Fractal Patterns Applied to Implant Surface: Definitions and Perspectives

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Fractal patterns are frequently found in nature, but they are difficult to reproduce in artificial objects such as implantable materials. In this article, a definition of the concept of fractals for osseointegrated surfaces is suggested, based on the search for quasi-self-similarity on at least 3 scales of investigation: microscale, nanoscale, and atomic/crystal scale. Following this definition, the fractal dimension of some surfaces may be defined (illustrated here with the Intra-Lock Ossean surface). However the biological effects of this architecture are still unknown and should be examined carefully in the future.

Key Words: dental implant, fractals, osseointegration, titanium

Fractals are mathematical objects where a pattern (line, surface, or volume) is repeated in different sizes, so that finally each part of an entire object looks similar at different scales; this characteristic is called self-similarity. Mathematical fractals are theoretical infinite objects following an exact self-similarity at each scale of observation, and they are used as tools for mathematical modeling in many fields, such as electronics, meteorology, and economics. However, this concept can be extended to nonmathematical objects, and these natural fractals are defined as repetitive patterns self-similar (or quasi- or statistically self-similar in most cases) across a finite range of scales.

These natural fractal objects are found everywhere around us: clouds, mountain chains, river networks, trees, ferns, snowflakes, sea waves, and even the design of the coastlines.[1] The degree of self-similarity is more or less loose depending on the object. The fractals in nature are very intriguing, and the concept of the "fractal nature of nature" is often discussed.[2] Moreover, many biological structures are fractal or fractal-like. For example, the organization of the cytoplasm is considered fractal.[3] Other simple examples are the organization of the vascular network and the pulmonary alveoli. In this last example, it is interesting to point out that the pulmonary alveoli stop their fractal subdivisions when they reach the specific functional size for the ideal circulation of the oxygen molecule (at normal body temperature).[4] Pulmonary alveoli do not look like perfect mathematical fractals, but in nature fractal architecture is rarely mathematically perfect and often seems calibrated to a specific function.[4] The fractal organization of a natural object and its biological functions are interlinked and may even codefine each other.

For all of these reasons, the concept of the fractal architecture of nature is particularly interesting in material science. Its influence and relevance on biological tissue response is unknown, but the fractal organization is thought to be more natural, and therefore more efficient. For example, the

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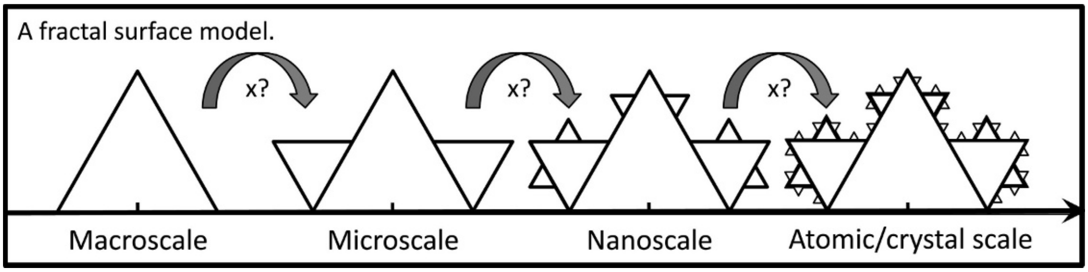

FIGURE 1. Following the classification system published in 2010, a fractal surface model can be defined as the repetition of a characteristic (or quasi-self-similarity) at the 3 scales of investigation (microscale, nanoscale, and atomic/crystal scale). The concept may be extended to the macrocharacteristics of the surface.

fractal architecture of trabecular bone is often used to explain its unique biomechanical properties,[5] and some authors have tried to use the fractal dimension of bone to evaluate its healing and remodeling.[6]

The application of this concept in implant surfaces, however, is far from simple. Dental implants are manufactured devices and therefore their characteristics are defined by various human engineering processes.[7–10] Some authors have tried to use fractal models to explain the atomic organization of materials such as metallic glasses,[11] but the determination of a clear model of fractal surface for a human-designed material remains uncertain, mainly because we are lacking a clear definition of what such a surface should be. The concept of fractal architecture in dental implant surfaces has already been debated,[12] as most metrological tools available (eg, reconstruction softwares for light interferometry or for scanning electron microscopy) try to define the apparent mathematical fractal dimension of the analyzed areas. But the tools have notable physical limitations (eg, inadequate definitions or reconstruction artifacts) and cannot investigate the different scales of a surface simultaneously. Therefore, the values given by these softwares for implant surfaces are mathematical abstractions, artifacts, or illusion of the metrology and do not have a clear conceptual justification. In order to find and maybe design a fractal dimension in these engineered materials, it is first necessary to clarify and define a relevant fractal concept in implant surface science.

In a recent classification system, a novel approach was suggested[13] that requires further discussion and clarification. This new concept requires consideration of the main characteristics of each surface at each scale: micrometric, nanometric, and atomic/crystal (Figure 1). Each scale has a specific relevance for the biological properties of the surface. The microtopography influences the biomechanical anchoring of the implant. The nanotopography modulates the surface energy and therefore the surface/protein interactions. The chemical organization of the material influences the chemical interlocking between the surface and the calcified tissues. Moreover, at each scale the characteristics influence the cell behavior.[13]

These 3 scales have been investigated widely in implant surface research and are therefore well-defined levels of biological interaction. A fractal surface could thus be defined as a surface where the same pattern is repeated at each scale of investigation. A good example would be a microrough surface that also presents a significant nanoroughness and a crystal/atomic modification (eg, with a calcium phosphate or fluoride impregnation); that is, each scale has a one-dimension modification, as illustrated in Figure 2 with the Ossean (Intra-Lock, Boca Raton, Fla) surface.[14] When considering this definition and the classification table previously published,[13] many combinations ap-

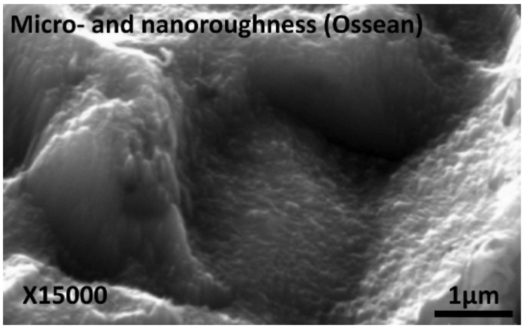

Figure 2. As shown in the 2010 classification article, the Intra-lock Ossean surface is a good illustration of fractal architecture. This scanning electron microscope picture clearly shows the nanoroughness covering the valleys and flanks of the microtopography. On the atomic scale, calcium phosphate low impregnation is detected. Three levels of self-similarity can therefore be defined.

pear possible for designing a fractal surface. This definition also implies that the characteristics of the surface at each scale (microtexture, nanotexture, chemical composition) are homogeneous all over the surface.

This system remains theoretical but has the advantage of giving a first definition of the fractal concept for surfaces in implantable materials. This notion of fractal architecture could even be extended to the macroscale (Figure 1), as the macrodesign of the implants plays a very significant role in the biological response and osseointegration process.[15–21] The next step is to determine the fractal dimension between each scale (the ''x?'' factor in Figure 1) and to investigate the effect of the variation of this dimension on the biological reactions. The topic is particularly interesting for in vitro tissue-engineering applications, where materials have to be designed and engineered very accurately in order to tailor cell growth and differentiation patterns. This may also be an interesting concept for the production of a new range of dental implant surfaces based on the fractal concept but with various dimensions and chemical modifications. As the general physiological conditions of the patients (eg, smoking habits,[22,23] diabetes,[24] nutrition,[25] stress[26]) play a significant role in the success of the osseointegration, the surface parameters may be tailored to optimize bone healing in different physiological environments. This concept offers many possibilities which require a careful testing and validation.[27]

If it is finally shown that the fractal architecture of implantable materials has a significant biological effect, it may open a new era in the design and conception of these materials. And the question of the ''fractal nature of nature'' will be even more intriguing.

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