Finite Element Analysis of Patient-Specific 3D Printed Bone Graft for Vertical Alveolar Ridge Augmentation

Claudia Benito Alston[1], Nicanor Moldovan[2], Clark Barco[2], Luis Solorio[1]
[1]Weldon School of Biomedical Engineering, Purdue University, [2]Richard L. Roudebush VA Medical Center

Statement of Purpose: Oral and maxillofacial reconstruction, which is performed on 1.5 million patients worldwide each year, is required for a variety of intraoral and extraoral critically sized bone defects.[3,6] These defects can originate from accidental injuries such as a car accident, congenital conditions such as cleft palate or diseases such as osteosarcoma which cause maxillofacial malignancies.[5] The current standard of care uses particulates of freeze-dried allografts covered by a titanium mesh, which is then secured in place by screws. What limits this approach is its variability, the length of time the patient is exposed to potential infection during surgery, and although the highly packed allograft signals cells to differentiate along the osteogenic lineage, tight packing often leads to diminished bone healing as blood vessels may fail to form.[6] To address these fallbacks, a 3D printable, biodegradable and implantable device with patient-specific shape and a porous core-cover structure was designed. The cover will be porous for cell infiltration and will be expected to withstand up to 500 N, the average human maximum mastication forces.[4] The purpose of this study was to assess for the design's ability to withstand these forces depending on its porosity, cover material thickness, and elastic modulus of the core material to optimize the graft's geometry with respect to its biomechanical functions, prior to fabrication.

Methods: The initial design originated from open source stl files that were imported into Autodesk Meshmixer (San Rafael, CA) to model the patient-specific graft. Using the sculpting tool in Meshmixer, the defect was filled, the same way it would in surgery, then a 1mm cover was extracted to surround the core as well as go past it to allow for screw attachment without penetrating the core. The screw holes were pre-designed with the help of an expert periodontist to avoid having to bore a hole with the screw during surgery, causing crack propagation. The core was designed to make direct contact with the defect, allowing for cell infiltration and bottom-up osteointegration. The model was then imported into ANSYS 11.0 (Swanson analysis system, ANSYS, Canonsburg, PA). As a means of limiting the voxels in the model, only the half of the jaw with the graft was included. The simulation was modeled with bottom surface of the jaw being fixed and implementing 250 N of downward vertical force distributed along the teeth and graft. Half the total peak masticatory force was used, due to half the jaw being used for the simulation. Simplified bolt models were made of standard screws used for intraoral bone grafts of an alveolar ridge, Pro-Fix Tenting Screws (Osteogenics Biomedical, Lubbock, Texas). These were modeled with a bolt pretension of 1 N. The materials modeled were polycapralactone (PCL)[2] for 3D printing of the cover. The osteoinductive core was modeled as a printable tricalcium phosphate/hydroxyapatite ceramic paste. The entire jaw bone was modeled as compact bone[7], for simplicity, and titanium alloy Ti-6Al-4V was used for the screw properties.[1] For comparative purposes the cover was modeled both as solid and as a construct with 0.25mm sized pores, to allow for cell infiltration.

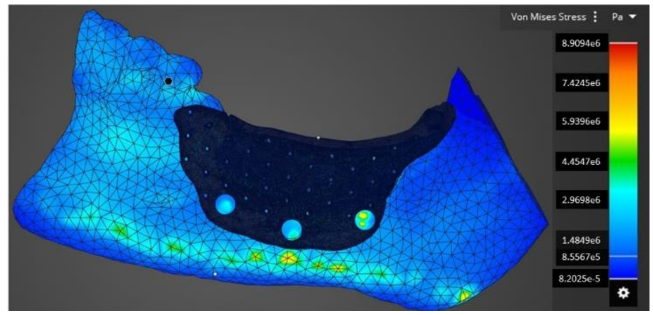

Figure: Bone graft and jaw bone Von Misses Stress showing a maximum on the screws and jaw of 8.91e6 Pa.

Results: After extensive iterative design of the cover, the simulation of the implantable device with both the porous and non-porous covers demonstrated no significant differences between these designs on the structural integrity of the model. A drawback to this model is that the pores caused the mesh contain 5X the number of voxels, slowing down the model. It is also worth noting that there doesn't appear to be any localized von misses stress maxima at the pores either, which indicates that they don't limit structural integrity. The maximum displacement in the porous cover is 3.11e-5 m whereas the solid cover possesses a maximum displacement of 18.624e-5 m. This may indicate an added structural effect of the pores by which they further distribute the downward force throughout the cover. This demonstrates the suitability of using the porous version of the cover, due to the additional benefit of allowing the diffusion of biological factors to support the osteoinductive role of the core. In conclusion, a cover thickness of 1mm, with 0.05mm thickening on the top ridge, pre-designed screw holes and 0.25mm distributed pores proved to maintain structural integrity under a chewing force of a healthy adult.

References: 1. (Bircan DA. Adv in Matls and Procs Tech. 2016;2(1):57-65), 2.(Eshraghi S. Acta Biomtlia. 2010;6(7):2467-2476.), 3. (Jonitz A, J Mater Sci Mater Med. 2011;22(9):2089-95.), 4. (Khan AA. Jrnl of Endo. 2007;33(6):663-666.), 5.(Liu M. Nanomtls. 2018;8(12):999.), 6. (Petite H, Natr Biotech. 2000;18(9):959-963.), 7.(Talmazov G. PLoS One. 2020;15(2):e0229360.