Quantitative ultrasound can be used to characterize the evolution of the bone-implant interface (BII), which is a complex system due to the implant surface roughness and to partial contact between bone and the implant. The aim of this study is to derive the main determinants of the ultrasonic response of the BII during osseointegration phenomena. The influence of the surface roughness parameters and the thickness $W$ of a soft tissue layer on the reflection coefficient $r_o$ of the BII was investigated using a two-dimensional finite element model.

When $W$ increases from 0 to 150 µm, $r_o$ increases from values in the range [0.45; 0.55] to values in the range [0.75; 0.88] according to the roughness parameters.

This numerical approach provides a better understanding of the ultrasonic response of the BII, which may be used in future numerical simulation realized at the scale of an implant.

Keywords: bone-implant interface, rough interface, osseointegration, quantitative ultrasound, finite element modeling

1. Introduction

The evolution of the implant biomechanical stability is the main determinant of the surgical success [1] and is directly related to the biomechanical properties of the bone-implant interface (BII) [2, 3].

Biomechanical techniques such as impact methods [4, 5, 6, 7] or resonance frequency analysis [8-10] have been applied ex vivo and in vivo to investigate the BII properties. In an ex vivo study using a coin-shaped implant model [11], the reflection coefficient of a 15 MHz ultrasonic wave interacting with the BII significantly decreases as a function of healing time, which may be explained by a decrease of the gap of acoustical properties at the BII related to a combined increase of i) the bone-
implant contact (BIC) ratio, ii) the bone Young’s modulus [12] and iii) bone mass density [13, 14]. More recently, a 10 MHz QUS device was validated first ex vivo using cylindrical implants [13], then in vitro using dental implant inserted in a biomaterial [15] and bone tissue [16] and, eventually, in vivo [17]. The sensitivity of this QUS device on changes of the periprosthetic bone tissue was shown to be significantly higher compared to the resonance frequency analysis in vitro [18] and in vivo [19]. These last results may be explained by a better resolution of the QUS device to changes of periprosthetic bone tissue compared to vibrational approaches.

A better understanding of the interaction between an ultrasonic wave and the BII could help improving the performances of QUS techniques. However, the various parameters influencing the interaction between an ultrasonic wave and the BII (such as periprosthetic bone quality and quantity) are difficult to control when following an experimental approach. Therefore, acoustical modeling and numerical simulation are useful because the influence of the implant and bone mechanical and geometrical properties can be precisely assessed.

A two-dimensional finite difference time domain (FDTD) method [20] and 3-D axisymmetric finite element model (FEM) have been used to model the ultrasonic propagation in a cylinder shaped implant [21] and in a model considering a more realistic geometry of a dental implant [22]. However, the aforementioned studies considered a fully bounded BII and did not account for a combined effect of the surface roughness and bone ingrowth around the implant. Since osseointegration was only modeled through variations of the biomechanical properties of periprosthetic bone tissue, the influence of the BIC ratio could not be considered either. More recently, a 2-D FEM has been developed to investigate the sensitivity of the ultrasonic response to multiscale surface roughness properties of the BII and to osseointegration processes [23]. The implant roughness was modeled by a simple sinusoidal profile and the thickness of a soft tissue layer comprised between the bone and the implant was progressively reduced to simulate osseointegration phenomena. Although the sinusoidal description of the surface profile may be adapted at the macroscopic scale because it is close to mimicking implant threading, it constitutes a strong approximation in the microscopic case because the surface roughness has random characteristics.

The aim of this paper is to model the interaction between an ultrasonic wave and a rough BII considering actual surface roughness.

2. Material and methods

The numerical model considered herein was similar to the one employed in [23, 24]. Briefly, two coupled 2-dimensional half-spaces were separated from each other by an interphase. The first domain corresponds to the implant made of titanium alloy (Ti-6Al-4V, noted (1) in Fig. 1) and the other one represents bone tissue (noted (3) in Fig. 1). The implant surface profile was defined by the results obtained using profilometry measurements, as shown in Fig. 1.
Fig. 1: Schematic illustrations of the 2-D model used in numerical simulations for an original roughness profile.

A soft tissue layer was considered between bone and the implant (noted (2) in Fig. 1) in order to model non-mineralized fibrous tissue that may be present at the BII just after surgery or in the case of non-osseointegrated implants [25]. The thickness $W$ of the soft tissue layer was defined as the distance between the highest point of the surface profile and the bone level, as shown in Fig. 1. A progression of osseointegration is associated to a decrease of the value of $W$.

All media were assumed to have homogeneous isotropic mechanical properties. The values used for the different media were taken from [24, 26-29].

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:

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

where $A$ is an arbitrary constant (all computations are linear) representing the signal amplitude and $f_c$ is its central frequency, which was set to 10 MHz throughout the study as it corresponds to the value used in the QUS device developed by our group [13, 15-19]. Moreover, the results obtained in [23] indicate that using a frequency equal to 10 MHz allows guaranteeing an acceptable sensitivity of the ultrasound response on changes of the biomechanical properties of the BII (a resolution of around 2-12 $\mu$m depending on the implant roughness was obtained).

The reflection coefficient was determined for each simulated configuration. To do so, the signal corresponding to the displacement along the direction of propagation was averaged along a horizontal line located at the top of the titanium implant. The signal corresponding to the averaged incident (respectively reflected) signal was noted $s_i(t)$ (respectively $s_r(t)$). The reflection coefficient in amplitude was determined following:

$$r_0 = A_r/A_i,$$  \hfill (2)  

where $A_i$ and $A_r$ are respectively the maximum amplitudes of the envelopes of $s_i(t)$ and $s_r(t)$ obtained using the modulus of their respective Hilbert’s transform.

The roughness profiles of each implant were obtained using a contact profilometer (VEECO Dektak 150) on a 2 mm long line for each sample. Different parameters were used to describe the roughness profiles: the average mean roughness $R_a$, the mean spacing between irregularities $S_m$, the maximum profile peak height $R_p$, and the maximum profile valley depth $R_v$. 


3. Results

Figure 2: Variation of the reflection coefficient $r_o$ of the bone-implant interface as a function of the soft tissue thickness $W$ for six implants with laser-modified surfaces roughness profiles.

Figure 2 shows the variation of the reflection coefficient $r_o(k)$ obtained for different roughness profiles as a function of the soft tissue thickness $W_k$, $k \in [0,12]$. Figure 2 shows the results obtained for the surface profiles corresponding to implants with laser-modified surface, which have a relatively low surface roughness. The results obtained with the different surface profiles are qualitatively similar. The values of $r_o$ first increase as a function of $W$ from 0.54 to a maximum value equal to around 0.92. Then, $r_o$ slightly decreases as a function of $W$ and tends towards 0.88 for all the profiles considered. However, an increase in $r_o$ occurs for smaller values of $W$ when considering surfaces with lower roughness. Similarly, the maximum value of $r_o$ is reached for lower values of $W$ when considering surfaces with lower roughness. The maximum peak height $R_p$ of the surface profile seems to have a higher influence on the variation of $r_o$ than the average roughness amplitude $R_a$, because the roughness profiles with similar $R_p$ lead to approximately similar ultrasonic responses. Note that the values of the reflection coefficient $r_o(0)$ obtained for $W_0 = 0$ (respectively $r_o(13)$ for $W_{13} = 100 \, \mu m$) correspond to the analytical values obtained for a planar bone-implant interface (respectively liquid-implant interface) and are weakly affected by the profile roughness.

4. Discussion

The originality of this study is to consider a realistic description of the bone-implant interface and to analyze the effect of the different roughness parameters and of osseointegration phenomena on the ultrasonic response of the BII. The reader is referred to [24] for further details on the present study.

Previous numerical studies [21, 22] have investigated the variation of the ultrasonic response of the BII during the osseointegration process, which was modeled by a variation of bone properties around the implant. In these two previous papers, a fully bonded BII and an absence of osseointegration were the two cases considered. The effect of the microscopic implant roughness was not accounted for.
[23] is the only study investigating the impact of microscopic implant roughness on the ultrasonic response of the BII but a sinusoidal profile was then considered. The variation of $r_a$ as a function of $W$ obtained in [23] in the case of a microscopic roughness is in qualitative agreement with the results of the present paper (see Fig. 2).

Different experimental studies have also evidenced the effect of osseointegration phenomena on the ultrasonic response of the BII. In particular, the effect of healing time on the ratio between the amplitudes of the echo of the BII and of the water-implant interface was studied in [11] using implants with an average roughness of $R_a = 1.9 \, \mu m$, which is of the same order of magnitude as the implants considered in this study (see Fig 2). Mathieu et al. (2012) found a decrease of the apparent reflection coefficient of 7.8% between 7 and 13 weeks of healing time, which corresponds to an increase of the BIC from 27 to 69%. The model considered herein predicts that an increase of the BIC from 27 to 69% should result in a decrease of $r$ by 7.3% in the case $R_a = 1.52 \, \mu m$, and by 10.7%, in the case $R_a = 2.52 \, \mu m$, which is relatively close to the experimental results. However, some discrepancies could explain the differences between experimental results and numerical predictions. First, the present study does not consider the changes of the bone material properties, which are known to occur during healing [13, 14, 30] and which induce a concurrent increase of the reflection coefficient as a function of healing time [22]. Second, in the experimental configuration, the ultrasonic wave is not fully planar due to the use of a focused immersed transducer, which has not been considered in the present study. Despite these limitations, a good agreement is obtained between numerical and experimental results.

This study has several limitations. First, only normal incidence of the ultrasonic wave was considered as it corresponds to an experimental situation of interest [11, 17]. Second, adhesion phenomena at the BII [11], which may cause a non-linear ultrasonic response [31], were not considered herein. Third, the variation of the periprosthetic bone geometrical properties was modeled by a bone level given by the parameter $W$ and actual bone geometry around the implant surface is likely to be more complex. Note that typical BIC values are comprised between 30 and 80% [11, 17, 32, 33]. Therefore, fully bounded interfaces are not likely to occur in vivo. Moreover, bone properties are known to vary during osseointegration [13, 14, 30], which was not taken into account. Fourth, bone tissue was modeled as an elastic, homogeneous and isotropic material, similarly to what was done in some previous studies [20-22, 34], whereas real bone tissue is known to be a strongly dispersive medium [35, 36]. Moreover, although mature bone tissue is known to be anisotropic [34, 37], the anisotropic behavior of newly formed bone tissue remains unknown [12, 13]. Fifth, two-dimensional modeling of the BII was considered and the 3-D results may be different. Future works should focus on a 3-D description of the interface and on improving the modeling of osseointegration phenomena to derive a more realistic description of the interaction between ultrasound and the BII.

REFERENCES


