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Ultrasonic characterization and multiscale analysis for the evaluation of dental implant stability: A sensitivity study

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ABSTRACT

With the aim of surgical success, the evaluation of dental implant long-term stability is an important task for dentists. About that, the complexity of the newly formed bone and the complex boundary conditions at the bone-implant interface induce the main difficulties. In this context, for the quantitative evaluation of primary and secondary stabilities of dental implants, ultrasound based techniques have already been proven to be effective. The microstructure, the mechanical properties and the geometry of the bone-implant system affect the ultrasonic response.

The aim of this work is to extract relevant information about primary stability from the complex ultrasonic signal obtained from a probe screwed to the implant. To do this, signal processing based on multiscale analysis has been used. The comparison between experimental and numerical results has been carried out, and a correlation has been observed between the multifractal signature and the stability. Furthermore, a sensitivity study has shown that the variation of certain parameters (*i.e.* central frequency and trabecular bone density) does not lead to a change in the response.

1. Introduction

A correct evaluation of dental implant stability is crucial for surgical success. First of all, two types of stability are of interest: (i) primary or mechanical stability and (ii) secondary or biological stability. Primary stability is reached during the implant placement, while secondary stability occurs after bone remodeling and osteo-integration. It is proven that long-term anchorage of a dental implant depends on the quantity and quality of the surrounding bone tissue, the peri-implant bone. Indeed, the bone remodeling occurring at the bone-implant interface [8] leads to changes in the bone mechanical properties [14]. From a mechanical point of view, modeling difficulties are mostly due to the complexity of newly formed bone tissue (a complex, anisotropic, porous-viscoelastic medium in constant remodeling), to its multiscale and time-evolving nature [7], but also to the boundary conditions at the bone-implant interphase. This means that primary and secondary stabilities are affected by several parameters, as bone quality, bone density or amount of bone in contact with the implant.

In literature, ultrasound based techniques have already been proven to be effective in the quantitative evaluation of primary and secondary stabilities of dental implant [15,16,18–21], for both experiments and numerical simulations. The technique is based on the following assumptions: (i) dental implants act as wave guides for ultrasounds; (ii) propagation in wave guides is considerably affected by changes in boundary conditions, *i.e.* by different levels of stability. The objective is to inspect the ultrasonic response of the implant information and correlate it to the evolution of stability, by using signal processing techniques. As already pointed out, the ultrasonic response depends on parameters like bone structure, geometry or mechanical properties, which, *in vivo*, all vary in parallel, and whose effect on stability is not clear. Thus, with the aim of analyzing the effect of these parameters, mechanical modeling is a key resource. Indeed, numerical simulation is advantageous with respect to experiences because it can perform, in a controlled manner, a sensitivity analysis with respect to parameters such as bone density and stiffness.

Now, two main issues arise: (i) how to evaluate the specific signature left from the aforementioned parameters on the signal and (ii) the extraction of the information.

Therefore, the signal issued from the measurements is complex. In recent studies developed by our group, the envelope of the signal

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has been taken into account in signal processing (see *e.g.* [20]). In the literature, similar irregular and complex biological data have already been approached with fractal and/or multifractal analysis [4,9,10], with the aim of characterization and classification of complex signals. In order to analyze the signal in its wholeness, more advanced signal processing techniques based on wavelet techniques have been introduced in the context of multifractal analysis; but we will use them with a slightly different purpose since, as we will see, multifractal analysis as such cannot be performed for such signals.

Following the technique employed in [15,16,18–21] different levels of implant stability will be artificially induced by a progressive unscrewing on the dental implant. This configuration has been used in both experimental and numerical analysis. The numerical results are obtained by using the finite element method.

This paper is structured as follows. After this introduction, Section 2 introduces the geometrical configuration of the problem (for which, with the aim of simplifying calculations, an axisymmetric geometry has been considered) and then provides the axial symmetric equations of motion; also the Finite Element (FE) analysis is introduced. Then, Section 3 presents a rapid overview on the wavelet based multiscale analysis. Section 4 is devoted to the presentation and discussion of the obtained results. Finally, Section 5 sets out conclusion and some perspectives.

2. Modeling wave propagation in the bone-implant system

2.1. Geometrical configuration and governing equations

The geometrical configuration reported in Fig. 1 shows the axial symmetry with respect to the implant central axis. According to that, an axisymmetric 2D model has been used. A contact planar transducer is placed on the emerging surface of the implant. A double-layer structure of a cortical bone 1 mm thick and an half-space of trabecular bone compose the considered bone model. In the geometrical configuration shown in Fig. 1, the titanium dental implant commercialized by Implants Diffusion International (IDI1240, IDI, Montreuil, France), with a length of L = 11.5 mm and a diameter of D = 4 mm, is recreated. In addition, a specific healing abutment is inserted in the upper part of the implant. When the implant is totally inserted in the bone specimen, as it is in the configuration considered in this work, we deal with the typical clinical set-up. In the present study, volume forces are neglected and it is assumed that all the considered media exhibit isotropic homogeneous mechanical properties.

The cylindrical coordinates are used and designated by (r, θ, z).

The axisymmetric equations of motion in each subdomain are the following:

$$\rho \ddot{u}_r - \frac{\partial \sigma_{rr}}{\partial r} - \frac{1}{r}\frac{\partial \sigma_{rz}}{\partial z} - \frac{\sigma_{rr} - \sigma_{\theta\theta}}{r} = 0, \tag{1}$$

$$\rho \ddot{u}_z - \frac{\partial \sigma_{zz}}{\partial z} - \frac{\sigma_{rz}}{r} = 0, \tag{2}$$

where ρ stands for the mass density, u_r and u_z represent, respectively, the radial and axial components of the displacement vector; σ_{rr}, σ_{rz}, $\sigma_{\theta\theta}$, σ_{zz} are the components of the stress tensor $\boldsymbol{\sigma}$; furthermore, the double dot indicates the temporal second partial derivative. According to Hooke's relation, the constitutive relation for an isotropic homogeneous material can be expressed as:

$$\boldsymbol{\sigma} = \frac{E\nu}{(1+\nu)(1-2\nu)} \quad \mathrm{Tr}(\boldsymbol{\epsilon})\mathbb{I} + \frac{E}{(1+\nu)}\boldsymbol{\epsilon}, \tag{3}$$

where E and ν are Young's modulus and Poisson coefficient, respectively, Tr() is the trace operator of a tensor, $\mathbb{I}$ is the identity tensor

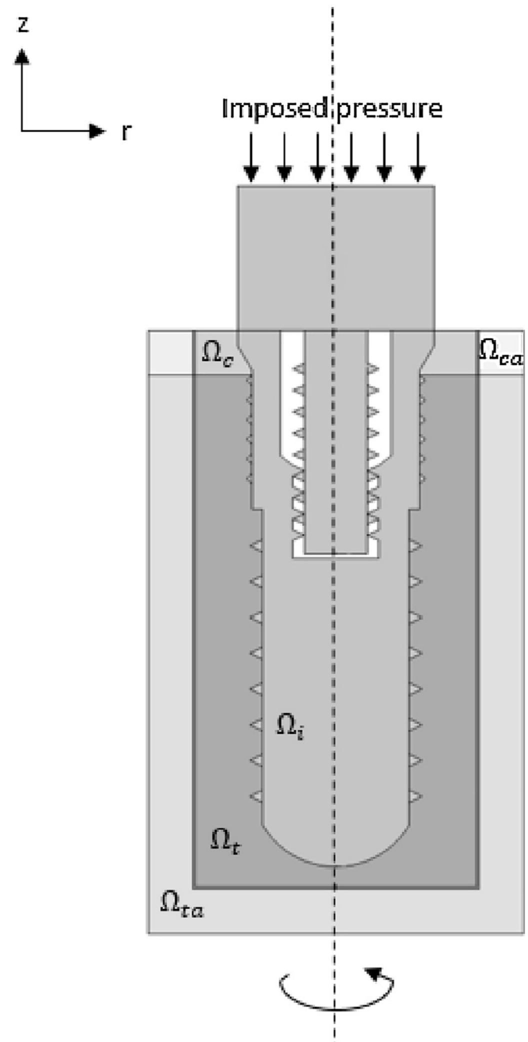

Fig. 1. Cross-section view of the 3-D axisymmetric geometrical configuration used in the numerical simulations. The domains are denoted with a subscript corresponding to the trabecular bone (Ω_t), the cortical bone (Ω_c), the implant (Ω_i), and the absorbing layers associated to trabecular and cortical bone (Ω_{ta} and Ω_{ca}, respectively).

and $\boldsymbol{\epsilon}$ is the strain tensor whose non-zero components are given by:

$$\epsilon_{rr} = \frac{\partial u_r}{\partial r}, \quad \epsilon_{\theta\theta} = \frac{u_r}{r}, \quad \epsilon_{rz} = \frac{1}{2}\left(\frac{\partial u_r}{\partial z} + \frac{\partial u_z}{\partial r}\right), \quad \epsilon_{zz} = \frac{\partial u_z}{\partial z}. \tag{4}$$

Young's modulus has been considered to be related to the density ρ according to the following power-law relation [5]:

$$E = E_0\left(\frac{\rho}{\rho_0}\right)^{1.96}, \tag{5}$$

where the subscript $_0$ indicates the reference values for the Young's modulus and the density.

The contact planar transducer, placed on the upper emerging surface of the implant specimen (see Fig. 1), generates a signal corresponding to a time pulse uniform pressure whose temporal history is expressed as follows:

$$p(t) = A\left[\exp -4(f_c t - 1)^2\right] \times \sin(2\pi f_c t), \tag{6}$$

where A is the amplitude, f_c is the pulse central frequency and t is the time.

The continuity of displacement and stress fields between the subdomains is imposed. Moreover, in order to prevent the non-