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Integrated biomechanical and topographical surface characterization (IBTSC)☆

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ABSTRACT

In an attempt to reduce the need for animal studies in dental implant applications, a new model has been developed which combines well-known surface characterization methods with theoretical biomechanical calculations. The model has been named integrated biomechanical and topographical surface characterization (IBTSC), and gives a comprehensive description of the surface topography and the ability of the surface to induce retention strength with bone.

IBTSC comprises determination of 3D-surface roughness parameters by using 3D-scanning electron microscopy (3D-SEM) and atomic force microscopy (AFM), and calculation of the ability of different surface topographies to induce retention strength in bone by using the local model. Inherent in this integrated approach is the use of a length scale analysis, which makes it possible to separate different size levels of surface features.

The IBTSC concept is tested on surfaces with different level of hierarchy, induced by mechanical as well as chemical treatment. Sequential treatment with oxalic and hydrofluoric acid results in precipitated nano-sized features that increase the surface roughness and the surface slope on the sub-micro and nano levels. This surface shows the highest calculated shear strength using the local model.

The validity, robustness and applicability of the IBTSC concept are demonstrated and discussed.

1. Introduction

Bones are constructed at different levels ranging from macro to nanoscale in hierarchical order. The structure, composition and organization of these levels are all optimized with respect to each other in order to create the remarkable mechanical properties of bones [1,2]. Bone properties such as structure and mass are affected by mechanical forces induced and since nature is restrictive in creating excessive amounts of bone in our bodies, bones which are not loaded have a tendency to resorb [3]. In dental implant treatments, resorption of bone needs to be prevented for successful result and avoiding problems with, for example, compromized esthetics [3–5]. Solutions to this problem have been obtained by modifying the surface roughness, oxide morphology and composition. A combination of different effects contributes to the enhanced performance, but with surface roughness as the dominant factor [6–10]. Based on the arguments cited above, the development of dental implants went from the original smooth machined titanium implant to the commercial implants of today comprising surface topographies ranging from threads to nano particles [11]. By introducing surface roughness on different length scales of the implant, the mechanical stimulation on corresponding tissue levels increases, which preserve and/or prevent resorption of bone or even regain it [3–5]. A crucial step and technical difficulty in the development of new implant surfaces is to characterize in detail the surfaces topography and relate it to *in vivo* results. Since most dental implants on the market today consist of surface features in a wide range of sizes, analysis using complementary characterization has been suggested [12–16]. However, the measuring techniques used as well as the settings of the instruments can highly influence the results [17]. Further, due to animal welfare, the traditional way to evaluate surface changes by *in vivo* studies such as for example removal torque measurements (RTQ) are under consideration and it is recommended that alternatives must be fully explored before any *in vivo* studies involving animals are undertaken [18,19]. Therefore there is a need for new, reliable screening methods for prediction of the *in vivo* performance for newly developed surfaces.

In the present study a characterization concept called the integrated biomechanical and topographical surface characterization

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Table 1
Sample description.

Abbreviation	Surface treatment
TS [14,20]	Turned
TS + ATII	Turned surface + oxalic acid treatment
TS + ATI	Turned surface + oxalic acid and dilute hydrofluoric acid (HF) treatment
CB [14,20]	Turned surface blasted with large TiO_2 particles, *i.e.* coarse blasted surface
CB + ATII	Coarse blasted surface + oxalic acid treatment
CB + ATI	Coarse blasted surface + oxalic acid and dilute hydrofluoric acid (HF) treatment

ATII and ATI will be referred to as the different chemical treatments of the surface.

(IBTSC) is presented. By applying this concept, surface features ranging from 250 μm to 150 nm can be analyzed and the biomechanical contribution from each size range evaluated.

Overall, the concept consists of two separate technologies,

(1) SEM/AFM surface characterization [14] and
(2) a local biomechanical model to estimate the surfaces ability to induce interfacial shear strength, which previously has been correlated to *in vivo* performance [20].

Both techniques are, if used separately, traditional in the field. However, by integration of topography and biomechanical analysis the concept is expected to reveal comprehensive surface properties of dental implants, aimed to be used for screening and development of new surfaces for the implant industry. The concept was developed using both test surfaces and commercially available implants since the latter offers the possibility to compare the outcome of the model with already existing clinical data [21]. In the present study robustness, applicability and validity of the model is proved by using the concept on a demanding, newly developed surface [22]. The challenge for the model is that the actual surface is based on a hierarchical structure comprising different size levels. This is made in order to mimic the natural processes for achieving high shear strength in the construction of natural bone.

2. Material and methods

2.1. Sample preparation

Commercially pure titanium discs (grade 4, diameter 6.25 mm) with a turned surface were used as raw material. One side of the samples were marked with a milled cross to make it possible to analyse the same spot after each surface modification step. The method has been used in previous studies [14,20] for analysis of test surfaces and commercially available surfaces and the method is in detailed described in [14]. In the present study two groups of samples are analysed, one with turned surfaces *i.e.* machined surface and the other with blasted surfaces *i.e.* turned surface blasted with titanium oxide particles. Details of the surface treatments are given in Table 1. By measuring the topography on the same spot after each treatment step, the topographical effects from each process step are recorded. None of the cleaning steps used were found to affect the topography [20]. Surface characterization and electrochemical properties of the CB, CB + ATII and CB + ATI surfaces have been described elsewhere, where the CB, CB + ATII and CB + ATI surfaces are called A, ATII and ATI, respectively [22]. SEM images of the blasted surfaces are shown in Fig. 1 and SEM and AFM images of the turned surfaces are found in Fig. 2.

OsseoSpeed™ like surfaces are also included in this paper for comparison since the surface of these commercially available dental implants (DENTSPLY Implants) has previously been analysed by the same methods as used in the present paper [14,20].

2.2. Topographic analysis

Atomic force microscopy (AFM) and 3D-scanning electron microscopy (3D-SEM) were used to obtain topographical information over a large length scale. Tapping Mode AFM measurements were performed on a Nanoscope® IIIa (digital instruments) at three different scan sizes: 10 × 10 μm, 5 × 5 μm and 3 × 3 μm (scan frequency 0.8 Hz, 512 lines). Only the turned surfaces were measured by the AFM technique since the blasting process induces surface features exceeding the maximum vertical resolution of the AFM instrument. 3D-SEM measurements (ESEM XL30, FEI Company) were performed on both turned and blasted surfaces (SE detector, 30 kV). To obtain 3D-images, stereo-pairs were collected by tilting the sample around the same point with a total tilting angle of 5.6° and 11.2° for the blasted and turned surfaces, respectively. Stereo-pairs were collected in XHD (Extra High Definition) format at four different magnifications: 247.84 × 186.24 μm (×500), 103.26 × 77.59 μm (×1200), 49.57 × 37.25 μm (×2500) and 24.78 × 18.64 μm (×5000).

Roughness analysis of both 3D-SEM and AFM data were performed by using the MeX® [23] software (Alicona Imaging GmbH) (for details see Ref. [14]). This program was also used to extract data to be used in the local model calculations (for details see Ref. [20]). The advantage of using the same software to analyse data collected by different techniques is that differences in parameter values due to the software are eliminated [15]. A Gaussian filter of different cut-offs were applied in the MeX® software to obtain the length scale dependence of the surface topography, for details see Ref. [14,20].

The ability of the surfaces to induce retention with bone was evaluated by using the local model [20]. The model gives a comparative parameter value, which can be used to analyse the performance of different surfaces in removal torque (RTQ) situations. The integrated concept of analysing the surfaces used in the present paper, where the length scale dependence of 3D-surface roughness parameters are combined with the calculation of induced shear strength by the local model, is called the integrated biomechanical and topographical surface characterization (IBTSC).

3. Results

The sequential changes in surface roughness induced when creating hierarchically structured surfaces have been analysed using the IBTSC concept where variable length scale dependence of surface features from 250 μm to 150 nm are analysed. By applying the IBTSC concept, the effect from surface features of different sizes on 3D surface roughness parameters is evaluated and the ability to induce shear strength is calculated by using the local model. Five 3D surface roughness parameters were chosen (S_a, S_{10z}, S_{tr}, S_{tr}, S_{dq}) due to their ability to separate between topographically similar surfaces and to their relevance for dental implant applications [14]. The results are plotted as log (parameter) vs. log (filter size) in μm, where the value of the log (filter size) gives the size of largest surface feature that is included in the analysis. All results are further discussed in Section 4 together with an analysis of the robustness, applicability and validity of the IBTSC concept.

The most commonly used 3D surface roughness parameter to describe the topography of dental implant surfaces is the amplitude parameter S_a (average height of the analysed area) where a value of 1.5 μm is widely accepted as a guideline for best osseointegration of titanium dental implants with a blasted surface [24–26]. All blasted (CB) surfaces analysed in the present paper achieves a S_a value around 1.5 μm using the largest filter size using 3D-SEM (see Fig. 3a), which corresponds to recommended settings [24–26], while significantly lower values are measured for the turned (TS)