The mechanical advantages of a bilayer ceramic scaffold for bone tissue engineering

Teja Guda, MR Appleford, S Oh, JL Ong
The University of Texas at San Antonio.

Introduction: Hydroxyapatite (HA) is known to be osteoconductive as it mimics native bone mineral. However, an ideal mix of porosity and strength, which is determined by the three dimensional architecture of the construct, is an essential requirement towards the development of bone graft substitutes. It is required that HA with ideal mix of porosity and strength can be functional under physiological conditions and thus allowing for complete incorporation and regeneration of functional bone tissue. Mimicking the cortical-cancellous architecture of human bone in tissue engineering scaffolds will enable the matching of both permeability and strength for custom site specific bone graft replacement design. As such, mechanical properties and optimization of bilayer scaffolds were investigated in this study.

Methods: Highly porous HA scaffolds were fabricated by twice coating polymer sponge templates with HA slurry, followed by sintered to 1230 C to ash the polymer template. To mimic natural trabecular bone, polymer templates were chosen such that the final scaffolds had three different pore sizes: 250, 340 and 450 µm. These trabecular samples were tested as is or paired with three different volume ratios (25:75, 35:65, 50:50 inner core to outer shell volume) of a denser (250 µm pore size) outer shell to prepare a bilayer scaffold.

All scaffolds were characterized in terms of their mechanical properties. The scaffolds were tested in pure compression in displacement control mode at a 0.125 mm/min. To analyze the explained differences in the load bearing capacity of the scaffold architectures and the advantage of the bilayer design, finite element analysis was used for the 25:75 volume ratio bilayer design compared to the purely trabecular design. The elastic moduli for the materials were those obtained experimentally from testing.

Results: The mechanical strength of the purely trabecular architectures (100:0 volume ratio) as compared to the bilayer architectures (volume ratios 50:50, 35:65 and 25:75 trabecular to cortical shell) are shown in Fig 1. All bilayer scaffold designs were significantly stronger than the corresponding purely trabecular design.

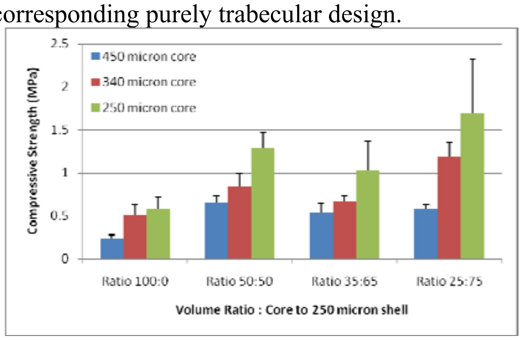

Fig 1. Compressive strength of the bilayer scaffold designs as compared to the purely trabecular design.

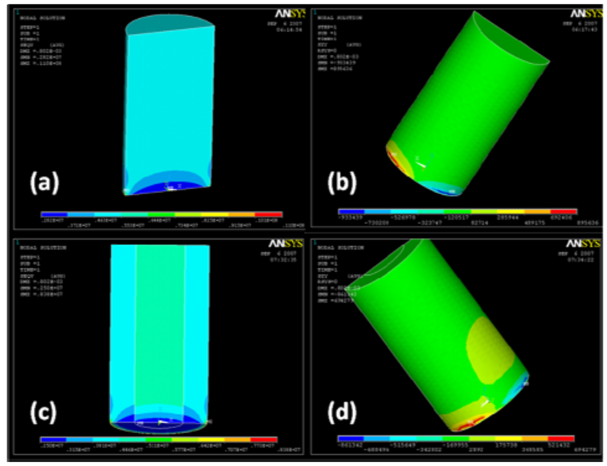

Fig 2. FEA results showing Von mises stress contours for the (a) trabecular and (c) bilayer as well as the shear stress profile for the (b) trabecular and (d) bilayer design.

Representative finite element analysis results are shown in Fig 2 for the 25:75 volume ratio of inner core to outer shell. It was observed that because of the difference in elastic moduli between the 250 µm (59 MPa) and the 450 µm (97 MPa), the load sharing discontinuity led to a 23% decrease in the effective Von mises stress transfer to the core and a 22% increase in the shear on the outer surface of the shell.

Discussion: The strength of the bilayer design was always significantly greater than the strength of the corresponding purely trabecular design ($p<0.05$). It was also observed that the 250 µm inner core which was paired with the 250 µm shell and served as a design control showed significantly greater strength than the purely trabecular design. The finite element analysis showed that the bilayer design resulted in the transmission of lesser effective stress to the weaker inner cores, and thus ensuing in the observed increase in strength. This was further validated by observations that the bilayer designs primarily failed by vertical crack initiation and spiral fracture crack growth (in the direction of loading) indicating significant shear stress effects while the trabecular architectures primarily failed in the more conventional horizontal crack growth and damage accumulation mode indicating tensile failure of individual struts.

Conclusions:

It was concluded that bilayer designs significantly increased the strength of HA scaffolds by a factor of 4 at high cortical shell volume ratios. Additionally, the improvement in mechanical properties in the bilayer design was attributed to changes in the effective load transmitted to the inner porous cores.