errors.

Some commercially available systems have a maximum lateral measuring range (depending on magnification objectives) of 200 × 200 µm and a maximal vertical range of 2 mm. The vertical resolution is about 0.1 nm, and the horizontal resolution is about 0.4 µm.[24]

Advantages in Implant Research. This is a very fast method with large measuring ranges, both vertical and lateral. Flank measurements of oral implants are possible.

Disadvantages in Implant Research. Surface irregularities with slopes exceeding 3 degrees are difficult to measure for surfaces with a low reflective capacity.[40] If the reflective light is too weak, invalid data for that point will result.

Scanning Probe Microscopes

Scanning probe microscopes (SPM) measure the interaction between a sharp tip and the sample surface. The tip is attached to a cantilever, and the vertical movement of the cantilever during surface scanning is registered. Scanning tunneling microscopy and AFM are the most common techniques in this group of instruments, and they are likewise the most suitable for topographic evaluations. For non-conductive surfaces, AFM is the only choice. The method uses a very fine tip (radius of 6 to 60 nm), which is drawn over the surface at constant speed and pressure. A tapping mode is also available in which the tip oscillates above the surface, just touching the surface at the bottom of its swing. The position of the tip is monitored by a detection system. The typical measuring range is 100 × 100 µm, and the maximum vertical range is about 6 µm. The vertical resolution is very fine, down to the picometer level, and the horizontal resolution is claimed to be about 100 pm. Studies published by Baro et al,[49] Taborelli et al,[50] Sawase et al,[51] and Cooper et al[52] are examples of investigations of different implant materials and surface modifications that used SPM for roughness evaluation.

Advantages in Implant Research. Because of the very high resolution of this technique, structures as fine as a protein molecule can be visualized and characterized. The relationship between surface roughness and biologic processes can be studied. Measurements can be performed in air or in liquid.

Disadvantages in Implant Research. The measuring area and especially the maximum measuring range in the vertical direction are too small for many implant surfaces. This means that measurements are not always possible or at least that the measured area has to be very selective, implying that the measurement may not be representative for the overall surface roughness. In a study published by Taborelli et al,[50] one of the titanium plasma-sprayed

Table 2 Typical Properties of Representative Systems of the 3 Major Types of Measuring Instruments

	Contact stylus instrument	Focus detection	Confocal laser scanning profilometer	Interferometry	Scanning probe microscope
Maximal area	100 × 100 mm	300 × 300 mm	2 × 2 mm	200 × 200 µm	100 × 100 µm
Maximal height range	8 mm	500 µm	108 µm	2 mm	6 µm
Horizontal resolution	1 µm	1 µm	0.5 µm	0.4 µm	100 pm
Vertical resolution	10 nm	5 nm	6 nm	0.1 nm	10 pm
Method suitable for screws?	No	No	Yes	Yes	No
Method suitable for cylinders?	Yes	Yes	Yes	Yes	Yes
Method suitable for polished surfaces?	Yes	Yes	Yes	Yes	Yes
Method suitable for turned or milled surfaces?	Yes	Yes	Yes	Yes	May exceed measuring range
Method suitable for blasted surfaces?	Yes	Yes	Yes	Yes	May exceed measuring range
Method suitable for TPS surfaces?	Yes	Yes	Yes	Yes	No

Data about maximal measuring range and resolution can only be used as a guideline since instruments are rapidly being improved.

surfaces investigated exceeded the measuring range of the instrument used. This indicated that the instrument was not appropriate for a topographic characterization of such a surface. In addition, the threaded part of dental implants cannot be evaluated in a non-destructive manner, making this technique unsuitable for evaluating the most commonly used types of oral implants.

Resolution levels and the advantages and disadvantages for the 3 major groups of instruments for surface topographic measurements are presented in Table 2.

STANDARDS AND THEIR APPLICABILITY FOR EVALUATING THE SURFACE ROUGHNESS OF ORAL IMPLANTS

Equipment

The measuring equipment and standards for surface topographic evaluations were originally developed for engineering applications, specifically mechanical engineering. They are, therefore, not specifically adapted to small samples such as oral implants.

Several national and international standards exist, but they are all written for 2-D measurements and the vast majority are for mechanical contact profilometer instruments only.[53–55] Mechanical contact profilometers have been used extensively in industry, whereas optical instruments and 3-D techniques are much newer and related to the development of computers. However, optical measuring techniques and 3-D measurements have attracted increased interest, and standards are expected soon. At present, the closest approach to a standard for 3-D measurements is the work by Stout et al.[56]

Calibration

An international recommendation on calibration of mechanical contact profilometers was expected in 1999. Only a draft is available at present.[57] Standards for optical and SPM instruments are still missing, but some of the recommendations for mechanical stylus instruments may be applicable. Calibration for parameter evaluation includes measurement on a plane glass. This surface should have an average height deviation close to 0, so values exceeding 0 are the result of electrical or vibration-induced noise. A measurement over a defined, scratched surface is also recommended. The third calibration measurement suggested is to be performed on a sample with known height and space properties of profile.

Evaluations

Surface topography consists of form, waviness, and roughness[58] (Fig 2). Different measuring equipment does influence the parameters listed above, but these parameters are influenced even more by how roughness measurement is separated from errors of form and waviness. Roughness is what is left when errors of form and waviness are removed.[53] This is done with different filter types. For 2-D measurements, a cut-off length is used to remove errors of form (Fig 3). The cut-off length should be at least 2.5 times the peak-to-peak spacing and always set to be one fifth of the measuring length.[59] The standard filter for digital 3-D measurements is a Gaussian filter.[60] For 2-D parameters, evaluations are described in different standards.[61,62] For 3-D standards, the work by Stout et al[56] functions as a guideline and has gained international acceptance in surface metrology.

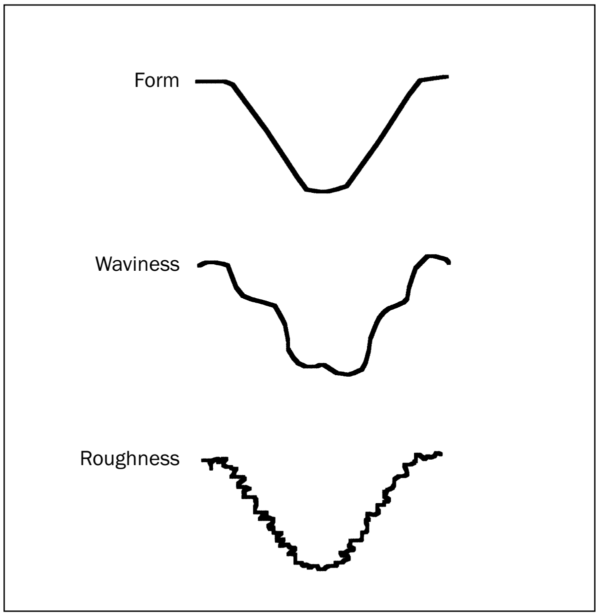
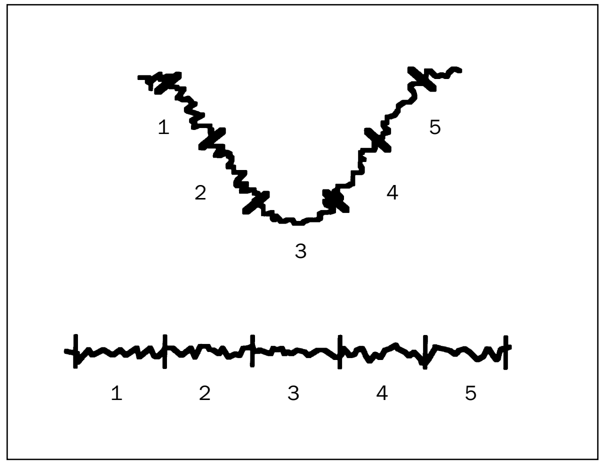


Fig 2 *(Left)* Thread of an implant demonstrating form, waviness, and roughness.

Fig 3 *(Below)* To exclude the assessment of form, a cut-off length is often used in 2-D evaluation.



RELEVANT RESOLUTION LEVEL OF SURFACE ROUGHNESS EVALUATIONS OF ORAL IMPLANTS

As indicated previously in this paper, the implant design/surface may be described with respect to form, waviness, and roughness. Form or implant design, best measured at the millimeter level of resolution, may indeed influence the bony response, as shown by poor long-term bone levels around cylindric implants in contrast to screw-type designs.[63] In the past, many investigators concentrated on implant waviness, since they were of the opinion that bone could not invade pores smaller than about 100 µm. This is indeed correct, if by bone one means osteonic bone with typical Haversian canals surrounded by circumferentially arranged osteocytes.[64] However, if not as complete Haversian systems, bone tissue may nevertheless invade pores down to the 1-µm level of resolution, as indicated by numerous authors.[65] The latter level of resolution is indicative of the true roughness of the implants. At this time there are even investigators who claim that the relevant roughness of an oral implant is at the nanometer level of resolution.[49,66] There is little evidence supporting this theory at present, but the notion is not without interest.

One cannot totally exclude the possibility that when surfaces are being altered with respect to their roughness at the micrometer level, there is a simultaneous change in surface roughness at the nanometer level which, according to this theory, is really the decisive factor in the biologic response. However, for the time being, without any solid evidence of the importance of surface roughness at the nanometer scale, it is suggested that oral implants are best evaluated at micrometer resolution and that waviness and roughness should be reported as separate entities in *every* study. The biologic response most probably depends on the combined effect of these 2 surface aberrations.

WHAT AREAS SHOULD BE EVALUATED IN DETERMINING SURFACE ROUGHNESS OF ORAL IMPLANTS?

On discs and cylinders, surface topography is mostly similar at different locations on the implant. This is not the case for screw-type designs. In the authors' experience, the thread tops are rougher than the flanks and generally rougher than the thread valleys. Surface roughness measurements from commercially available and experimental screws support this statement. In fact, surface roughness may vary by several hundred percentage points at different locations on the same implant (Tables 1 and 3). The only exception was the Bonefit implant surface (Institut Straumann AG, Waldenburg, Switzerland), which had a very similar topography at different measuring locations. For all other commercial and experimental implants tested, the surface roughness varied at different locations. Therefore, a mean value supposedly representing the whole screw should be based on measurements from different locations, since it is known from studies of retrieved threaded implants that bone is formed around all parts of the implant—the thread tops, valleys, and flanks.[67] The roughness of all these regions must be considered when surfaces of oral implants are evaluated. The Nobel Biocare implants (Nobel Biocare AB, Göteborg, Sweden) had smoother valleys than flanks, as did turned and blasted experimental screws. The blasted implants were all turned prior to the blasting procedure. This reflects the importance of the manufacturing history.

NUMBER OF MEASUREMENTS

Based on 9 measurements on each screw (3 tops, 3 valleys, and 3 flanks), 3 screws were found to be sufficient to obtain reliable mean value.[65] The present authors have performed up to 48 measurements on one dental implant,[46] but this is time-consuming, and it is desirable to reduce the number of measurements. Eighteen measurements were performed on turned and blasted screws prepared with different roughness[65]; the mean value was stable after 9 measurements (3 tops, 3 valleys, and 3 flanks). Figure 4 shows the areas of a threaded implant that the authors suggest should be evaluated for a proper description of surface topography of an oral implant.

TWO- OR THREE-DIMENSIONAL EVALUATIONS OF SURFACE ROUGHNESS OF ORAL IMPLANTS

To obtain a reliable surface characterization with 2-D profile measurements, at least 25 scans are needed.[68] Furthermore, Ohlsson[42] found that the distance between the scans should not exceed 20 µm. The closer together the scans can be performed, the more likely it is that small changes in the horizontal direction will be detected.

Isotropic surfaces are surfaces that have the same topography independent of the measuring direction, while anisotropic surfaces have a clear directionality and differ considerably in roughness if a 2-D measurement is performed along or across the dominant direction (the so-called lay; Fig 5). Anisotropic surfaces should always be measured across the lay, where the surface irregularities are the most pronounced.[69,70] In most publications the parameter value refers to profile measurements, ie, 2-D evaluation.[1,2,25–30] Lucchini et al[36] used 2 height-descriptive 3-D parameters to characterize the unfiltered surface.

Dong et al[39] listed 6 reasons why 3-D topographic analysis is superior to 2-D:

Table 3 Surface Roughness Measured with Optical Profilometry at Different Sites on Experimental Turned or Blasted Screws

Experimental screw	S_a (SD)	S_{cx} (SD)	S_{dr} (SD)
Turned			
Top	1.17 (0.1)	9.74 (0.6)	1.40 (0.1)
Valley	0.67 (0.2)	8.16 (0.7)	1.23 (0.1)
Flank	0.67 (0.1)	7.26 (0.5)	1.28 (0.1)
Blasted (25 µm)*			
Top	1.48 (0.1)	10.35 (0.5)	1.51 (0.1)
Valley	0.90 (0.1)	9.61 (0.2)	1.30 (0.0)
Flank	0.96 (0.1)	9.40 (0.5)	1.37 (0.1)
Blasted (75 µm)*			
Top	1.62 (0.1)	12.25 (0.5)	1.56 (0.1)
Valley	1.21 (0.1)	11.16 (3.5)	1.40 (0.0)
Flank	1.31 (0.2)	11.45 (0.4)	1.46 (0.1)
Blasted (250 µm)*			
Top	2.43 (0.2)	14.67 (0.7)	1.85 (0.1)
Valley	1.99 (0.1)	12.80 (0.9)	1.74 (0.1)
Flank	2.03 (0.1)	13.16 (0.9)	1.78 (0.0)

Gaussian filter size 50 × 50 µm.
*Blasted with Al_2O_3 particles with average sizes of either 25 µm, 75 µm, or 250 µm. All blasted implants were turned prior to blasting.
S_a = Arithmetic mean of the departures of the roughness area from the mean plane (corresponds to 2-D R_a); S_{cx} = average spacing between the irregularities crossing the mean plane (S_m in 2-D); S_{dr} = developed surface area ratio, ie, a ratio between the 3-D measurement and a 2-D reference plane (no corresponding 2-D measurement).

1. Since surface topography is 3-dimensional in nature, only 3-D analyses can accurately represent the natural characteristics of the surface topography. Qualitative as well as quantitative evaluation helps to identify sizes, shapes, and volumes of surface features such as pits and troughs, and whether the surface has an orientation (Fig 5).
2. Three-dimensional parameters are more realistic than those obtained from a 2-D profile.
3. Three-dimensional analysis can provide some functional parameters such as lubrication volume, debris volume, and contact area.
4. The statistical analysis of 3-D surface topography is more reliable and more representative, since the large volume of data obtained using 3-D topography increases the independence of the data.
5. Three-dimensional images can be produced with the help of a computer and a suitable image processing technique.
6. Two-dimensional systems normally use analog measures, while 3-D systems mainly use digital techniques. Digital systems are more flexible in processing and storing data.

The present authors, therefore, recommend the use of 3-D evaluations.

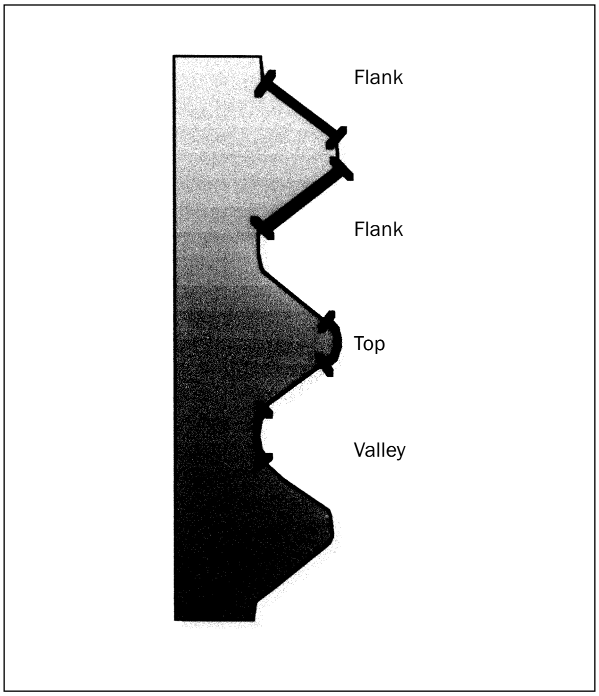
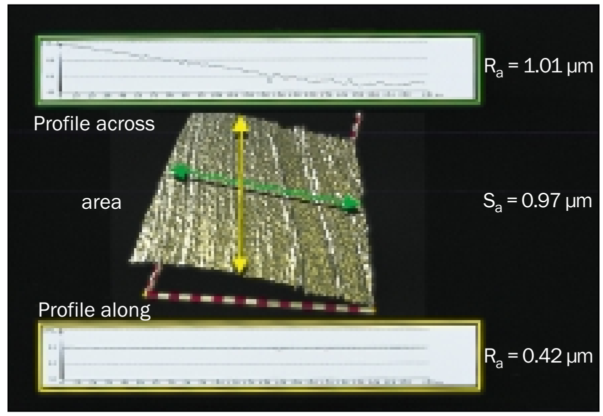


Fig 4 *(Left)* Schematic drawing showing the areas of a threaded implant that need to be measured.

Fig 5 *(Below)* Example of profiles along and across the lay of a turned screw flank. Two quite different profiles, numerically and visually, were obtained. Also pictured is an area measurement of the same sample; this image includes all features and identification of the surface structure that can be done, for example, if a dip in the profile represents a pit or a trough.



WHICH SURFACE PARAMETERS SHOULD BE INCLUDED IN EVALUATIONS OF ORAL IMPLANTS?

Height, Space, and Hybrid Parameters

Parameters are used to numerically describe the appearance of the surface topography. Three major groups exist: height, space, and hybrid parameters. Height parameters are solely descriptive of height. Spatial or texture parameters describe the horizontal distance between the irregularities. Hybrid parameters include spatial and height information; examples are parameters that describe the developed area or the slope and curvature of the irregularities. Many of the parameters belonging to these groups have 2-D counterparts, but some parameters that characterize directional properties are available only for 3-D measurements.

One problem is that there are so many different surface roughness parameters (more than 150 can be found in the literature), and some were invented for a specific measurement application[20] and are not always useful in a broader sense. However, surface topography cannot be characterized well with only one parameter, since one surface may have the same height deviation but differ in spatial distribution when compared to another (Fig 6). Thus, well-known parameters that describe the different properties inherent in the topography ought to be included when evaluating oral implants. There is still uncertainty about which set of parameters is the most suitable for implant evaluations. Stout et al[56] suggested a set of 13 parameters. Their application was mainly in mechanical engineering, but the work can also provide guidance in other areas of surface metrology.

To describe the surface topography of a dental implant, some representative parameters from the 3 major groups must be included. For spatial description, in addition to an average wavelength parameter, a texture direction parameter (S_{tr}) should be added. The reason for this is that the orientation of surface irregularities has been shown to affect different cells in soft tissue.[71,72] It is not known how the orientation of surface irregularities will affect bone cells, but a texture direction parameter should be evaluated at this stage of insufficient knowledge. For characterization of orthopedic implants, functional parameters such as surface bearing index and valley fluid retention index are examples of useful parameters.

Thus far, parameters used in endosseous implant research have almost solely been height descriptive, as is R_a, the most commonly used parameter. R_a is known to be quite stable and insensitive to occasional high peaks or deep valleys. However, in the literature, very different values are reported when seemingly similar surfaces have been evaluated. For example, on "machined" surfaces R_a values of 0.08 µm,[52] 0.15 µm,[38] 0.35 µm,[26] 0.7 µm,[73] 1.3 µm,[25] and 4.7 µm[48] have been reported. For titanium plasma-sprayed surfaces, a wide range of R_a values have also been reported, from a low of 0.5 µm,[52] to intermediate values of 2.4 µm,[48] 3.1 µm,[38] or 4.0 µm,[73] to extremely high values of 18.9 µm[27] or 37.9 µm.[26] The different values are a result of using different measuring equipment, different lengths of measurement (R_q will increase with the root of the measuring length),[74] and the use of either 2-D or 3-D evaluations. Furthermore, different filter sizes may have been used to separate roughness, waviness, and form. Information about which wavelength of roughness has been considered to be waviness is almost always lacking. All of the above factors clearly reflect the difficulties in interpreting data from different studies without suitable standards for oral implants.

The vast majority of surface topographic investigations present only one height-descriptive parameter—R_a, R_q, or R_{max}.[1,25,26,28–30,41,49] R_a is the arithmetic mean of the departures of the roughness profile from the mean line and defined for a profile (2-D). R_q is the root mean square parameter corresponding to R_a, and R_{max} is the maximum peak-to-valley height within the sampling length. Only a few studies of implant roughness have been published with height and spatial parameters presented.[2,35,48,52,75]

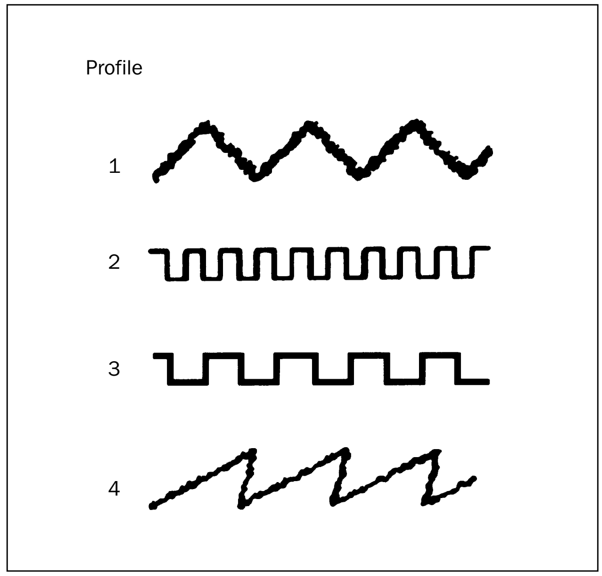


Fig 6 Four different profiles with the same average height deviation (R_a).

Fractals

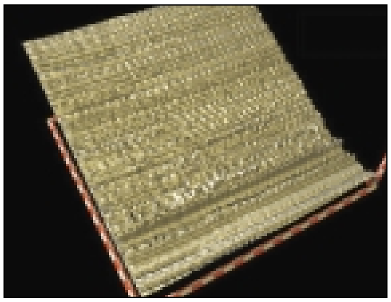
The fact that the conventional parameters are scale-dependent may be confusing, and attempts have been made to find a parameter that is scale-independent. A surface will have a fractal dimension (D) if it has a self-similar structure, that is, it has the same appearance at any scale. Coastlines and leaves from ferns are claimed to have a fractal dimension. However, to characterize manufactured surfaces with fractals is more doubtful.[24]

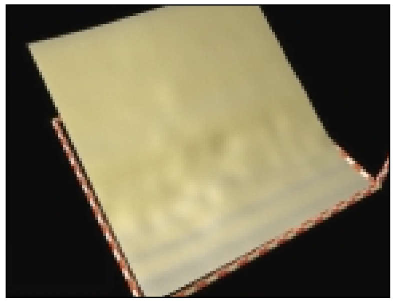
ROUGHNESS, WAVINESS, AND FILTERING OF MEASUREMENTS

There is no accepted standard definition of when roughness becomes waviness. What is regarded as roughness for a large implant may be waviness for a smaller one (femoral versus a dental implant). The size of the filter must be decided before evaluation and is a subjective decision that to a great extent will influence the parameter values. The filter size should be selected with regard to the roughness thought important for the application, ie, tissue, individual cells, proteins. Sometimes waviness parameters are used in profile evaluations. These parameters are the same as roughness parameters but include longer wavelengths while excluding those that are shorter. Roughness plus waviness and roughness values may be of more importance than roughness alone when relating biologic response to a certain degree of irregularity. Schwartz and Boyan[76] speculated about the influence of surface roughness and surface topography in cell response. They referred to a study by Martin et al,[75] who used a cell culture model to investigate surfaces with similar surface roughness but with differing distributions of the rough areas. They found that cells cultured on the rougher surfaces showed greater differentiation. This study was more concerned with different surface roughness on the same sample, but the idea of implementing longer wavelengths in the evaluation is interesting.

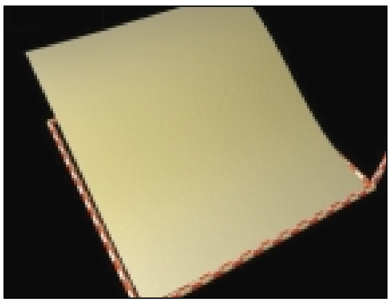
Buser et al[38] sought a better method for capturing small and long-range features. In that study, they used a contact profilometer with a tip diameter of 0.6 µm and measured areas of 2 mm in length. The authors of the present paper have previously used a filter size of 50 × 50 µm when evaluating screw-type dental implants. This decision was based on numerous measurements on turned and blasted screws. Figure 7a demonstrates a turned surface, the original measurement, and what was regarded as waviness and roughness using different filter sizes. For surfaces that include short and long wavelengths,

Fig 7a Turned screw flank, original unfiltered measurement, and what is regarded as waviness and roughness when the filter size is set to 50 × 50 µm and 250 × 250 µm, respectively.


Original measurement, turned flank


Waviness (50 × 50 µm)


Roughness (50 × 50 µm)


Waviness (250 × 250 µm)

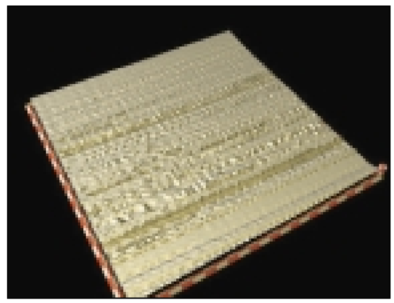
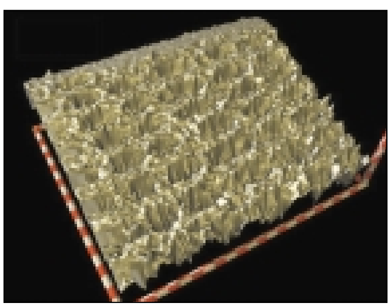
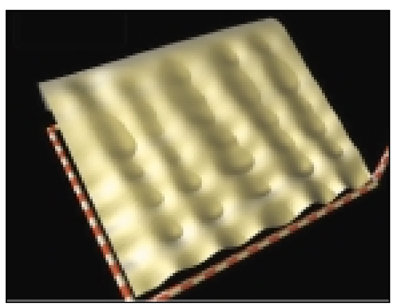
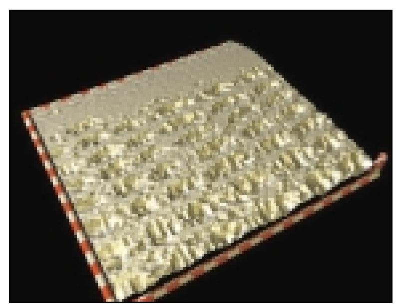
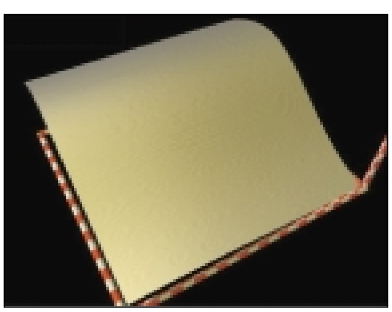

Roughness (250 × 250 µm)

Fig 7b Turned screw flank patterned with laser technology, original unfiltered measurement, and what is regarded as waviness and roughness when the filter size is set to 50 × 50 µm and 250 × 250 µm, respectively. For this surface modification, it is obvious that the larger filter size is needed for the longer wavelengths to be included in the evaluation.


Original measurement, laser flank


Waviness (50 × 50 µm)


Roughness (50 × 50 µm)


Waviness (250 × 250 µm)

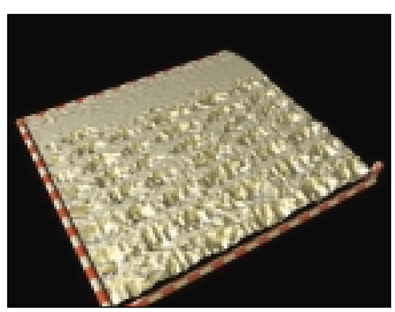

Roughness (250 × 250 µm)

Table 4 Surface Roughness (S_a) Evaluated with Different Gaussian Filter Sizes on Different Commercially Available Dental Implants

Filter size	Nobel Biocare	TiOblast	Osseotite	SLA	Bonefit
25 × 25 µm	0.57	0.74	0.62	0.86	1.56
50 × 50 µm	0.75	1.09	1.07	1.44	2.10
100 × 100 µm	1.13	1.95	1.94	2.34	2.86
150 × 150 µm	1.59	2.86	2.70	3.07	3.56
200 × 200 µm	2.03	3.60	3.31	3.72	4.14
250 × 250 µm	2.47	4.18	3.84	4.31	4.63
300 × 300 µm	2.91	4.66	4.35	4.85	5.05

A total of 27 measurements was taken on each implant type. Each screw was measured at 9 sites, and 3 screws from each manufacturer were measured.

Table 5 Average Height Deviation (S_a) of Experimental Screws Evaluated with Different Filter Size

Filter size	Turned	Blasted (25-µm particles)	Blasted (75-µm particles)	Blasted (250-µm particles)	Laser-patterned
25 × 25 µm	0.68	0.86	1.01	1.50	0.93
50 × 50 µm	0.84	1.12	1.38	2.15	1.36
100 × 100 µm	1.13	1.70	1.99	3.03	1.76
150 × 150 µm	1.47	2.35	2.68	3.72	2.03
200 × 200 µm	1.80	2.94	3.37	4.30	2.29
250 × 250 µm	2.14	3.43	3.97	4.83	2.61
300 × 300 µm	2.48	3.84	4.46	5.30	3.03

Values represent the mean value obtained from 27 measurements from each modification (3 screws, 9 measurements on each) except for the laser-patterned screws. These screws were measured only on the flank areas; thus, this mean value is based on 9 measurements.

a larger filter size is needed if the longer wavelengths are to be included in the parameter calculations (Fig 7b).

Tables 4 and 5 demonstrate that the parameter values are highly affected by different Gaussian filter sizes for both commercial and experimental dental implants. Table 6 provides the parameter values achieved on discs prepared with the same method as some of the experimental screws (turned and blasted with average particle sizes of 25 and 250 µm, respectively). The values differed significantly from those obtained on screws with the same surface modification. This indicates that it is not always possible to transfer achieved roughness values from one design to another. Table 6 also shows that discs are less sensitive to different filter sizes than screw-type implants; this is, of course, related to the fact that discs have no major form included in the measurements. The authors' recommendation is to present roughness and waviness evaluations separately. Information about filter size must be included in the description of the topographic evaluation.

Table 6 S_a Value* for Turned and Blasted Discs when Evaluated with Different Gaussian Filter Sizes

Filter size	Turned	Blasted (25-µm particles)	Blasted (250-µm particles)
25 × 25 µm	0.18	0.50	1.04
50 × 50 µm	0.22	0.61	1.57
100 × 100 µm	0.29	0.68	2.18
150 × 150 µm	0.36	0.71	2.52
200 × 200 µm	0.43	0.73	2.72
250 × 250 µm	0.50	0.75	2.85
300 × 300 µm	0.56	0.77	2.96

*Calculated from 12 measurements (4 discs from each surface modification, 3 measurements on each).

SUGGESTED GUIDELINES FOR THE EVALUATION OF ORAL IMPLANTS

Method for Measurement

Confocal laser scanning profilometers and interferometers are the only acceptable methods available at present able to evaluate densely threaded oral implant designs. For flat or cylindric implants, mechanical contact profilometers may additionally be used.

Preferably, 3-D measurements should be performed. In exceptional cases, 2-D measurements may be acceptable, but at least 25 scans should be performed no more than 20 µm apart. Furthermore, 2-D measurements must always be measured across the lay, ie, perpendicular to the main direction of irregularities.

Suggested Areas for Measurement

On screw-type implants, tops, valleys, and flanks should be evaluated, in 3 different measuring areas. The measuring areas should be as large as possible to allow for different wavelengths inherent in the topography. Selecting only a flat portion of a screw for analysis is unacceptable. Cylindric implants should be measured on at least 3 different areas, each as large as possible. In addition, at least 3 samples of a batch should be evaluated.

Filtering Process

The filter should be chosen in such a way that values for waviness plus roughness and roughness can be presented separately. Filter size must be specified.

Parameters

For numeric evaluation, at least one height, one space, and one hybrid parameter should be presented. Preferred height parameters are R_a and R_q for 2-D, and for 3-D, S_a and S_q are preferred. Preferred space parameters are S_m for 2-D, and for 3-D, S_{cx} and S_{tr} should be used. Preferred hybrid parameters are Δ_q for 2-D and $S_{\Delta q}$ and S_{dr} for 3-D. Mathematical descriptions are found in the work by Stout et al.[56]

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