Modeling Interfacial Shear Strength at a CAP-Modified Titanium and Bone

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Statement of Purpose: An interfacial bond, which exceeds the cohesive strength of either bone tissue or implant, characterizes the bone bonding phenomenon attributed to calcium phosphate (CAP) materials but not to metals [1]. However, CAP plasma-sprayed metallic implants have also demonstrated clinical problems of inflammatory response and implant failure under loading [2]. For this reason, CAP-coated surfaces have been largely replaced by microtextured metallic surfaces. A new technology has been recently developed, comprising the discrete crystalline deposition (DCD) of calcium phosphate (CAP) nanoparticles (20-80nm nominal size) on the surface of a microtextured titanium implant. We have shown such small CAP nanofeatures render titanium implants bone-bonding [3]. We have also shown bone-bonding as a mechanical interlock rather than a chemical phenomenon [3]. For this reason, we designed a mathematical model to address the question: Can the bone-bonding phenomenon be achieved exclusively by micro-mechanical interlocking mechanism?

Methods: A two-dimensional finite element analysis (FEA) was implemented to model the bone-bonding interface using a commercial software ANSYS v8.1. A commercially pure titanium implant surface treated by a dual acid etch (H_2SO_4/HCl) method and subsequently by the CAP-DCD was chosen for the modeling. We made the following approximations and assumptions in the construction of the model: (1) the acid etched implant surface was simplified to a single semicircular feature with a diameter of 1μm, (2) a 40 nm thick uniform layer of TiO_2 was placed onto this surface, (3) 20 nanocrystals of CAP, also semicircular in shape, were uniformly distributed along the surface of the implant (4) bone tissue, of homogeneous character, filled up the rest of the concave implant surface (Fig.1) (5) no bonding or adhesion was assumed at the implant/bone interface, and (6) the TiO_2/bone and CAP/bone interfaces were modeled as frictionless contact surfaces by surface-to-surface contact elements (CONT172/TARGET169) with bone as the contact surface and TiO_2 and CAP as the target surfaces. The model was designed to predict whether failure of the bone or failure of the TiO_2/CAP interface would occur for a given tensile load. Failure of bone was assumed to occur if the local maximum equivalent von Mises stress exceeded the failure strength of 1.7 MPa measured in our in vivo experiment. Failure of the TiO_2/CAP interface was assumed to occur if the equivalent von Mises stress in the interface exceeded the average shear strength of 1.75 GPa. The interface stress was calculated as the average of the modal stress for the TiO_2 and CAP at the interface. The model was analyzed (1) by increasing applied loads until the failure criterion for bone or the TiO_2/CAP interface was met and (2) by maintaining the failure criterion for bone while decreasing failure criterion for the interface such that the interface would fail under applied load.

Results/Discussion: The load was determined to be 44 KPa when the maximum equivalent von Mises stress inside the bone was measured to be 1.7 MPa (Fig. 2), and that on the TiO_2/CAP interface was measured to be 1.02 MPa. This shows that the maximum von Mises stress will reach the failure criterion for the bone (1.7 MPa) before that for the TiO_2/CAP interface (1.75 GPa), and thus the fracture will first occur in the bone.
If we maintain the load and decrease the strength of the TiO_2/CAP interface to 1.02 MPa, which is 3 orders of magnitude lower than reported previously, the bone will remain intact and the TiO_2/CAP interface will fail.

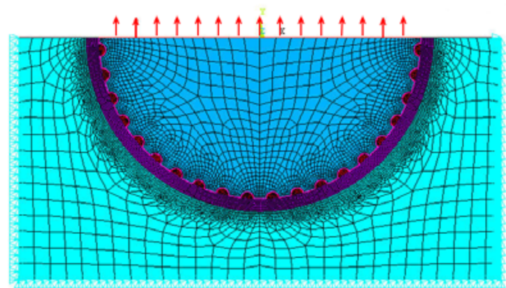

Figure 1. ANSYS model with meshing and uniformly distributed load pulling upwards.

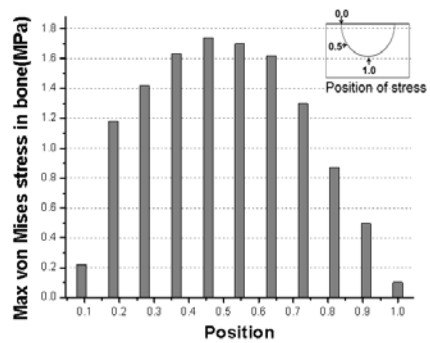

Figure 2. Stress distribution in bone at the failure (load = 44 KPa, E_{bone} = 17 GPa)

Conclusions: The model can withstand 44 KPa pressure due to mechanical interlocking, and shows that the bone-bonding phenomenon can be achieved exclusively by micro-mechanical interdigitation. The results also indicate that the bone will fail before the TiO_2/CAP interface, which is in accordance to our in vivo experimental results.

References: 1. Hench & Wilson. Science 1984; 226:630-636. 2. Geesink et al. J Bone Jt Surg. 1992; 74:534-547 3. Mendes & Davies (2006). 25th Meeting Canadian Biomaterials Society.

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