Review

Classification of osseointegrated implant surfaces: materials, chemistry and topography

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Since the founding of the osseointegration concept, the characteristics of the interface between bone and implant, and possible ways to improve it, have been of particular interest in dental and orthopaedic implant research. Making use of standardized tools of analysis and terminology, we present here a standardized characterization code for osseointegrated implant surfaces. This code describes the chemical composition of the surface, that is, the core material, such as titanium, and its chemical or biochemical modification through impregnation or coating. This code also defines the physical surface features, at the micro- and nanoscale, such as microroughness, microporosity, nanoroughness, nanotubes, nanoparticles, nanopatterning and fractal architecture. This standardized classification system will allow to clarify unambiguously the identity of any given osseointegrated surface and help to identify the biological outcomes of each surface characteristic.

Osseointegration and implant surface engineering.

Osseointegrated implants are used widely in the dental [1,2], maxillofacial, and ear–nose–throat [3,4] fields and, although not as frequently, also in orthopaedic surgery [5–10]. Osseointegration is defined experimentally as the close contact between bone and implant material in histological sections [11] and, in clinical terms, as the stability and ankylosis of an implant in bone [12]. Originally observed in implants with titanium surfaces, osseointegration was considered the result of a foreign body response: the surgical trauma arising from implantation induces a severe oxidative stress, and results in the overproduction of free radicals and oxygenated derivatives at the titanium surface, which lead to the thickening of the titanium dioxide (TiO_2) layer of the surface. Calcium and phosphorus ions from the bone matrix are then incorporated within the TiO_2 porous layer, making the bone/implant interface highly dynamic. Conversely, the contamination or destruction of the TiO_2 layer leads to the pathological loss of osseointegration, called peri-implantitis [13]. Nowadays, the term osseointegration is also used with non-metal surfaces [14], although the underlying biochemical mechanisms are different, because they are not related to titanium oxidation.

Many research efforts have been directed towards improving the bone/implant interface, with the aim of accelerating bone healing and improving bone anchorage to the implant, typically following two different approaches [15,16].

In the first strategy, the interface is improved chemically by incorporating inorganic phases, such as calcium phosphate, on or into the TiO_2 layer. This inorganic chemical modification might stimulate bone regeneration and increase the biochemical interlocking between bone matrix proteins and surface materials [2]. Biochemical surface modification is a variant of this first strategy and specifically refers to the incorporation of organic molecules, such as proteins, enzymes or peptides, to induce specific cell and tissue responses [17–22].

In the second strategy, the interface is improved physically by the architecture of the surface topography. At the micrometre level, the reasoning for this approach is that a rough surface presents a higher developed area than a smooth surface, and thus increases bone anchorage and reinforces the biomechanical interlocking of the bone with the implant, at least up to a certain level of roughness [2]. At the nanometre level, the roughness increases the surface energy, and thus improves matrix protein adsorption, bone cell migration and proliferation, and finally osseointegration [23].

Many techniques have been developed during the last 30 years with the aim of improving osseointegration from a physical or chemical standpoint [2]. The first osseointegrated surfaces were produced by industrial machining of a bulk titanium implant, which led to minimally rough surfaces with some residual periodic microgrooves. Despite the clinical success of these machined surfaces, further processes have been developed to improve the microtopography of the surface, using for example titanium plasma spraying, acid-etching or grit-blasting. Acid-etching is often performed using hydrofluoric, nitric, or sulfuric acid and combinations thereof. Grit-blasting is performed by projection of silica (sand-blasting), hydroxyapatite, alumina or TiO_2 particles, and is followed commonly by acid-etching (Figure 1) to homogenize the microprofile of the implant and to remove as much as possible of the residual blasting particles.

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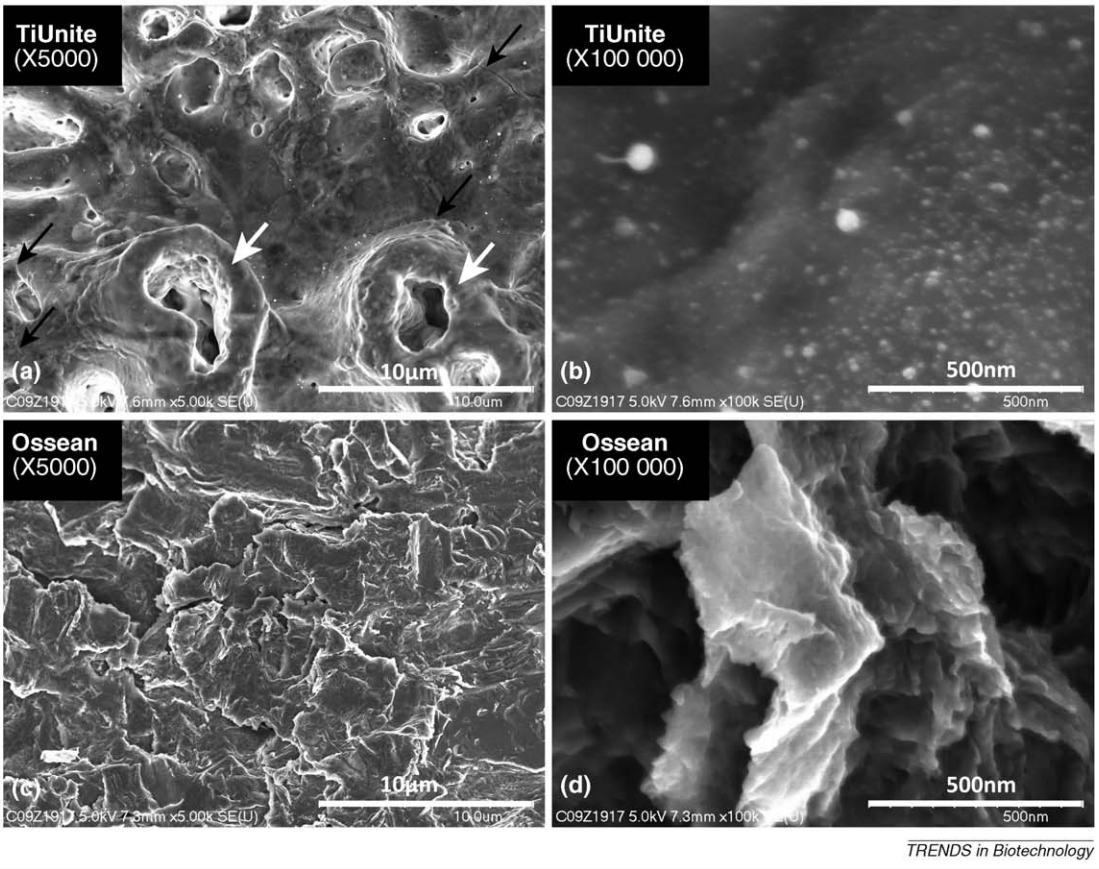

Figure 1. Main morphology characteristics of two commercially-available dental implant surfaces, observed by FE-SEM. The top row shows TiUnite (Nobel Biocare, Gothenburg, Sweden), which is an anodized surface with a typical microporous topography as illustrated by the white arrows in **(a)**. Some cracks can also be seen on this surface (black arrows). At higher magnification, a nanosmooth surface can be seen **(b)**. The bottom row shows Ossean (Intra-Lock, Boca-Raton, Florida), which is a grit-blasted/acid-etched microrough surface **(c)**. As the result of a proprietary final treatment, Ossean exhibits a typical dense nanoroughness which can be seen at high magnification **(d)**.

Many engineering processes can combine the chemical and physical modifications of the surface. For example, electrochemical anodization of the titanium surface [24–26] can promote a micrometre-scale thickening and an ionic impregnation of the TiO_2 layer, whereas the collapse of the surface material results in porous structures and associated micro- (Figure 1) or nano- (Figure 2) topography [27–29].

Coating the surface with different kinds of ceramics is another trend in this field. Plasma sprayed hydroxy-apatite (PSHA) coatings of 20–50 μm thickness can be applied to microrough surfaces and results in strong osteoconductive properties; however, the mechanical resistance of the interface between the coating and titanium is considered to be a weak point, and implant failures have been reported. In order to improve PSHA coating, a number of techniques

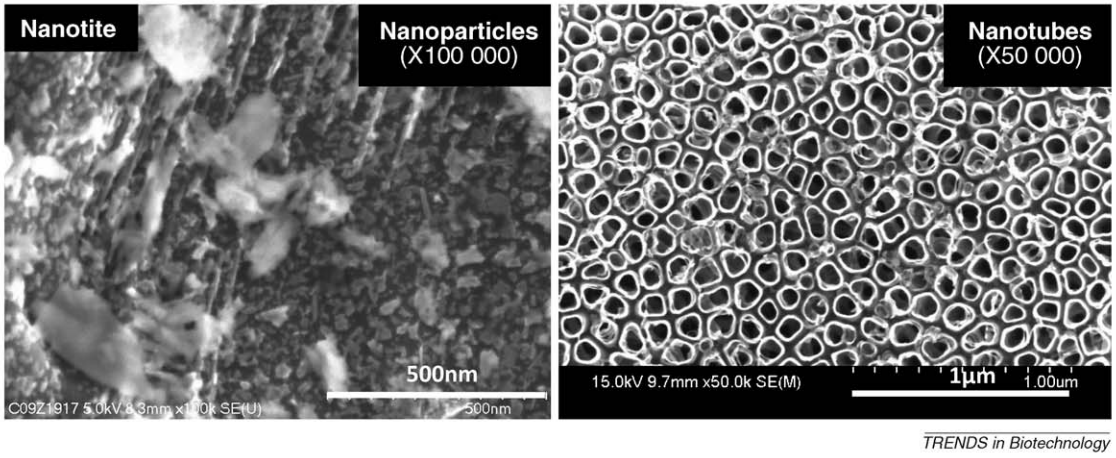

Figure 2. Morphology characteristics of two different titanium implant surfaces with specific nanostructures, observed by FE-SEM. Nanotite (3I, Palm Beach Gardens, USA) is a surface covered with calcium phosphate nanoparticles produced by DCD onto a dual acid-etched surface. On the right, these experimental TiO_2 nanotubes (produced by anodization) are typical examples of surface homogeneous nanopatterning.

Table 1. Codification system for osseointegrated implant surfaces

Level of characterization			Characteristics and their definitions.		Tools required for characterization and suggested guidelines.
Type	**Code**	**Definition**	**Code**	**Definition**	
Chemical	**Core**	Core material	**G4Ti**	Commercially Pure Grade 4 Titanium	1/ XPS for accurate atomic composition, on a 300 µm diameter round area. 2/ AES for in-depth elemental profiling down to 100nm deep. Two acquisitions, on a peak and in a valley of the microtopography. 3/ EDX probe for chemical identification of structures observed during morphology examination with SEM.
			G5Ti	Ti-6Al-4V Grade 5 Titanium	
			YTZP	Yttria-stabilized Tetragonal Zirconia Polycrystals	
			YPSZ	Yttria-Partially Stabilized Zirconia	
			PSHA	Plasma-Sprayed Hydroxy-Apatite (thick coating)	
	Mod	Modification		**Impregnation** (elements X **within** the core material)	
			X-RI	<1% : Residual Impregnation	
			X-LI	1 to 5% : Low Impregnation	
			X-HI	> 5% : High Impregnation	
				Coating (elements X **on** the core material)	
			X-CC	Continuous Coating. On the whole surface	
			X-DC	Discontinuous Coating. >50% total surface	
			X-SC	Sprinkled Coating. <50% total surface	
				Pollution	
			OPol	Organic pollution	
			X-IPol	Inorganic pollution. X = elemental composition	
Physical	**Micro**	Microtopography		**1/ Morphology type (number of dimensions D)**	1/ FE-SEM and metrologic software for : - direct characterization of the surface morphology at the micro and nanometer levels. - quantitative morphology for the evaluation of height deviation amplitude (Sa) and spatial density (Sdr%) at the micrometric level. - revealing fractal architectures and repetitive profiles down to the nanometric level. 2/ Interferometer (IFM) on a 230x230 µm square area, for evaluation of the mean height deviation amplitude (Sa) and spatial density (Sdr%) at the micrometric level. 3/ AFM on a 20x20 µm square area for a non quantitative overview of the nanotopography.
			R	Rough (1D)	
			Pa/Po	Patterned or Porous (2D)	
			X-Pt	Particle (3D). X = elemental composition	
				2/ Height deviation amplitude (Sa)	
			S	Smooth. Sa = 0 to 0.4 µm	
			Mi	Minimal. Sa = 0.5 to 1 µm	
			Mo	Moderate. Sa = 1 to 2 µm	
			Ma	Maximal. Sa > 2 µm	
				3/ Spatial Density (developed area ratio, Sdr%)	
			Fo	Flattened out. Sdr% < 100%	
			Ru	Rugged. Sdr% > 100%	
	Nano	Nanotopography (number of dimensions D)	**S**	Smooth	
			R	Rough (1D)	
			Pa/Po/T	Patterned/Porous/Tubes (2D)	
			X-Pt	Particle (3D). X = elemental composition	
	Archi	Global architecture	**F/NF**	Fractal/Non Fractal	
			Ho/He	Homogeneous/Heterogeneous	
			LC/EC	Local Cracks/Extended Cracks along the surface	
			X-RP	Random Particle. X = elemental composition and associated characteristics	

have been developed with the aim of producing a thin-film coating (<5 µm), such as sol-gel deposition, sputtering coating techniques [30] or ion-beam-assisted deposition (IBAD) [31,32]. Alternatives to continuous thin coatings have also been developed, such as the incorporation of calcium phosphate nanoparticles using discrete crystalline deposition (DCD) onto a dual acid-etched surface (Figure 2) [33] or calcium phosphate low impregnation within the oxide layer [34].

The surface preparation processes are numerous and the parameters defining each process (e.g. temperature, pressure, time, type and size of blasting particles, type and concentration of etching acids) can be modified extensively. Thus, the number of different surfaces is almost unlimited and they are difficult to group in categories other than by their engineering process. The development of an exhaustive and consensual classification system, based on standardized chemical and physical parameters, is thus needed.

A coding system to classify osseointegrated surfaces

Even for a specialist, it is often difficult to understand exactly the surface characteristics described in a particular publication, mostly because of the lack of standardized evaluation methods and a consensual terminology with regard to the description of the relevant implant surface features. Moreover, underlying commercial interests sometimes lead to obscuring the true nature of an implant surface.

The accurate characterization of surfaces is obviously an uncompromising prerequisite in order to be able to compare and evaluate the results that have been obtained. Most of the relevant surface parameters can be characterized easily using standard analytical methods, such as spectroscopy, electron microscopy or interferometry [35]. A clear terminology for each characteristic should also be defined. This allows us to classify the surface characteristics of a given implant by their chemical and physical features, independent of the respective production process.

The codification system proposed in this paper is built as a table with five entries, regrouped in two types of characterization, as shown in Table 1. The first type is based on the chemical composition of the surface, that is, the composition of the core material and its chemical or biochemical modifications. The second type is based on the physical characteristics of the implant surface, that is, its topography at the micro- and nanoscale and its global architecture. The different surface features and the associated methods of characterization are described below. This

Table 2. Characterization codes for two different commercially-available dental implant surfaces

Surface	Chemical characteristics		Physical characteristics		
	Core Material (Core)	Modification (Mod)	Microtopography (Micro)	Nanotopography (Nano)	Global Architecture (Archi)
Ossean (Intra-Lock, Boca-Raton, Florida)	Commercially Pure Grade 4 Titanium (G4Ti)	Calcium Phosphate (CaP) Low Impregnation (LI)	Rough (R) Moderate (Mo) Flattened out (Fo)	Rough (R)	Fractal (F) Homogeneous (Ho)
	Core.G4Ti	Mod.CaP-LI	Micro.R.Mo.Fo	Nano.R	Archi.F.Ho
	Characterization Code = **Core.G4Ti / Mod.CaP-LI / Micro.R.Mo.Fo / Nano.R / Archi.F.Ho**				
TiUnite (Nobel Biocare, Gothenburg, Sweden)	Commercially Pure Grade 4 Titanium (G4Ti)	Phosphorus (P) High Impregnation (HI)	Porous (Po) Moderate (Mo) Flattened out (Fo)	Smooth (S)	Non Fractal (NF) Homogeneous (Ho) Extended Cracks (EC)
	Core.G4Ti	Mod.P-HI	Micro.Po.Mo.Fo	Nano.S	Archi.NF.Ho.EC
	Characterization Code = **Core.G4Ti / Mod.P-HI / Micro.Po.Mo.Fo / Nano.S / Archi.NF.Ho.EC**				

system allows to define a characterization code for each surface (Table 2).

To illustrate this codification system, two very different surfaces are described in Figure 1: TiUnite (Nobel Biocare, Gothenburg, Sweden) is an anodized surface [24,35], and Ossean (Intra-Lock, Boca Raton, FL, USA) is a grit-blasted/acid-etched/calcium phosphate impregnated surface [34,36]. Their characterization code was defined following this system, as shown in Table 2. Nanotite (3I, Palm Beach Gardens, FL, USA) is another commonly used implant surface (Figure 2), but its characterization code is not defined here, as not all required surface characteristics have been described accurately.

Core materials and chemical modifications

Definitions

Each implant surface can be defined by its constituting core material. This latter can be altered by chemical (or biochemical) modifications, which introduce specific ions, crystals or molecules, either onto or within the core material (Table 1).

In currently available osseointegrated implants, two materials are mainly used: these are predominantly titanium, and to a considerably lesser extent zirconia. Titanium is commonly used in its grade 4 or 5 forms because of their excellent chemical and mechanical properties. Grade 4 titanium (G4Ti), also called commercially pure titanium, only has less than 1% impurities, such as iron and oxygen. Grade 5 titanium (G5Ti), also called Ti-6Al-4 V, is a titanium alloy that incorporates 6% aluminium and 4% vanadium, and thus, shows greater mechanical strength. Zirconia implants are made currently either of yttria-stabilized tetragonal zirconia polycrystals (Y-TZP) or yttria-partially stabilized zirconia (Y-PSZ) [14].

A significant issue is to define which thickness of the peripheral part of the implant bulk material might be considered as the surface. In physical terms, the surface could be defined as the outermost layer, which is only a few nanometres thick. In many titanium implants, the pristine thickness of the TiO_2 layer varies from 10 to 100 nm [37] and can rise to micrometres in anodized implants [27,38]. In the classification system presented here, the surface will be defined as the 100-nm-thick superficial layer of the implant. Following this definition, in an implant surface coated with a micrometre thick layer of hydroxy-apatite (HA), the HA coating should be considered as the surface core material.

Tools of analysis

The exact definition of the atomic composition of a surface typically requires different spectroscopy techniques. Osseointegrated implant surfaces often present a rugged topography at the micro- and nanoscale, which results in challenging scenarios for appropriately controlled angulation for the spectral analytical beam. Thus, only three types of analyses are particularly suitable and should be utilized to evaluate the chemical composition.

X-ray photoelectron spectroscopy (XPS), also termed electron spectroscopy for chemical analysis (ESCA), is used to determine accurately the quantitative mean atomic composition (given as a percentage) [39] of wide and thin round surface areas (typically 300 μm in diameter, 5–7 nm depth). XPS can also determine the chemical state of detected elements, such as the different oxidative states of phosphorus in phosphates, and thus allows us to characterize the core material after chemical modification [35].

Auger electron spectroscopy (AES) is less accurate than XPS, but is able to analyze considerably smaller areas of <10 nm in diameter, which is ideal to confirm the chemical homogeneity of a surface [36]. Coupled with an ion sputter source, AES can perform an in-depth chemical profiling of the surface, particularly the first 100 nm [35]. It is thus particularly useful for the characterization of a thin coating on a core material or a deep impregnation within a TiO_2 layer.

Energy dispersive X-ray spectroscopy (EDX) is a simple elemental analysis that can be coupled to scanning electron microscopy (SEM) to determine the elemental composition of specific surface areas down to the nanoscale, and thus, to identify particles or structures observed with SEM.

Surfaces modification: impregnation, coating, pollution.

Chemical or biochemical modifications of the surface core material can be either superficial or integrated, which is accounted for in the modification categories impregnation (residual, low or high) and coating (continuous, discontinuous, sprinkled), as summarized in Table 1.

Impregnation here implies that the chemical or biochemical adjuvant is fully integrated within the core material architecture, and is thus detected as a stable component during in-depth profile with AES and not detectable during morphological analysis with SEM, even at the highest possible resolution. For example, calcium phosphate crystals within the TiO_2 layer of a surface can be considered as impregnated [34]. Different degrees of impregnation can be distinguished. A maximal threshold of 1% and 5% chemical modification of the core material for respectively residual and low impregnation appears relevant [34,35,39]. The concept of high impregnation also implies a true chemistry modification of the TiO_2 layer, as often observed with anodized implants. However, these thresholds are quite theoretical since the percentages of atomic composition of a surface are dependent on the carbon environmental contamination [35].

Coating, on the other hand, means than the chemical or biochemical adjuvant remains only superficially associated with the core material (even if partial impregnation might be unavoidable) [40]. Discontinuous and sprinkled coatings can be detected easily using EDX during SEM morphology, while a continuous coating is revealed more clearly using AES depth profiling.

However, as previously explained, the definition of coating and core material might become difficult in some cases. Following our previously defined terminology, coatings that are thicker than 100 nm would be considered core material. For example, a 300-nm thick calcium phosphate IBAD coating is considered as a calcium phosphate core material without chemical modification [31], whereas a 30-nm-thick CaP IBAD coating constitutes a chemical modification of a core material using CaP [40]. Although these two different IBAD-coated surfaces might appear similar, they exhibit very different osseointegration performances [32].

A final issue is how to classify contamination or pollution of the surfaces. Such pollution may have a significant impact on the biological results, and is easily detectable during XPS analysis. If environmental CO_2 and nitrogen contaminations from the air are unavoidable and normal to a reasonable level [35,39], inadequate surface treatment and implant handling (during packaging for example) can lead to severe organic contamination (indicated by a thick carbon overcoat on the implant) or high inorganic pollution with unexpected ions (magnesium, sulfur, silicon, calcium, zinc) [39]. This kind of surface pollution is typically inhomogeneous across the implant, and should not be mistaken for controlled chemical or biochemical modifications.

Crystalline structure: the missing parameter

The major core materials used in implants (TiO_2, zirconia, HA) all show specific crystalline architecture. TiO_2 may be found in the amorphous phase or in three main crystal forms (anatase, rutile, brookite) on an implant surface, with very different ratios [37]. The rutile form is the most common and stable, but the surface treatment considerably influences the crystal composition and structure of the surface [38,41]. X-ray diffraction (XRD) allows us to determine these structural parameters, such as the proportions in various crystalline phases, the main crystal orientation, grain size, crystallinity and strain [32]. Currently, these parameters were almost never assessed in commercially available surfaces, and may be added to the classification if relevant data are reported in the future [42,43].

Topography

The topography of a surface is characterized typically by a succession of peaks and valleys, which can be quantified using either 2D profiles or 3D parameters (Box 1), although 3D evaluation is more exhaustive than 2D [15,44]. Micrometric and nanometric features should be characterized separately.

Defining microscale features

At the microscale, the topography of an implant surface can increase the contact surface between the bone and the implant, and consequently, the biomechanical interlocking between bone and implant [15]. However, bone biology relies on a specific anabolism/catabolism turn-over, and bone formation and bone remodelling require spaces greater than 50 μm [45]. Consequently, the functional osseointegrated area is considerably lower than the theoretical surface developed area [2]. Moreover, the effects of the various patterns of microtopography on osseoconduction and bone apposition are still unclear and require more investigations.

Microstructures are defined by their number of dimensions (Table 1). Microrough surfaces have one micrometric dimension (the peak heights). Micropatterns have two micrometric dimensions (dimensions of the repetitive pattern), such as the micropores created by anodization (Figure 1a). Microparticles have three micrometric dimensions.

Box 1. Key surface parameters for the quantitative description of implant surface topography

2D Profile evaluation

- **Ra.** Roughness average of profile (amplitude parameter), defined as the integral of the absolute height values of peaks and valleys along the evaluated profile.
- **Rz.** Vertical parameter: mean height from peak to valley along the roughness profile.
- **Rsm.** Horizontal parameter: average interpeak distance along the roughness profile.

3D Surface evaluation

- **Sa.** Amplitude parameter: average surface height deviation amplitude, calculated on 2D standards extended to 3D standards.
- **Sds.** Spatial parameter defined as the density of summits, i.e. the number of peaks per area. This parameter is sensitive to noisy peaks and should be interpreted carefully.
- **Sdr%.** Hybrid parameter integrating both the number and height of peaks on a determined surface, and expressing the spatial density. Sdr is defined as the developed interfacial area ratio and expresses the increment of the interfacial surface area relative to a flat plane baseline. For a totally flat surface, Sdr = 0%. When Sdr = 100%, it means that the roughness of a surface doubled its developed area.

The roughness of osseointegrated implants is classified commonly into four categories based on the amplitude of the mean height deviation (Sa) of a surface area (Table 1) [15,23]. The roughness category should always be complemented with parameters that describe the exact nature of the microstructures (rough, patterned, particled), as well as the spatial density (flattened out, rugged), as defined in Table 1.

Defining nanoscale features

At the nanoscale, a more textured surface topography increases the surface energy. A high surface energy increases its wettability to blood, and the spreading and binding of fibrin and matrix proteins. It thus favours cell attachement and tissue healing, particularly directly after implantation, which is an important point in the osseointegration process. Nanotopography might also directly influence cell proliferation and differentiation, because it has been suggested that nanopatterning can modulate cell behaviour [46–50].

By definition, all surfaces show nanotopography, but not all of them have significant nanostructures. A nanostructure is an object of intermediate size between molecular and micrometre-sized structures, and often defined between 1 and 100 nm. When fully describing nanostructures, it is necessary to differentiate between the number of nanoscale dimensions (Table 1). Nanotextured surfaces have one dimension at the nanoscale (peak height), which can also appear in repetitive and homogeneous forms as nanoroughness or nanorugosity (Figure 1d) [34]. Nanopatterns have two nanoscale dimensions, that is, the dimensions of the repetitive pattern are nanometric. Examples of these are nanotubes produced by anodization (Figure 2) [51,52], or chemically produced nanopatterned surfaces [48,53]. Nanoparticles have three nanoscale dimensions, that is, each of their three spatial dimensions is in the nanometre range (Figure 2).

Repetitiveness and homogeneity are key parameters to define the nanostructure of an implant surface, but these are difficult to quantify and are considered qualitative morphological parameters. If nanostructures are not clearly visible (no patterns, no particles, insignificant texture) or not homogeneous and repetitive, the surface should be considered as nanosmooth (Figure 1b).

Tools of analysis

At least three analytical methods are used commonly to assess the topography of an implant surface.

Atomic force microscopy (AFM) can in theory resolve the surface topography at near-atomic resolution, but it is less useful for osseointegrated surfaces that are microrough, because their microtopography significantly interferes with the vertical piezoelectric AFM scanning probe, which makes any quantitative assessment unreliable [44]. Nevertheless, AFM can allow us to differentiate surfaces with different degrees of nanotexturing and can be valuable if used as a qualitative method [36].

Light interferometry (IFM) is an efficient tool for the evaluation of the quantitative parameters of the microtopography of large areas, but it requires a standardized evaluation method and filtering technique [44]. The microroughness of the surface might interfere with the light beams and cast a shadow on its nanotopography, similar to AFM, thus the use of IFM for an evaluation of the nanotopography requires an original filtering approach [23,54]. Moreover, commercially available osseointegrated implant surfaces are often not homogeneous across their entire range, and it has thus been suggested to use repetitive measurements with IFM to define the global mean values related to the microtopography of a dental implant [44].

SEM is the gold standard for morphology characterization at the micrometre level (SEM with tungsten source). Field emission (FE)-SEM is required to increase the analytical resolution and to observe and characterize the nanotopography and associated nanostructures (Figures 1 and 2) [34,54]. Coupled to an auxiliary EDX detector, this technique also allows us to identify efficiently the elemental composition of the observed structures. Coupled with a metrology software, this tool allows us to perform both morphology characterization and topography quantification (i.e. quantitative morphology), both at the micrometre [34] and the nanometre level.

The above three techniques are complementary. During the characterization of a topography, the key issue is to select the adequate tools and methods to evaluate standardized qualitative and quantitative parameters.

Global architecture: fractals, homogeneity, cracks

Several features should also be considered in this codification system, such as the presence of cracks (Figure 1a) or the heterogeneity of the topography across the implant [35], as detailed in Table 1. The fractal architecture should also be assessed, since this concept is particularly interesting in surface and materials science [55]. Natural fractals are repetitive patterns that are self-similar across a finite range of scales. Many biological structures are fractal or fractal-like [56]. Its influence and relevance on biological tissue response is unknown, but implant surfaces might reveal this type of repetitive patterns at the micro-, nano- and crystal scales during quantitative morphology.

A classification system to highlight the biological outcomes

Despite the extensive literature in the field of osseointegrated surfaces, the lack of a hierarchical approach and standardized parameters makes it difficult to evaluate the significance of the effect that the numerous topographic and chemical modifications have on implant performance [1,2,57]. Despite this, some basic information can be drawn regarding the main biological outcomes of the various surface characteristics.

In titanium surfaces, the biological effects of surface chemistry are related mainly to the architecture of the TiO_2 layer [29]. As osseointegration is related directly to the dynamic thickening of the TiO_2 layer, implants with thick TiO_2 layers, such as anodized implants, exhibit a strong bone response in that they increase the bone mineral matrix precipitation on the implant surface. However chemical modifications can also induce strong bone responses. The objectives of impregnation or coating with inorganic elements are thus to stimulate the biochemical interlocking between bone matrix and the TiO_2 layer,

through precipitation of bone mineral or proteins on the surface, and perhaps through direct cell stimulation. Calcium phosphate impregnation [34] and coating [33] have been investigated widely and have shown good bone responses, but the exact underlying mechanisms and the optimum calcium phosphate levels and incorporation methods clearly appear not to be consensual. High impregnation with phosphorus [58] or magnesium [25,26] also significantly increases bone response, and low fluoride impregnation [59,60] appears to stimulate bone cell differentiation through direct cell signalling pathways ; nevertheless, the exact mechanisms remain unclear. Finally, the biological outcomes of the crystal architecture might also be highly significant, as was previously shown for implants that were covered with titanium in anatase form [42,43]. However, these latter parameters have almost never been investigated for commercially available implant surfaces.

It thus appears that there are many ways to improve the bone response chemically, but the exact biological outcomes of an individual modification are often not clear, because chemical and physical parameters are often interrelated, but frequently not completely characterized [61]. Many published results might thus be debatable and there is no clear consensus regarding the underlying biological mechanisms.

There is a greater consensus in the field with regard to the relevance of physical modifications, because the biological outcomes presumed to be related to the microtopography of an implant have been investigated widely for commercially available implants, despite the lack of standardized terminology, methods or parameters of analysis [57]. A large number of investigations have demonstrated that stronger bone responses are obtained with moderately rough surfaces (Sa, 1–2 μm) compared to surfaces in other categories. However, the significance of this observation is in fact limited because it is only based on an amplitude parameter (Sa or Ra). The correlation between biological outcome and a spatial parameter, such as Sds or Sdr% (See Box 1 for definitions), in a given microtopography remains unclear [57]. Moreover, the biological effects of microroughness and microporosity have not been investigated accurately.

The effects of the nanotopography on the biological response are almost entirely unknown for commercially available implants [23]. Nanofeatures of the most important commercially available dental implants have been assessed only recently [54], and any prior data have not considered the potential impact of nanostructures on the performance of these implants. A few experimental studies already have shown that modulation of the nanotopography of an implant surface has a significant impact on the behaviour of bone cells [47–49]. It might even be possible to design specifically a desired nanotopography to increase and control bone cell proliferation and even differentiation [62]. We thus anticipate that this topic will be discussed widely in the near future.

As mentioned above, to date, implant surfaces have been classified simply by the way they are produced (e.g. grit-blasting, acid-etching, anodization) and not by their detailed chemical and physical features [2]. In many studies, surface characterization is thus not as exhaustive as could be wished, which has led to incomplete and potentially biased data, and to difficulty in cross-evaluating the numerous studies available and performing meta-analysis [57]. Using a simple characterization code for each tested surface, it should become possible to correlate data from the literature in a relevant and standardized way, and thus help to better understand and interpret the published results. This simple tool might be particularly useful to establish an inventory of surface-related osteogenic behaviours, particularly in the field of bone tissue engineering that requires an accurate library of knowledge [63].

Conclusions

The classification system proposed here is based on standard analytical methods and a well-defined terminology. The objective of this system is to give a clear and standardized overview of the main surface characteristics of a given implant surface using a simple characterization code, and to allow comparisons between studies. This approach will allow us to improve and deepen our knowledge about implant surfaces, and is a significant step towards establishing a clear link between surface characteristics and biological responses. It is also a prerequisite for the development of new 'intelligent' surfaces for which all chemical and physical parameters are optimized to control bone cell behaviour through surface contact.

In the future, it is anticipated that this classification will be completed and eventually modified. The characterization of the crystalline surface architecture might be the next upgrade of this codification. With a clear and defined codification system in hand, the first step will be to characterize all main commercially available implant surfaces accordingly, and to call for detailed technical sheets accompanying any future implants, which will provide the potential user with invaluable information, and thus might further the field by a more transparent and clear definition of the products.

Disclosure of interest

Like most specialists in the area of implant surface research, the authors of this paper are involved currently in experimental studies with a number of dental implant companies. This classification article thus does not aim to give qualitative opinions and is strictly founded on physical and chemical definitions, to avoid any conflict of interest. This work has not been supported by grants from any commercial companies.

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