Investigating the Bone-Implant Interface Using Quantitative Ultrasound: A Numerical Approach

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Abstract

Introduction

The success rate of endosseous implants depends on their long-term stability, which relies on the osseointegration process, *i.e.* the creation of a bone-implant interface (BII). Such stability is determined by the quantity and the biomechanical properties (structure, composition and material properties) of bone tissues located around the implant surface. The temporal and spatial evolution of these biomechanical properties are not fully understood yet, and there is a need to develop techniques to assess them. For instance, Quantitative Ultrasound (QUS) is a nondestructive method sensitive to the mechanical properties of bone tissue. Recently, the interactions of ultrasonic waves with the BII have been shown to reflect the Bone Implant Contact (BIC) ratio (1). Nonetheless, the QUS *ex vivo* measurements performed with standardized implants immersed in water emphasized the difficulty to locally analyze osseointegration phenomena, because of i) limitations in controlling the bone distribution at the BII and ii) the relatively poor lateral resolution of QUS methods (around 1 mm). This study therefore aims to numerically replicate the experiment performed in (1) in order to improve our understanding of the interactions of ultrasonic waves with the BII in a controlled environment.

Methods

Specimens

We used an already existing standardized coin-shaped titanium implant model intended for animal experimentation with a planar BII (1-2), adapted for studying ultrasonic reflection phenomena at the BII. A Teflon ring around the implant creates a few hundred micrometers thick bone chamber in order to isolate newly-formed bone. After 12 weeks of healing in rabbit cortical bone, 8 implants were extracted and imaged with neutron tomography, to map the

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3D bone spatial distribution close to the implant (2). A reference BIC ratio was calculated from the first layer of bone in immediate contact with the titanium implant. The resulting 3D images are used as propagation domain in the numerical wave propagation model.

Elastic wave propagation model

The wave propagation model is decomposed into two coupled simulation domains. On the one hand, the wave propagation across the water path between the transducer and the implant is achieved using a semi-analytical model based on Green's functions. On the other hand, the wave propagation across the bone-implant system is carried out by solving the elastodynamics equations using an open-source finite-difference time-domain (FDTD) simulation software (3), by considering a 3D staggered grid where specific material properties are assigned to each voxel based on the neutron tomography maps. This coupled model is composed of three sequential steps described as follows:

- Semi-analytical emission and forward propagation of the focused pulse through the water domain, which delivers a pressure field.
- FDTD simulations: the pressure field from the previous step is used as input for the simulation of the interactions of the focused wave with the BII. After propagation of the elastic waves in the bone-implant system, an output pressure field is recorded.
- The backpropagation of the output pressure field from step 2 is calculated semi-analytically to reconstruct the acoustic response at the transducer location.

QUS maps

By spatially moving the transducer location in the plane parallel to the implant, we can reconstruct a 2D map of the maximum amplitude of the wave reflected at the BII for each of the 8 specimens. The post-processing of the map allows reducing the influence of the Teflon ring, thereby highlighting the bone distribution at the BII.

Results

The observed local decrease of the amplitude received between a non-osseointregated implant (before surgical insertion), and an implant harvested after 12 weeks of healing time is strongly correlated with the local bone quantity at the BII from the neutron microtomographic data. Non-osseointegrated areas of the BII and high concentration of mineralized tissues can then be straightforwardly discriminated. The averaged amplitudes of the 2D maps consistently decrease with the reference BIC ratio of the samples, leading to a coefficient of determination R^2=0.71 ($p < 0.01$), in accordance with the experimental results reported in (1).

Conclusion

The proposed coupled wave propagation model presents several advantages to address such complex configuration: i) it prevents numerical dispersion that would otherwise hinder such simulations if using numerical tools only and ii) it drastically reduces the computational burden thanks to the two semi-analytical steps. The present numerical approach underlines the sensitivity of the QUS technique to both bone quantity and spatial distribution at the BII from 3D high-resolution data, thereby confirming previously observed experimental evidence. Future works will aim to provide further insights into the correlation of the resulting QUS maps with the experimental data, by applying advanced signal processing techniques, such as spectral analysis or colocalization methods, to the acoustic response of the BII.

References

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