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MEASUREMENT OF THE PROPAGATION OF A GUIDED WAVE IN A DENTAL IMPLANT

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ABSTRACT

Ultrasound techniques can be used to characterize and stimulate dental implant osseointegration. The acoustical energy transmitted to the bone-implant interface is an important parameter for both applications since it should be sufficiently low to avoid damaging the surrounding tissues, but sufficiently high for stimulation purposes to enhance bone growth. However, the interaction between an ultrasonic wave and a dental implant remains unclear. The objective of this study combining experimental, analytical and numerical approaches is to investigate the propagation of an ultrasonic wave in a dental implant by assessing the amplitude of the displacements along the implant axis.

An ultrasonic transducer was excited in transient regime at 10MHz. Laser interferometric techniques were employed to measure the amplitude of the displacements, which varied between 3.2 to 8.9 nm according to the position. The results show the propagation of a guided wave mode along the implant axis with a first arriving signal velocity equal to 2110 m.s-1 and frequency components lower than 1 MHz, which was confirmed by the analytical and numerical results. This work paves the way to improve techniques for the characterization and stimulation of the bone-implant interface.

1. INTRODUCTION

Dental implants are routinely used in the clinic and have allowed substantial progresses in oral and maxillofacial surgeries [1]. However, a lack of implant osseointegration may lead to aseptic loosening and to surgical failures, which are difficult to anticipate [2]. The evolution of the implant biomechanical stability is a strong determinant of the surgical success [3] and may be assessed by measuring the biomechanical properties of the implant-bone interface (IBI) [4].

Biomechanical techniques such as impact methods [5, 6] or resonance frequency analysis [7] have been applied ex vivo and in vivo to investigate the BII properties. In an ex vivo study using a coin-shaped implant model [8], the reflection coefficient of a 15 MHz ultrasonic wave interacting with the IBI significantly decreases as a function of healing time, which may be explained by a decrease of the gap of acoustical properties at the IBI. More recently, a 10 MHz QUS device was validated first ex vivo using cylindrical implants [9], then in vitro using dental implant inserted in bone tissue [10] and, eventually, in vivo [11]. 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 [12] and in vivo [13].

Ultrasound and more specifically low intensity pulsed ultrasound (LIPUS) may also be employed to stimulate bone remodeling [14]. Different studies have shown the potential of ultrasound to stimulate osseointegration using animal models with dental implants [15-17]. More recently, an ultrasonic therapy was assessed clinically and confirmed that LIPUS can be used to promote dental implants osseointegration [18]. However, the precise mechanism of action of LIPUS remains poorly understood [19, 20] and strongly depends on the nature of the signal corresponding to the stimulation.

The amount of energy transmitted to the IBI is an important parameter for applications corresponding to the ultrasonic characterization and stimulation of the IBI. Concerning the characterization, the acoustical energy should be sufficiently low so that the tissues around the implant would not be damaged due to excessive micromotion which could be detrimental to osseointegration [21]. Concerning the stimulation, the acoustical energy must be sufficiently high to obtain a significant impact on the implant osseointegration.

However, the interaction between an ultrasonic wave and a dental implant still remains unclear due to the complex geometrical configuration. Numerical simulation of wave propagation in a dental implant [22] has already been carried out using finite element modeling, and the guided nature of the ultrasonic wave propagating in cylindrical implants has been evidenced [23]. However, no previous study was able to show whether guided waves could propagate in dental implants.

The aim of the present study is to investigate the interaction between an ultrasonic wave and a dental implant using experimental and numerical approaches.

2. MATERIAL AND METHODS

2.1 Dental implant

A 10 mm long and 4.1 mm diameter conical dental implant made of grade 5, Ti-Al6-V4 titanium alloy, was used in the present study. The implant was manufactured by Zimmer Biomet under the reference TSVT4B10. The geometrical configuration of the measurements is shown in Fig. 1. The implant was slightly polished locally on its extremity and laterally in regions of interest where laser ultrasonic measurements were carried out. Polishing was necessary to obtain a planar surface and therefore maximize specular reflection of the laser interferometer at the implant surface.

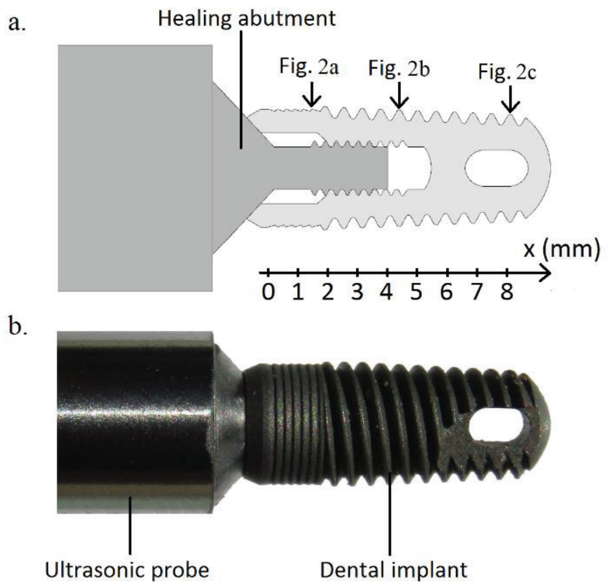

Figure 1: (a) Schematic representation of the experimental setup with an ultrasonic transducer screwed into a dental implant. The x-axis corresponds to the implant axis. Arrows represent the positions corresponding to the results shown in Fig. 2. (b) Ultrasonic probe and dental implant used experimentally.

2.2 Ultrasonic device

The ultrasonic device composed of a 5 mm diameter planar ultrasonic monoelement contact transducer was manufactured by Imasonic. It generates a broadband ultrasonic pulse propagating perpendicularly to its active surface. The probe was used in echographic mode. Its center frequency was equal to 10 MHz, with a frequency bandwidth approximately equal to 6–14 MHz. The probe was rigidly attached to a titanium alloy dental healing abutment with a 5 mm long threaded part, which can be screwed into the implant. The ultrasonic probe was connected to a pulse generator (Sofranel, model 5052PR) via a standard coaxial cable. The pulse excitation had an amplitude of 100V and a duration of 200 ns.

2.3 Laser-ultrasonic measurements

A laser interferometer (BMI SH 140), suited for the detection of ultrasound at the surface of cylinders with millimeter diameter [24, 25], was used in order to evaluate the amplitude of the displacements occurring at the implant surface. The displacements were measured at the extremity of the implant and at different positions along the implant axis. Only one channel was used for each measurement, which were made successively at each position. The surface of the implant where the displacements were measured was set perpendicularly to the axis of the beam of the laser interferometer so that the laser signal reflected by the implant could be correctly received by the laser interferometer. The size of the laser beam at the implant surface was about 100 µm. An oscilloscope was used to capture the signal given by the interferometer. Signals were averaged 500 times for each measurement. A calibration procedure allowed to derive the amplitude of the displacements at the surface of the implant and the frequency of the displacements was estimated from these signals.

Similarly as in [26], for all measured signals, the time of flight of the first arriving signal (FAS) was defined as the time for which signals first had an amplitude superior to a threshold equal to 0.5 nm, which is around 2.5 times higher to the magnitude of the noise.

2.4 Numerical simulation

The experimental configuration was reproduced numerically using a 2D axisymmetric model, corresponding to half of the schematic representation shown in Fig. 1a. The approach was detailed in [22] and is briefly reminded in what follows. All the boundaries of the implant and of the ultrasonic transducer were considered as free. All parts considered in this model were assumed to have homogeneous isotropic mechanical properties and to be composed of Ti-Al6-V4.

The acoustical source is modeled by a broadband ultrasonic pulse with a normal stress σ_{11} (t) applied at the top surface of the transducer defined by:

$$\sigma_{11}(t) = A\, e^{-4\,(f_c t-1)^2} \sin(2\pi\, f_c\, t) \qquad (1)$$

where A is an arbitrary constant representing the signal amplitude and f_c is its central frequency.

All simulations were performed in the time domain using a finite element software (COMSOL Multiphysics). Once the solution was obtained, the displacements were determined on the extremity of the implant.

3. RESULTS

3.1 Experimental measurements of displacements along the implant threading

Figure 2 shows the variation of the measured displacement as a function of time at three different locations along the implant threading. The peak-to-peak amplitude of the displacement as a function of time along the implant axis was comprised between 3.2 nm and 8.9 nm. Figure 2 shows that for each position, and especially towards the end of the threading (Fig. 2c), the most energetic contribution is of relatively low frequency and arrives at a relatively short time. This low frequency contribution corresponds to the main component of the ultrasonic wave, whereas the contributions issued from multiple reflections of the ultrasonic wave on the implant boundaries are less energetic and arrive later. Moreover, a wave propagation velocity of around 2110 m.s-1 was estimated by considering the evolution of the time of flight of the FAS as a function of the position of the measurement along the x-axis.

Figure 3 represents the frequency spectra associated to the three signals shown in Fig. 2. Most components of the spectra are comprised between 0 and 1.5 MHz. For each spectrum, energetic contributions are present around 300 kHz and 900 kHz. For relatively low values of x (Fig. 3a and 3b), an important number of contributions may be distinguished around 300 kHz and 900 kHz, while for higher values of x (Fig. 3c), the signal has fewer frequency components.

3.2 Numerical validation

The numerical validation of experimental results was performed through the comparison of displacements obtained at the extremity of the implant. Similarly as for experimental results, the frequency components of numerical data are lower than the central frequency of the excitation signal (f_c = 10 MHz). However, frequency components obtained numerically are higher than for experimental data, and are mostly comprised between 0 and 4 MHz.

4. DISCUSSION

4.1 Propagation of a guided wave in the implant

Figure 3 shows that the frequency spectra corresponding to the displacement measured experimentally are mainly composed of low frequencies (mostly between 300 kHz and 2 MHz) compared to the excitation central frequency (10 MHz). Figure 3 also shows that the amplitude of high frequency components tends to decrease along the implant axis. The observation of low-frequency components may result from the attenuation of the ultrasonic wave while propagating along the 1 cm long titanium implant. Although the frequency range obtained numerically is slightly higher than that obtained experimentally, the numerical results confirm that only low frequencies (mostly between 1 and 3 MHz) are obtained in the implant.

Moreover, the wave velocity of the FAS was experimentally assessed around 2110 m.s^{-1}, which is significantly lower than the bulk longitudinal velocity (Cp = 5810 m.s^{-1} in titanium alloys). These two results (slow and low frequency wave propagation) indicate the presence of a dispersive ultrasound wave guided by the implant structure.

4.2 Amplitude of displacements and transmitted energy

The experimental results show that the amplitude of the displacement always remains inferior to 10 nm, which is far from the critical level of micromotion (around 50 µm to 150 µm) that may prevent osseointegration [21].

Regulations from the US Food and Drug Administration (FDA) indicate an exposure limit of 720 mW/cm² for diagnostic ultrasound equipment [27]. In our case, the average intensity transmitted by the ultrasonic wave to the implant may be derived from [28]:

$$I = \frac{1}{2} Z_{Ti} v_m^2, \qquad (2)$$

where Z_{Ti} is the acoustical impedance of the titanium alloy and v_m is the particle velocity.

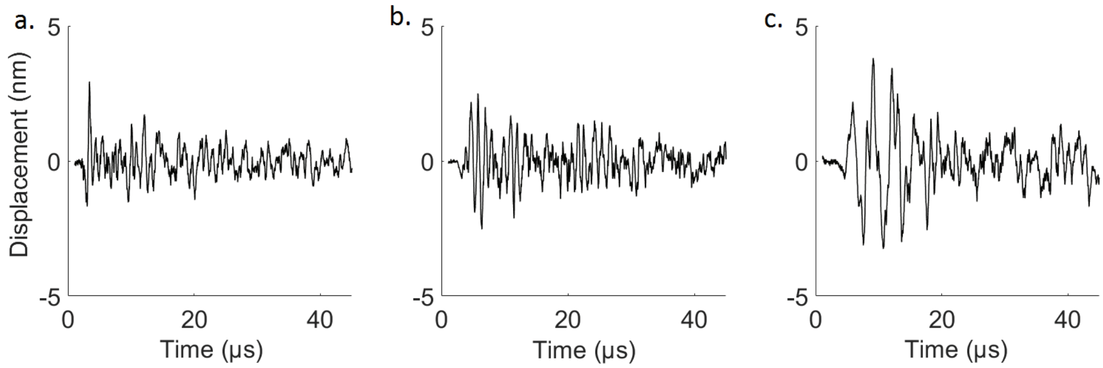

Figure 2: Variation of the displacement at the implant surface measured experimentally as a function of time (a) at the beginning of the threading (x = 1.5 mm), (b) at the middle of the threading (x = 4.35 mm), and (c) at the end of the threading (x = 8.3 mm).

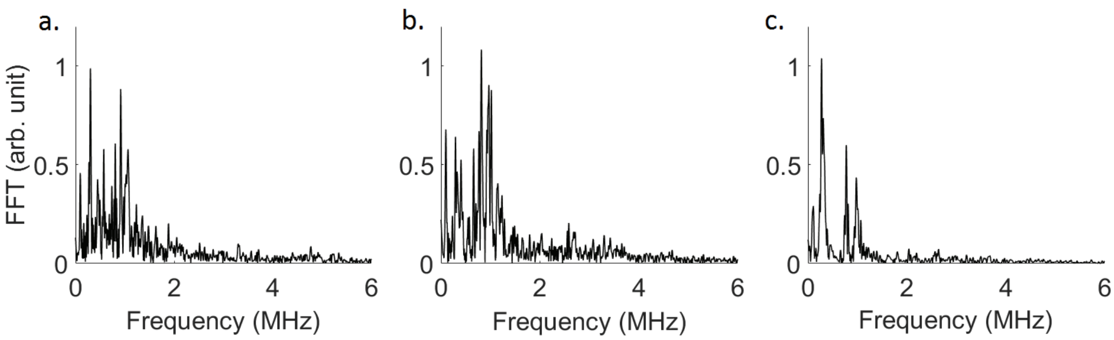

Figure 3: Frequency spectra corresponding to the modulus of the Fast Fourier Transform (FFT) of the signals measured experimentally (a) at the beginning of the threading (x = 1.5 mm), (b) at the middle of the threading (x = 4.35 mm) and (c) at the end of the threading (x = 8.3 mm).

Considering the particle velocity measured at the extremity of the implant (around 18 mm.s-1), the average intensity sent by the ultrasonic transducer is around 460 mW/cm², which therefore respects FDA requirements.

The excitation signal sent to the transducer is similar to the one used in previous studies by our group on the QUS device aiming at assessing implant stability [11, 12]. Most studies on LIPUS stimulation of implant osseointegration focused on lower intensities, around 30 or 40 mW/cm² [15, 16, 18], but applied during longer duration in the harmonic regime, while we worked in transient mode. Therefore, the amplitude of the displacement measured herein are not representative of displacements generated by LIPUS stimulation. However, the present study emphasizes that mechanical stimulation induced by ultrasound is highly sensitive to the geometrical configuration and provides an estimation of the energy sent by an ultrasonic wave to the IBI.

4.3 Limitations

This study has several limitations. First, the implant measured experimentally had been partially polished on one side, which removed a small part of its threading and may have influenced the results.

Second, the present study only considered the situation where the implant was surrounded by air. The values of displacement of the implant are likely to be lower when considering an implant surrounded by bone or by soft tissues, and the energy transmitted to these media would therefore be lower.

Third, several approximations have been made in the numerical model. In particular, the acoustical source was considered to have a uniform pressure. The geometry of the implant was also approximated, since real threading cannot be thoroughly axisymmetric. A 3D model would therefore depict more precisely the real configuration.

5. CONCLUSION

This study emphasizes that the propagation of an ultrasonic wave in a titanium dental implant is guided by the implant structure. For characterization purposes, the results indicate that it is not necessary to consider high frequency transducers since ultrasound propagate at frequencies comprised between 300 kHz and 2 MHz in the implant. For stimulation purposes, the results indicate that the intensity transmitted to the IBI is highly sensitive to the considered structure. The reader is referred to [29] for further details on the present study.

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