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Reflection of an ultrasonic wave on the bone-implant interface: Comparison of two-dimensional and three-dimensional numerical models

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Abstract: Quantitative ultrasound is used to characterize osseointegration at the bone-implant interface (BII). However, the interaction between an ultrasonic wave and the implant remains poorly understood. Hériveaux, Nguyen, and Haiat [(2018). *J. Acoust. Soc. Am.* **144**, 488–499] recently employed a two-dimensional (2D) model of a rough BII to investigate the sensitivity of the ultrasonic response to osseointegration. The present letter aimed at assessing the validity of the 2D assumption. The values of the reflection coefficient of the BII obtained with two and three-dimensional models were found not to be significantly different for implant roughness lower than 20 μm . 2D modeling is sufficient to describe the interaction between ultrasound and the BII.

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1. Introduction

The evolution of the biomechanical properties of the bone-implant interface (BII) is the main determinant of the implant success (Mathieu *et al.*, 2014). The use of quantitative ultrasound (QUS) is a promising method to retrieve information at the BII since it is noninvasive, relatively cheap, and does not involve ionizing radiations. The principle relies on the dependence of the ultrasonic propagation within the implant on the boundary conditions given by the properties of the BII (Mathieu *et al.*, 2012). *In vitro* (Vayron *et al.*, 2018b) and *in vivo* (Vayron *et al.*, 2014, 2018a) studies have proven the potentiality of QUS to evaluate dental implant stability and have evidenced a better resolution compared to the resonance frequency analysis technique, which is currently used in clinical practice.

Despite the good performances of QUS techniques, it remains difficult to control the different parameters influencing the interaction between an ultrasonic wave and the rough BII since they may vary simultaneously. Acoustical modeling is the only way to gain a further understanding of the interaction between ultrasonic waves and the BII. Recently, a two-dimensional (2D) finite element model was developed to investigate the sensitivity of the ultrasonic response to surface roughness properties of the BII and to osseointegration processes (Hériveaux *et al.*, 2018, 2019). The implant roughness was first modeled by an idealized sinusoidal profile (Hériveaux *et al.*, 2018) and then by actual implant roughness profiles (Hériveaux *et al.*, 2019). Osseointegration phenomena were simulated by progressively reducing the thickness of a soft tissue layer comprised between the bone and the implant. Using the 2D model is interesting from a computational viewpoint but the plane strain assumption is a strong approximation when considering the effect of the implant surface roughness.

The aim of the present study is to quantify to what extent a 2D model can accurately describe the interaction between ultrasound and the BII. To do so, a three-dimensional (3D) model using a bi-sinusoidal implant roughness was considered herein. Results were then compared to the ones obtained from the 2D model developed in Hériveaux *et al.* (2018).

2. Material and methods

2.1 Description of the problem

Two coupled half-spaces separated by an irregular interphase were considered. The first half-space represents an implant made of titanium alloy (Ti-6Al-4V) and the other one represents

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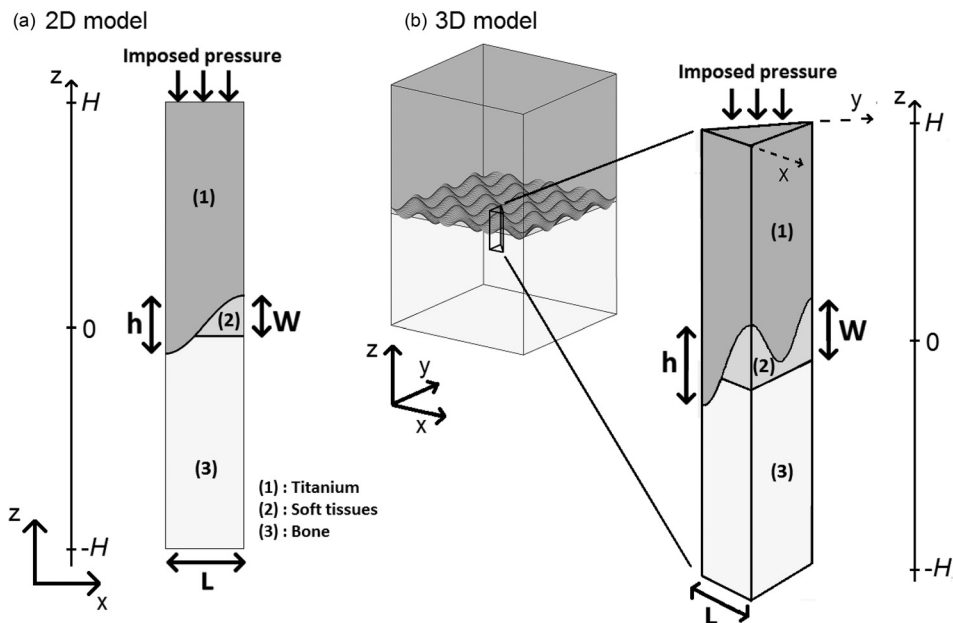


Fig. 1. (a) Schematic illustration of the 2D model used in numerical simulations. (b) Schematic illustrations of the geometrical configuration of the BII and of the 3D model used in numerical simulations.

cortical bone tissue, as shown in Fig. 1. Figure 1(a) represents the 2D model developed in Hériveaux *et al.* (2018). Figure 1(b) represents the 3D model introduced in the present study. The implant surface roughness was modeled by a bi-sinusoidal function $s(x,y)$ of amplitude h and half-period L given by

$$s(x,y) = \frac{h}{2} \sin\left(\frac{\pi x}{L}\right) \sin\left(\frac{\pi y}{L}\right). \quad (1)$$

Due to the symmetry of the problem, 3D simulations were performed on a triangular prism corresponding to a single half-sine period of the interface, i.e., for $x \in [(-L/2); (L/2)]$ and $y \in [(-L/2); -x]$ as represented in Fig. 1(b). Symmetric boundary conditions were applied to the surfaces parallel to the direction z by imposing zero displacements following the normal direction of the lateral surfaces. As shown in Fig. 1, a layer of soft tissue was introduced between the cortical bone and the implant in order to model non-mineralized fibrous tissue that may be present at the BII in the case of non-osseointegrated implants (Heller and Heller, 1996) and/or immediately after surgery. The thickness W of the liquid layer decreases when osseointegration processes increase at the BII.

The acoustical source was modeled as a broadband ultrasonic pulse with a uniform pressure $p(t)$ applied at the top surface of the implant domain (see Fig. 1) defined by

$$p(t) = A e^{-4(fc t - 1)^2} \sin(2\pi f_c t), \quad (2)$$

where A is an arbitrary constant (all computations are linear) representing the signal amplitude and $f_c = 10$ MHz is its central frequency.

The total lengths of the domains corresponding to the implant and to cortical bone ($H = 3$ cm) were chosen to be able to distinguish the signal reflected from the interface and to avoid any reflection from the boundaries of the simulation domain.

All materials considered in this model were assumed to have homogeneous isotropic mechanical properties. The values used in the present study for the different media are shown in Table 1 and were the same as in Hériveaux *et al.* (2018, 2019).

Table 1. Material properties used in the numerical simulations.

	C_p (m s ⁻¹)	C_s (m s ⁻¹)	ρ (kg m ⁻³)
Soft tissue	1500	10	1000
Titanium	5810	3115	4420
Cortical bone tissue	4000	1800	1850

The governing equations have been described in detail in [Hériveaux et al. \(2018\)](#) and the reader is referred to this publication for further details.

2.2 Finite element simulation

The system of dynamic equations was solved in the time domain using the commercial finite element software COMSOL Multiphysics. The implicit direct time integration generalized- α scheme ([Chung and Hulbert, 1993](#)) was used to calculate the transient solution. The elements size was chosen equal to $\lambda_{\min}/10$, where λ_{\min} corresponds to the shortest wavelength in the simulation subdomain. In the 2D model, the implant and bone subdomains were meshed by structured quadrangular quadratic elements, and the soft tissue subdomain was meshed with triangular quadratic elements. In the 3D model, all the domains were meshed with tetrahedral quadratic elements. The time step was chosen using the stability Courant–Friedrichs–Lewy condition $\Delta t \leq \alpha \min(h_e/c)$ where $\alpha = 1/\sqrt{2}$, h_e is the elements size and c is the slowest wave velocity in the considered subdomain. For simulations presented here, the time step is set at $\Delta t = 4 \times 10^{-10}$ s. The duration of the simulations was equal to 1.5 μ s.

2.3 Signal processing

To determine the reflection coefficient, the signals representing the displacement along the direction of propagation (z -direction) obtained with the 2D model (respectively, 3D model) were averaged over a line (respectively, over a surface) perpendicular to the direction of the incident wave and located at the top of the titanium implant. The first measured signal corresponds to the average incident signal, noted $s_i(t)$. The second one corresponds to the averaged reflected signal, noted $s_r(t)$. The moduli of the Hilbert’s transform of $s_i(t)$ and $s_r(t)$ were computed, and the maximum amplitudes of these envelopes are noted A_i and A_r , respectively. The reflection coefficient in amplitude is determined using

$$R = A_r/A_i. \tag{3}$$

R_{2D} (respectively, R_{3D}) denotes the reflection coefficients obtained using the 2D (respectively, 3D) model.

2.4 Comparison between 2D and 3D models

The comparison between the reflection coefficients obtained with the 2D and 3D models was realized based on the difference of the reflection coefficients computed for a set of parameters composed of 10 values of h , 4 values of L , and 14 values of W , which is listed in Table 2.

For each combination of surface roughness amplitude h_i ($i \in [1, 10]$) and half-period L_j ($j \in [1, 4]$), the reflection coefficient $R_{2D}(i, j, k)$ [resp. $R_{3D}(i, j, k)$] was determined for $W = W_k$, $k \in [1, 14]$ with the 2D model (resp. with the 3D model). An error function $e(h_i, L_j)$ was defined in order to assess the difference between the ultrasonic response of the 2D and 3D models following:

$$e(h_i, L_j) = \sum_{k=1}^{14} \frac{|R_{2D}(i, j, k) - R_{3D}(i, j, k)|}{14}. \tag{4}$$

3. Results

Figure 2 shows the variation of the reflection coefficients R_{2D} and R_{3D} as a function of the soft tissue thickness W for different values of h . The dependence of R_{2D} and R_{3D} with respect to W is qualitatively similar for all values of h . However, the difference between R_{2D} and R_{3D} increases when h increases. Figure 3 shows the variation of the error function e as a function of h for different values of L . The results further confirm that e increases as a function of h for all values of L . Moreover, except for values of h/L relatively close to 1, e increases as a function of L . In all cases, the value of e within the considered range of geometrical parameters is always lower than 0.03, which corresponds to the case $L = 90 \mu$ m and $h = 50 \mu$ m (see Fig. 3).

Table 2. Values of the geometrical parameters used in the numerical simulations.

	Values considered
Surface roughness amplitude h (μ m):	{1; 3; 5; 10; 15; 20; 25; 30; 40; 50}
Surface roughness half-period L (μ m):	{50; 70; 80; 90}
Soft tissue thickness W (μ m):	{0; 2; 5; 10; 15; 20; 25; 30; 40; 50; 60; 70; 80; 100}

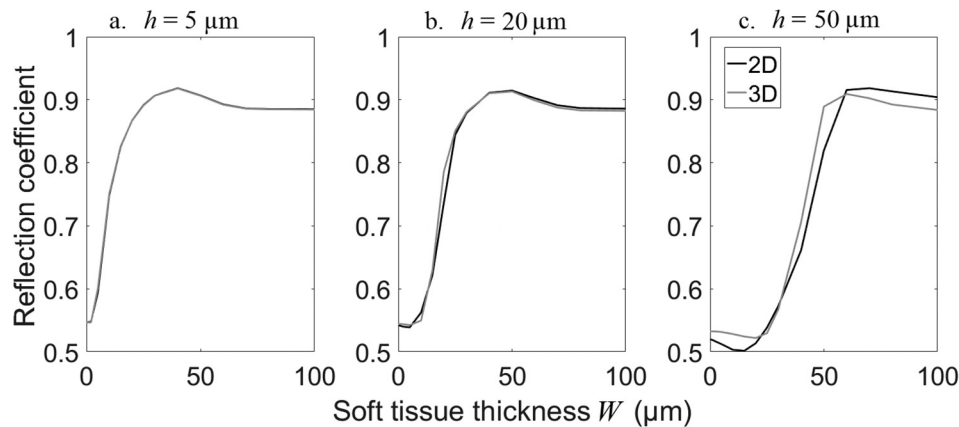


Fig. 2. Variation of the reflection coefficients R_{2D} and R_{3D} of the BII as a function of the soft tissue thickness W for roughness parameters $L = 50 \mu\text{m}$ and (a) $h = 5 \mu\text{m}$, (b) $h = 20 \mu\text{m}$, and (c) $h = 50 \mu\text{m}$.

4. Discussion

The originality of this study is to consider a 3D description of the BII and to compare the effect of the different roughness parameters and of the osseointegration level on the ultrasonic response of the BII with results obtained with a 2D model.

Figures 2 and 3 show that the difference between R_{2D} and R_{3D} increases when h increases. When the interface is perfectly smooth ($h = 0$), the 2D and 3D models lead to the same exact results. Therefore, the difference between the 2D and 3D cases increases as a function of h , which may explain the increase of e as a function of h . Although significant, the dependence of e as a function of L is relatively weak. Note that the behavior of e as a function of L is different for low values of L ($L = 50 \mu\text{m}$), which may be explained by the fact that multiple scattering becomes significant when h/L becomes close to 1 (Hériveaux *et al.*, 2018). However, the difference between R_{2D} and R_{3D} remains below 0.03 for all values of h and L considered. The average experimental error ε corresponding to the determination of the reflection coefficient was found to be around 0.011 (Mathieu *et al.*, 2012). The difference between results obtained with 2D and 3D models for values of h lower than $20 \mu\text{m}$ is lower than the experimental error (see Fig. 3). Implants with sand-blasted (Strnad and Chirila, 2015) or laser modified surfaces (Orsini *et al.*, 2000; Hériveaux *et al.*, 2019) have typical arithmetical mean roughness R_a comprised between 0.9 and $5 \mu\text{m}$, which corresponds to values of h between 3 and $16 \mu\text{m}$. Consequently, for standard values of implant roughness, the 2D modeling of the BII should be sufficient to derive an accurate description of its ultrasonic response in reflection.

The influence of the anisotropy of surface profiles on the ultrasonic response of the BII was investigated. The variation of the reflection coefficient as a function of the soft tissue thickness for surface profiles with an amplitude of $h = 20 \mu\text{m}$, a value of L in the x direction equal to $L_x = 50 \mu\text{m}$ and 4 different values of L in the y direction L_y comprised between 25 and $100 \mu\text{m}$ was shown to be relatively weak (lower than 0.03). The anisotropy of surface profiles seems to play a minor role on the ultrasonic response of the BII when considering the values given above. Note that isotropic surface profiles correspond to the main configuration of interest when

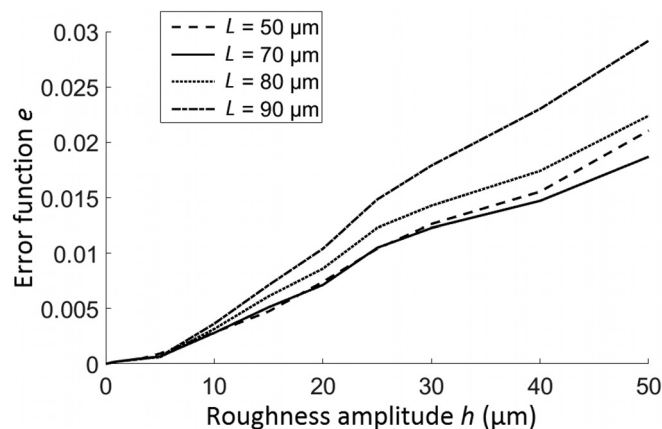


Fig. 3. Variation of the cost function e as a function of the roughness height h for different values of roughness half-period L .

considering the BII (Nouri and Wen, 2015), in particular because usual implant surface treatments such as sand-blasting or acid-etching lead to isotropic surface profiles (Albrektsson and Wennerberg, 2019). Goransson and Wennerberg (2005) investigated the influence of surface profile anisotropy on osseointegration phenomena and found that no significant difference could be evidenced between the osseointegration of implants with isotropic or anisotropic surface profiles. Therefore, the development of implants with anisotropic profiles remains scarce.

This study has several limitations. First, a sinusoidal function of amplitude h and half-period L is used to describe the implant surface roughness, similar to what was done in Hériveaux *et al.* (2018). Taking into account real surface as it was done in Hériveaux *et al.* (2019) is likely to lead to different results, and the equivalence between 2D and 3D models in this configuration still needs to be confirmed. However, a real 3D surface would require a much more complex meshing process and important associated computational costs. Second, only the normal direction of propagation from the implant to the bone tissue was studied because it corresponds to the experimental situation of interest (Mathieu *et al.*, 2012). Future studies should account for oblique incidences, and the equivalence between 2D and 3D models needs to be confirmed in this case.

5. Conclusion

This study validates the use of a 2D model of the BII developed in Hériveaux *et al.* (2018) by showing a good equivalence between 2D and 3D sinusoidal models. The values of the reflection coefficient of the BII obtained with both models were found not to be significantly different for implant roughness lower than $20\ \mu\text{m}$. Therefore, 2D modeling is sufficient to describe the ultrasonic propagation at the BII. The results obtained in the present study lead to a better understanding of the interaction between an ultrasonic wave and the BII, which could help to improve the use of QUS to characterize the BII.

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