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Research Article

Skewness and Kurtosis: Important Parameters in the Characterization of Dental Implant Surface Roughness—A Computer Simulation

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The surface roughness affects the bone response to dental implants. A primary aim of the roughness is to increase the bone-implant interface shear strength. Surface roughness is generally characterized by means of surface roughness parameters. It was demonstrated that the normally used parameters cannot discriminate between surfaces expected to give a high interface shear strength from surfaces expected to give a low interface shear strength. It was further demonstrated that the skewness parameter can do this discrimination. A problem with this parameter is that it is sensitive to isolated peaks and valleys. Another roughness parameter which on theoretical grounds can be supposed to give valuable information on the quality of a rough surface is kurtosis. This parameter is also sensitive to isolated peaks and valleys. An implant surface was assumed to have a fairly well-defined and homogenous "semiperiodic" surface roughness upon which isolated peaks were superimposed. In a computerized simulation, it was demonstrated that by using small sampling lengths during measurement, it should be possible to get accurate values of the skewness and kurtosis parameters.

1. Introduction

For dental implants, the primary rationale of surface roughness is to get an increased retention strength. Implant surface roughness is normally characterized by a number of surface roughness parameters [1]. There is no consensus as to which combination of roughness parameters that best characterize the important topographical features of implant surface roughness [2]. Hansson and Norton [3] assumed that a rough implant surface can be conceptualized as consisting of small pits. Assuming that bone grows into these pits, creating retention, it was found that the retention strength depends upon the size, shape, and packing density of these pits. A theoretical study did not show any clear relationship between the estimated retention strength, using the method suggested by Hansson and Norton [3] and the values of a set of surface roughness parameters [4]. Wennerberg and Albrektsson [1] suggested the use of at least one height, one space, and one hybride parameter for characterization of implant surface roughness. For 2D measurements, one of the height parameters R_a (average roughness) and R_q (root-mean-square roughness), the space parameter RS_m (mean width of profile elements), and the hybrid parameter R_{dr} (developed length ratio) were suggested. The limitations of this recommendation are immediately realized when considering the two surfaces in Figure 1. These surfaces are mirror images of each other, and the values of the suggested set of parameters are exactly the same for these surfaces; these parameters cannot discriminate between surfaces which are mirror images of each other. It is however quite obvious that the interface shear strength is much higher for the surface in Figure 1(a) than in Figure 1(b). The number of bone plugs which protrude into pits on the surface per length unit is exactly the same for the two surfaces, while the shear strength of the individual bone knobs, protruding into the pits, is much higher for surface in Figure 1(a) than for surface in Figure 1(b). If the surface characterization is supplemented by the skewness parameter (R_{sk}), a discrimination between

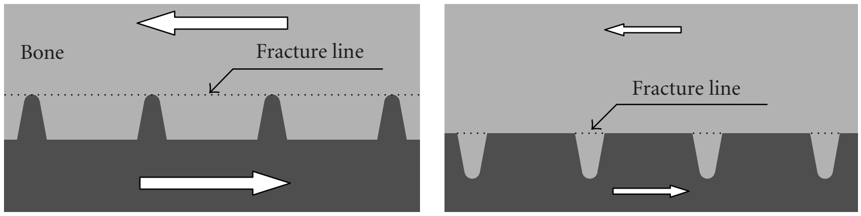

Figure 1: Two rough surfaces in cross-section. The R_a, R_q, RS_m, and R_{dr} parameters are the same for the two surfaces. The interface shear strength is much higher for surface (a) than for surface (b).

these two surfaces is achieved. The absolute value of the skewness is the same for the two surfaces, but the sign is different; a plus sign for the surface in Figure 1(a) and a minus sign for the surface in Figure 1(b).

An even better representation of a rough surface is obtained if the kurtosis parameter (R_{ku}) is added. This parameter is a descriptor of the peakedness of the surface [5]. As the modulus of elasticity of the implant material is substantially higher than that of bone, stress peaks will arise in the bone adjacent to the roughness peaks [6]. The sharper the asperities of the surface roughness, the higher the stress peaks in the bone [7]. Excessive bone stresses will result in bone resorption [8, 9]. This means that theoretically the kurtosis parameter is important in the characterization of implant surface roughness.

A review of the literature on bone implants shows that the skewness and kurtosis parameters are seldom used in the characterization of surface roughness. The explanation for this is probably the experience in surface metrology that these parameters often show a high spread which is explained by the fact that in the mathematical expressions of skewness and kurtosis the departures from the mean line are raised to the power of three and four, respectively (Table 1). This makes the values of these parameters strongly influenced by outliers, deviating from the general pattern, which is also mentioned in the standard EN ISO 4287 : 1998.

According to Albrektsson and Wennerberg [10], implant surfaces with an S_a (3D average roughness) value between 1.0 μm and 2.0 μm (moderately rough surfaces) show stronger bone responses than smoother and rougher surfaces. They also found that the majority of the dental implants, currently on the market, have S_a values within that interval. S_a is a three-dimensional height parameter—the average departure from the mean surface within the sampling area. The two-dimensional analogue of the S_a parameter is the R_a parameter—the average departure from the mean line within the sampling length.

The metrology standard EN ISO 4288 : 1997 differentiates between periodic and nonperiodic profiles. For nonperiodic profiles the recommended sampling length, when measuring skewness and kurtosis, depends on the R_a value. For R_a values between 0.1 and 2 μm, the prescribed sampling length is 0.8 mm. This means that if a moderately rough implant surface is regarded as nonperiodic, a sampling length of 0.8 mm should be applied for the measurement of skew and kurtosis. For surfaces having a periodic profile, the prescribed sampling length is based on the mean width of profile elements (RS_m) to the effect that the sampling length will be 2–6.25 times the mean width of profile elements. The mean width of profile elements seems to be less than 40 μm for most moderately rough implant surfaces of today [11] which, according to EN ISO 4288 : 1997, means that a sampling length of 0.08 mm should be applied. Thus, the decision of whether to regard a dental implant surface as having a periodic or nonperiodic surface profile has a big impact on the choice of sampling length. A periodic profile leads to a sampling length of 0.08 mm, while a nonperiodic profile gives the sampling length 0.8 mm. The standard EN ISO 4288 : 1997 does not provide clear information regarding the discrimination between a periodic and nonperiodic profile. An inquiry at a company specialized in surface metrology gave the answer that a blasted, etched, or plasma sprayed surface should be regarded as having a nonperiodic profile. The standard EN ISO 4288 : 1997 recommends that measurements be made on five consecutive sampling lengths; these five sampling lengths constitute the evaluation length.

In metrology, the surface topography is assumed to consist of three basic components: form, waviness, and roughness, which are superimposed upon each other [1]. Roughness is what remains when the form and waviness components have been subtracted from the real contour of the surface. This subtraction is effected by a digital filter; normally a Gaussian filter [12]. According to the standard EN ISO 4287 : 1998, the characteristic wavelength of the filter (the cutoff) should equal the sampling length.

The aim of the present study was to investigate the effect of the sampling length on the accuracy which can be expected when measuring skewness and kurtosis on fairly well-defined and homogenous "semiperiodic" surfaces upon which isolated peaks of higher amplitude are superimposed. The study was performed by computerized simulation. The mathematical expressions of the 2D surface roughness parameters dealt with in this study are given in Table 1.

2. Method

A set of graphs was defined by the functions

$$A_n\left(\frac{\{1+\sin[x/(B_n RS_m)]\}}{2}\right)^3, \quad 0 < x < 2\pi B_n RS_m, \tag{1}$$

Table 1: 2D surface roughness parameters dealt with in the present study.

Parameter name	Symbol	Digital implementation of mathematical formula	Type	Description
Average roughness	R_a	$\frac{1}{m}\sum_{i=1}^{m}\lvert z(x_i)\rvert$	Height	Average absolute deviation from profile mean line
Root-mean-square roughness	R_q	$\sqrt{\frac{1}{m}\sum_{i=1}^{m} z^2(x_i)}$	Height	Root-mean-square deviation from profile mean line
Skewness	R_{sk}	$\frac{1}{m}\sum_{i=1}^{m}\frac{z^3(x_i)}{R_q^3}$	Height	Third central moment of profile amplitude probability density function
Kurtosis	R_{ku}	$\frac{1}{m}\sum_{i=1}^{m}\frac{z^4(x_i)}{R_q^4}$	Height	Fourth central moment of profile amplitude probability density function
Mean width of profile elements	RS_m		Space	Mean separation of excursions above profile mean line
Developed length ratio	R_{dr}	$\frac{1}{x_m - x_1}\sum_{i=1}^{m-1}\sqrt{(z_{i+1}-z_i)^2+(x_{i+1}-x_i)^2}$	Hybrid	The relationship between stretched length and scanned length

where A_n and B_n are random parameters, each with a rectangular distribution between 0.5 and 1.5. The profile of a basic surface roughness was constructed by placing these graphs sequentially. A sample of this profile is shown in Figure 2(a). This means that the width of the profile elements varied randomly between $0.5RS_m$ and $1.5RS_m$ with a mean of RS_m. The amplitude of the profile elements varied randomly between 0.5 and 1.5. Each profile element was assumed to be represented by 50–150 measurement points depending on the length of it. This basic surface roughness was assumed to define the bone response and the anchorage strength of a bone implant.

Another set of graphs was defined by the functions

$$3.125C_n\left(\frac{\{1+\sin[x/(70D_nRS_m)]\}^3}{8}\right)^{20}, \quad 0 < x < 140\pi B_nRS_m, \tag{2}$$

where C_n and D_n are random parameters, each with a rectangular distribution between 0.5 and 1.5. An outlier profile was constructed by placing these latter graphs sequentially. This means that the mean width of the outlier profile elements was 70 times as large as the mean width of the basic roughness profile elements. A sample of the outlier profile is shown in Figure 2(b). The amplitude of the outlier profile elements varied randomly between 1.5625 and 4.6875, being 3.125 times as big as the amplitude of the basic roughness profile elements. Each outlier profile element was assumed to be represented by 3500–10500 measurement points depending on the length of it. A surface roughness with outliers was constructed by superimposing the outlier profile on the basic surface roughness profile (Figure 2(c)).

Using a routine written in Visual Basic, Microsoft, the skewness and kurtosis parameters were calculated for the cases below. For each case, five consecutive simulations were made. The averages of these five simulations are reported.

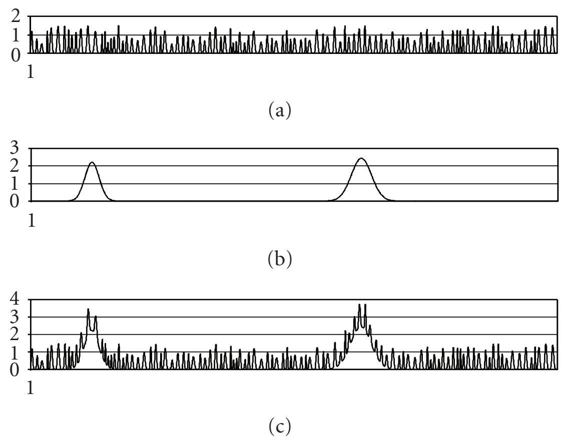

Figure 2: (a) A sample of the basic surface roughness profile. (b) A sample of the outlier profile. (c) A sample of the outlier profile superimposed on the basic surface roughness.

Basic Surface Roughness.

(i) Without filter. Sampling length: $5RS_m$, $10RS_m$, $25RS_m$, $50RS_m$, and $100RS_m$.

(ii) Gaussian filter. Sampling length: $5RS_m$, $10RS_m$, $25RS_m$, $50RS_m$, and $100RS_m$.

The characteristic wavelength of the filter was equal to the sampling length.

Surface Roughness with Outliers.

(i) Without filter. Sampling length: $5RS_m$, $10RS_m$, $25RS_m$, $50RS_m$, and $100RS_m$.

(ii) Gaussian filter. Sampling length: $5RS_m$, $10RS_m$, $25RS_m$, $50RS_m$, and $100RS_m$.

The characteristic wavelength of the filter was equal to the sampling length.

Table 2: Average value of skewness after five consecutive simulations.

Sampling length	Basic surface roughness		Surface roughness with outliers	
	Without filter	Filter	Without filter	Filter
$5RS_m$	1.10	0.94	1.18	1.04
$10RS_m$	1.10	1.09	1.15	1.18
$25RS_m$	1.12	1.09	1.49	1.89
$50RS_m$	1.10	1.12	2.12	2.49
$100RS_m$	1.13	1.13	2.24	2.25

Table 3: Average value of kurtosis after five consecutive simulations.

Sampling length	Basic surface roughness		Surface roughness with outliers	
	Without filter	Filter	Without filter	Filter
$5RS_m$	3.04	2.61	3.42	3.11
$10RS_m$	3.06	3.05	3.24	3.58
$25RS_m$	3.14	3.05	4.72	7.26
$50RS_m$	3.08	3.16	8.49	10.57
$100RS_m$	3.22		9.70	9.34

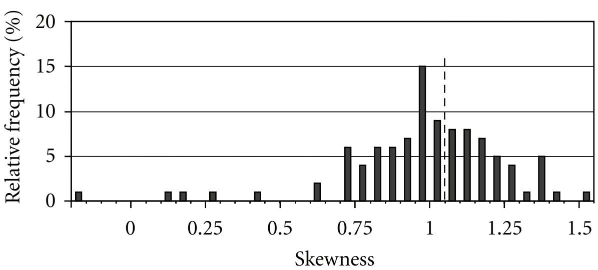

Figure 3: Frequency distribution for skewness for the basic surface roughness with outliers. Sampling length = filter size = $5RS_m$. The dashed line represents the true value (Table 2).

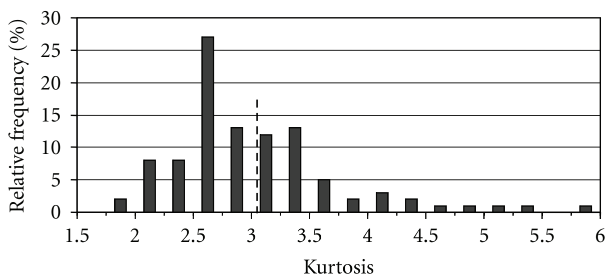

Figure 4: Frequency distribution for kurtosis for the basic surface roughness with outliers. Sampling length = filter size = $5RS_m$. The dashed line represents the true value (Table 3).

Using Gaussian filter, additionally, 100 consecutive simulations were made of measurement of skewness and kurtosis on surface roughness with outliers for the sampling length $5RS_m$. All numerical filterings were performed according to the method described in EN ISO 4288 : 1997.

3. Results

For the measurement of the basic surface roughness, without filter, variations in the sampling length had minor effects on the skewness and kurtosis values (Tables 2 and 3). Since the basic surface roughness had no outliers, these values can be regarded as the "true values" for skewness and kurtosis. Application of a Gaussian filter resulted in a small decrease in the skewness and kurtosis values for the shortest sampling length. This is what should be expected since the shortest sampling length implied the smallest characteristic wavelength for the Gaussian filter.

The overall picture of the measurement without filter of skewness and kurtosis on the surface roughness with outliers was that the bigger the sampling length the more the obtained values deviated from the true values (Tables 2 and 3). The bigger the sampling length the higher were the values obtained. For the sampling lengths $5RS_m$ and $10RS_m$, the deviation from the true values amounted to about 10% or less. The application of a Gaussian filter did not improve the results.

In Figures 3 and 4, the frequency distribution of values obtained with filter for skewness and kurtosis with the sampling length $5RS_m$ is given. Rather sharp peaks are seen for values 10–15% below the "true values".

4. Discussion

Surface roughness has been a main focus in dental implant research for more than a decade [10]. Using a theoretical approach, Hansson and Norton [3] tried to identify geometrical features of a surface roughness which would maximize the bone-implant interface shear strength. The measurement in animal studies of the torque required to remove an implant after a certain healing time has been a preferred tool to evaluate implant surface roughness. For cylindrical

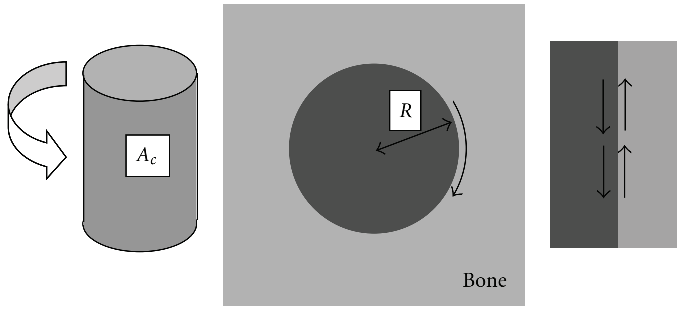

Figure 5: Removal torque = $\int \tau_i R dA_c$, where τ_i is the bone-implant interface shear strength, R the distance from the implant surface to the long axis of the implant, and A_c the contact area between implant and bone.

and screw-shaped implants, there is a direct mathematical relationship between removal torque and interface shear strength which is expressed in the following formula:

$$\mathrm{RTQ} = \int \tau_i R dA_c, \tag{3}$$

where RTQ is the removal torque, τ_i the bone-implant interface shear strength, R the distance from the implant surface to the long axis of the implant, and A_c the contact area between implant and bone (Figure 5). This confirms that an important requirement which should be satisfied by a rough implant surface is that it should give a high bone-implant interface shear strength.

The different kinds of implant surface roughness used have primarily been characterized by surface roughness parameters. Moderately roughened surfaces, characterized as having an S_a value in the range of 1 to 2 μm, have been identified as giving a stronger bone response than smoother or rougher surfaces [10]. For 2D measurements one of the height parameters R_a and R_q, the space parameter RS_m, and the hybrid parameter R_{dr} have been suggested [1]. As mentioned in the Introduction, these parameters, or their 3-dimensional counterparts, cannot discriminate between the two surface roughnesses in Figure 1. In a removal torque study, the maximum torque is obtained immediately before fracture occurs at the implant bone interface. At fracture, the bone plugs protruding into the irregularities of the rough surface (Figure 1) are sheared off. The total length of the fracture line in Figure 1(a) is about four times as big as that in Figure 1(b). A rough estimate is thus that the expected interface shear strength and the removal torque, for an implant having the surface in Figure 1(a), are four times as big as the corresponding values for the same implant having the surface depicted in Figure 1(b). If, by Hansson and Norton [3], the postulated reduced bone strength immediately adjacent to the implant surface, is considered the differences in anchorage strength achieved by these two surfaces get even greater. A parameter which can discriminate between the two surfaces in Figure 1 is skewness. With this background, the absence of the skewness parameter in most papers dealing with implant surface roughness is striking. The reason for this is probably an experience that this parameter normally shows a high spread; in the standard EN ISO 4287 : 1998, expressed as being "strongly influenced by isolated peaks or isolated valleys."

It belongs to common engineering knowledge that sharp peaks at the interface between two different materials tend to give rise to stress concentrations. Bone is sensitive to stress concentrations [13]. The kurtosis parameter is a measure of the peakedness of a surface. On theoretical grounds, it can therefore be concluded that this parameter could give valuable additional information on the quality of a bone implant surface roughness. Kurtosis is even more sensitive to isolated peaks and isolated valleys than skewness.

Surface roughness profiles can show indefinite variations. This simulation was made on a fairly homogenous and well-defined "semiperiodic" basic surface roughness upon which isolated peaks of higher amplitude had been superimposed. It was found that long sampling lengths, corresponding to those recommended by EN ISO 4288 : 1997 for nonperiodic profiles, resulted in big errors for skewness and kurtosis. A tendency was that the shorter the sampling length the smaller the error. In the present simulation, a sampling length of five times the mean width of profile elements, in combination with a Gaussian filter, gave rather accurate results. The frequency distribution of values obtained for skewness and kurtosis for short sampling lengths can give additional information. Much research effort has been spent on developing implant surfaces which will optimize the bone response. These modern implant surfaces are likely to be topographically homogenous and well defined. Hence, it should be possible to get accurate values of skewness and kurtosis for these surfaces. Since the values of skewness and kurtosis, on strong theoretical grounds, can be supposed to influence the bone response and the anchorage strength, it is suggested that these parameters be included in the set of parameters used to characterize dental implant surface roughness.

5. Conclusion

A primary aim of the surface roughness of dental implants is to increase the bone-implant interface shear strength. The surface roughness parameters normally used for characterization of dental implant surface roughness cannot discriminate between surfaces expected to give a high interface shear strength from surfaces expected to give a low interface shear strength. The skewness parameter can achieve this discrimination. Kurtosis is another parameter which theoretically is important in the evaluation of the quality of a rough implant surface. A problem with these two parameters is that they are sensitive to isolated outliers. By using small sampling lengths during measurement, it should be possible to get accurate values of the skewness and kurtosis parameters.

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