1. Werkstoffwissenschaftliche Tagung, 17 September 2009, Basel

Mechanical testing of 3D-printed scaffolds for bone augmentation

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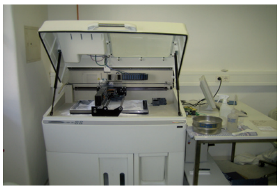
INTRODUCTION

Bone replacement with scaffolds is an established technique in the clinical routine. The macro-, micro- and nano-structural elements of many porous scaffolds resemble that of engineering foams, but do not follow the architecture of mechanically loaded long bone.

Nano-porous spray-dried hydroxyapatite hollow spheres as well as tri-calcium phosphate (TCP) powder in combination with anorganic binders can be used to realize 3D-printed scaffolds with micro-passages and macro-canals following the general architecture of long bones. Print quality and mechanical stability were tested by means of synchrotron-radiation based micro computed tomography (SRµCT) and mechanical loading tests.

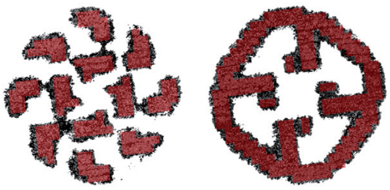
SCAFFOLD FABRICATION

Three different cylindrical designs were printed layer-by-layer with a multi-color 3D-printing system (Spectrum Z510, Z-Corporation, USA). Each design was fabricated in different sizes, corresponding to 100%, 125% 150%, 175% and 200% of the original design. As raw materials a powder mixture (di-calcium phosphate anhydrous and calcium carbonate) and 20% phosphoric acid as an anorganic binder has been used. The layer thickness was 125 µm and the binder-volume ratio corresponded to 0.371.

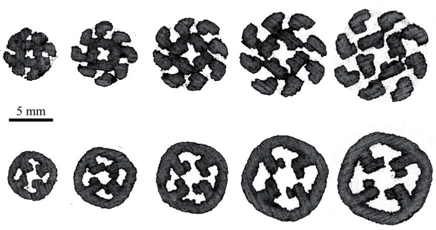


SRµCT

SRµCT allows for non-destructively imaging the internal structure of the scaffolds with high spatial and density resolution.

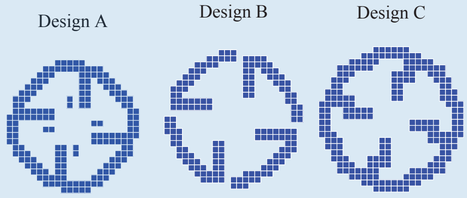


Comparison of slices through the 3D tomographic datasets of design A and the print design show the close similarity of scaffold and pattern. However, the fabricated scaffolds exhibit a larger volume, and the smaller pores are filled with TCP particles.

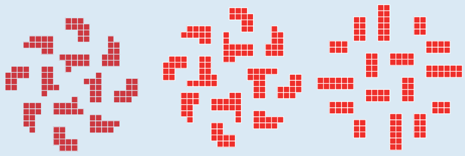


SRµCT images of scaffolds of different sizes show that print quality increases with scaffold size.

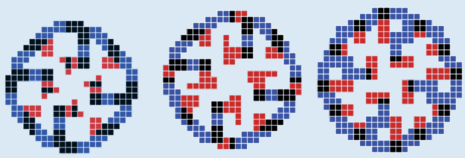
BIOMIMETIC SCAFFOLDS FOR BONE AUGMENTATION



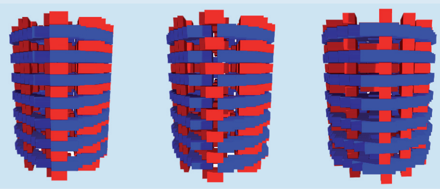
Layer 1 (voxel length 240 µm)



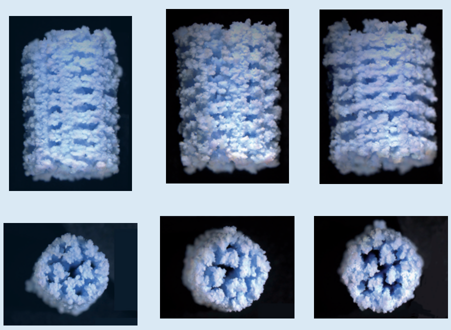
Layer 2 (voxel length 240 µm)



Layer 1 and Layer 2, overlaps in black



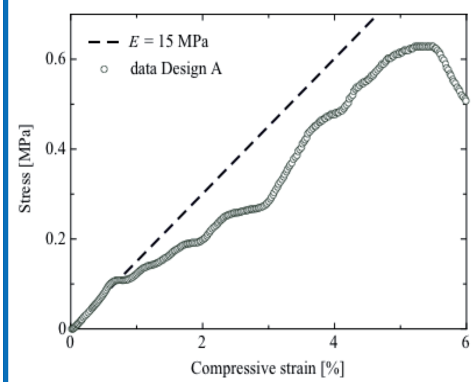
3D schematic representation



Photographs of the scaffolds realized by rapid prototyping

MECHANICAL TESTS

Stress-strain curves of the TCP scaffolds were recorded using the universal testing machine D020 (Zwick GmbH&Co, Ulm, Germany). Young's moduli were determined from the linear fits within the initial stages of compres-



The tri-calcium phosphate scaffolds have a Young's modulus that is about three orders of magnitude smaller than that of the healthy human tibial cortical bone. The preparation procedures should be optimized to reach the mechanical properties of bony tissues.

Scaffold	Length [mm]	Diameter [mm]	Weight [g]	Young's modulus [MPa]
A1	7.4	5.4	0.173	21.2 ± 0.4
A2	7.4	5.5	0.170	35.7 ± 0.2
A3	7.5	5.4	0.167	17.6 ± 0.2
A4	7.4	.5.4	0.167	38.8 ± 0.4
A5	7.4	5.4	0.161	15.0 ± 0.3
A6	7.4	5.4	0.154	32.8 ± 0.2
A				**27 ± 4**
A 125%	9.3	6.7	0.325	58.0 ± 0.3
A 150%	11.2	8.0	0.550	31.4 ± 0.8
A 150%	11.2	8.0	0.550	57.2 ± 0.8
A 175%	12.9	9.3	0.817	40.4 ± 0.4
A 175%	13.0	9.3	0.828	51.6 ± 0.5
B1	7.5	5.7	0.174	19.5 ± 0.4
B2	7.5	5.7	0.181	17.4 ± 0.4
B3	7.5	5.7	0.164	18.0 ± 0.4
B4	7.5	5.6	0.163	21.1 ± 0.5
B5	7.5	5.7	0.164	23.1 ± 0.4
B				**20 ± 1**
C1	7.5	6.2	0.193	29.3 ± 0.1
C2	7.5	6.3	0.198	28.2 ± 0.4
C3	7.5	6.1	0.188	31.3 ± 0.8
C4	7.5	6.1	0.196	19.4 ± 0.2
C5	7.5	6.1	0.213	49.8 ± 0.4
C				**32.5 ± 5**

CONCLUSION AND ACKNOWLEDGEMENT

3D powder printing is a promising method for the fabrication of TCP porous scaffolds. Even though specific designs can be achieved with high precision, the scaffolds do not reach the mechanical properties of cancellous bone. Post processing procedures, e.g. treatment with H_3PO_4 to increase the mechanical properties of the scaffolds, have to be optimized. SRµCT is well suited for the characterisation of the scaffold morphology. Registration of the digital 3D datasets with the print designs yields information on print quality. Further analysis of the tomography dataq will serve for the quantification of scaffold porosity and pore interconnectivity.