3D Evaluation of Porous Scaffolds for Bone Augmentation

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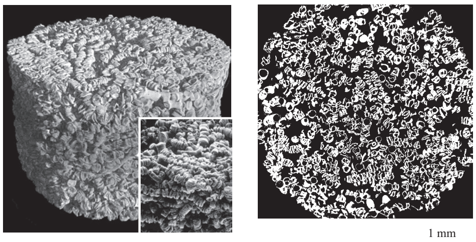
INTRODUCTION

Scaffolds for bone augmentation should provide a 3D template for the in-growth of bone tissue. For this reason, a scaffold needs an interconnective porosity with macropores of at least 100 μm. Computed X-ray microtomography (μCT) is a unique technique to analyze 3D porosity, it is a non-invasive and a non-destructive method suitable to assess quantitatively and qualitatively interconnective porosity of biomaterials. In this study, μCT is used to characterize the complex 3D interconnective porosity of a bioresorbable scaffold for bone augmentation. The obtained 3D and 2D analysis are compared in a quantitative manner. The method was applied to a synthetic bone graft substitue. μCT characterization revealed the presence of open interconnected macroporosity of the implant which may promote bone ingrowth after implantation.

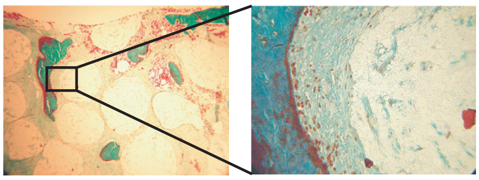
PLGA SCAFFOLD

μCT measurements of a porous PLGA scaffold of cylindrical shape (diameter 5 mm, height 3.6 mm) were performed with a monochromatic X-ray beam having a photon energy of 9 keV. The spatial resolution was experimentally determined to be 5.4 mm on the basis of the modulation transfer function. The inner structure of the scaffold can also be visualized by μCT. The slices of the scaffold indicate interconnected porosity that is accessible from outside the sample. These binary date are used to evaluate the pore architecture in a quantitative manner [Müller et al. Biomolecular Engineering 19 (2002) 73].



μCT and SEM image (inset) of the outer shape of a PLGA scaffold on almost identical scale (left). The images demonstrate the complex structure of the porous sample. Slice of the tomograph obtained from the PLGA scaffold (right). The image was obtained after thresholding and filtering the binary data.

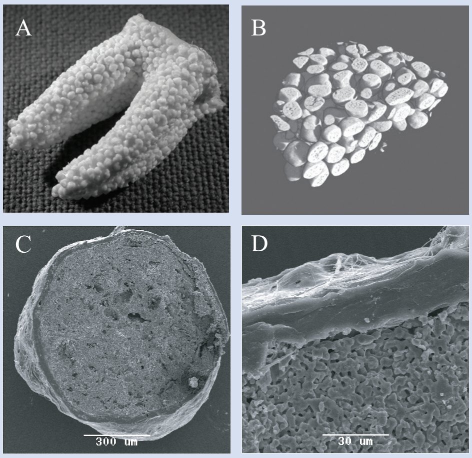
HISTOLOGY



Histological evaluation of bone in-growth into a RootReplica™ after 6 months of implantation in a human extraction socket. The colors correspond to the following substances: Undifferentiated tissue (light green), newly formed bone (dark green), osteoid that indicates bone formation (red) and granules (white). Note the in-growth of bone tissue into the macropores (left) as well as into the porous granules (right). Pictures courtesy of F. Weber, ZZMK, University of Zurich.

CERAMIC PLGA-COMPOSITE

The degradable dental implant RootReplica™ is used to close the bone wound after tooth extraction by inserting an exact copy of the tooth root that is made chair-side within 5 min. RootReplica™ prevents the resorption of the surrounding bone by stabilizing the adjacent bone structure, preventing infections and providing a high porosity for tissue in-growth. The degradable TCP-PLGA-composite RootReplica™ is completely replaced by autologous bone over time [www.degradable.ch].

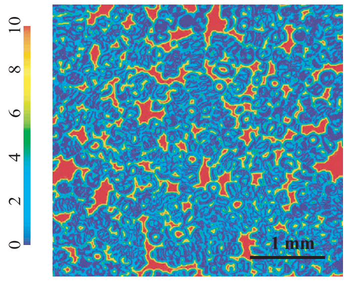


RootReplica™ is an exact copy of a tooth root (A) that provides an open porous structure (B, μCT image) where the individual granules (C, SEM picture) are fused together by the polymer layer that covers each granule (D, SEM picture). The scaffold shows an interconnected macroporosity among the granules, as well as a microporosity within each granule.

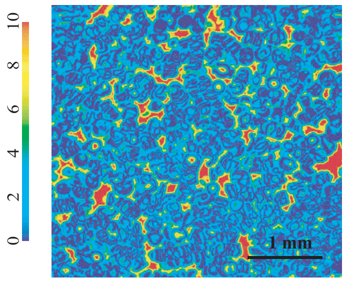
The interconnected porosity of RootReplica™ originates from the polymer-coated ceramic granules that are fused together to form an exact copy of the socket. The three dimensional architecture of the implant was characterized by μCT, revealing an inter-connected macroporosity among the granules as well as a microporosity within the granules. This interconnected porosity promotes bone in-growth, as evidenced by the ongoing formation of new bone formation in a RootReplica™ 6 months after implantation.

ANALYSIS

2D Analysis



3D Analysis



The comparison of the 2D and 3D distance map of a part of one representative slice demonstrating that larger distance to material for the 2D than for the 3D analysis by the colored areas.

A way to characterize the pore architecture is distance mapping, where the minimal distance of each voxel to material is determined. This value is the color label of the distance map. Dark blue means "zero" or material. For the labeling of pores, however, the 2D analysis gives only an upper limit, because material can be present above and below the pixel in a distance closer than in the 2D plane. Consequently, the mean value for the distance is considerable larger for the 2D analysis than for the 3D analysis. The obtained values for the mean distance to material within the sponge calculated from 2D and 3D data of the whole tomograph differ significantly: 12.5 μm for 3D and 17.6 μm for the 2D analysis. If the pores exhibit a spherical shape as frequently found, the derived mean pore diameter, however, is overestimated only by 6% in the 2D image analysis with respect to the 3D evaluation.

CONCLUSION AND ACKNOWLEDGEMENT

Synchrotron-radiation-based μCT is an appropriate method to quantify the micro-architecture of porous materials. This technique can be applied to different porous materials and composites. The power of μCT was demonstrated on the characterization of the complex pore architecture of a porous PLGA scaffold. It was further applied to assess the interconnected porosity of a bone graft substitute for dental applications, where porosity seems essential for in-growth of bone tissue. Indeed, the porous structure supported the formation of new bone within the synthetic bone graft after 6 months of implantation in a human tooth extraction socket.