Investigations of FFF 3D-printed zirconium dioxide implants

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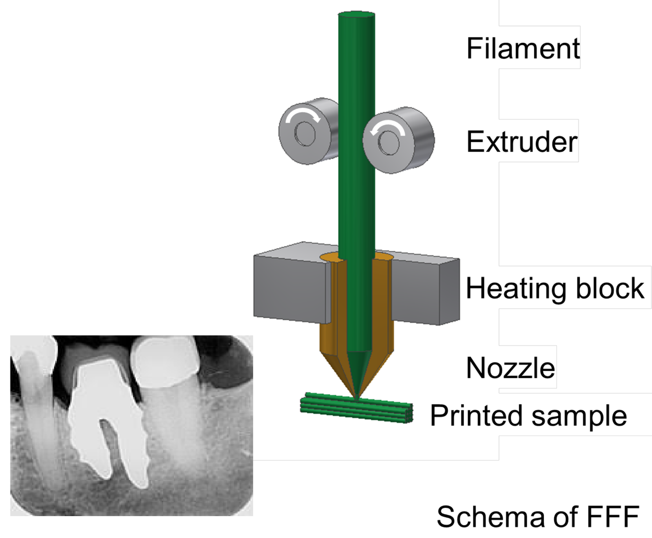
Motivation

Stable and reliable bone anchorage is crucial in dentistry. Zirconium dioxide (ZrO_2) is a promising alternative to titanium due to its aesthetics, high biocompatibility, reduced biofilm formation, lower wear, and less inflammation. Fused Filament Fabrication (FFF) 3D printing offers design flexibility and cost-effective production. We aim to use FFF to create patient-specific, root-analog implants tailored to bone structure, reducing the need for pre-drilling. Furthermore, FFF 3D printing allows direct integration of surface modifications to enhance osteointegration, eliminating extensive post-processing.



Scheme

Surface topography

Optimized surface topography can lead to better cell adhesion. FFF shows native procedural structures due to the printing process by a nozzle and the layered structure of AM (Fig. 1).

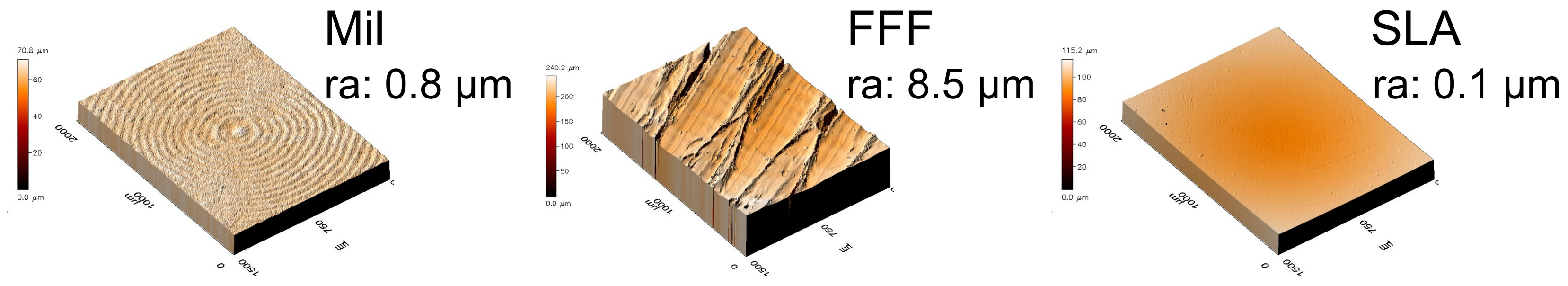


Fig. 1 - White light interferometry of native surfaces

Evaluation of FFF printed zirconia

The initial step in optimizing the osteogenic potential of innovatively manufactured ZrO_2 surfaces was to compare FFF-printed ZrO_2 (FFF), stereolithographically printed ZrO_2 (SLA) and conventionally milled ZrO_2 (Mill). Ideally, the surfaces initially support attachment (Fig. 2&4), proliferation (Fig. 3) and later osteoblastogenic differentiation (Fig. 5).

Adhesion

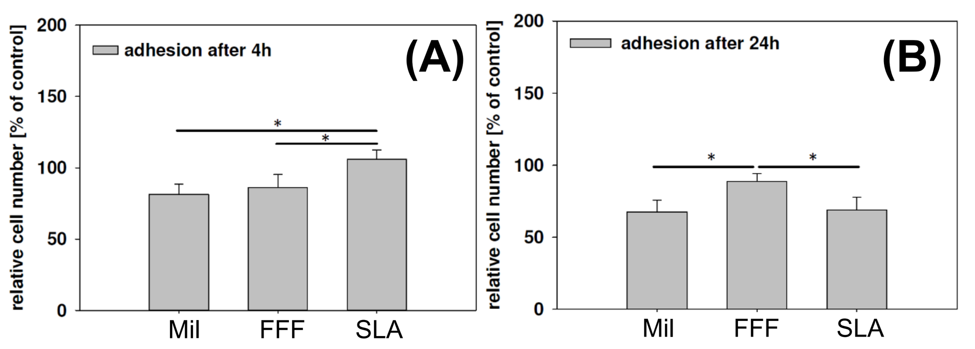


Fig. 2 - Initial adhesion **(A)** was, better on SLA surfaces. However, after 24h **(B)** significantly more cells were adherent to FFF surfaces. * =p < 0.05.

Proliferation

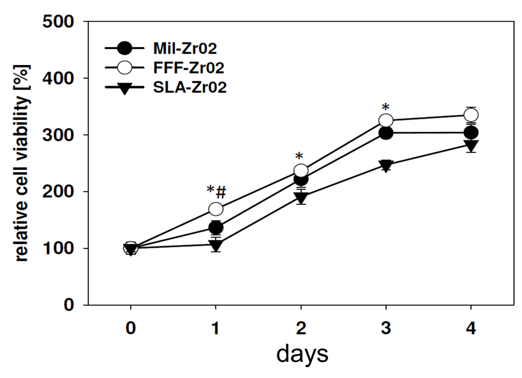


Fig. 3 - Proliferation on FFF surfaces was superior. * = p < 0.05, FFF vs. SLA, # = p < 0.05 FFF vs. Mil

Cell coverage

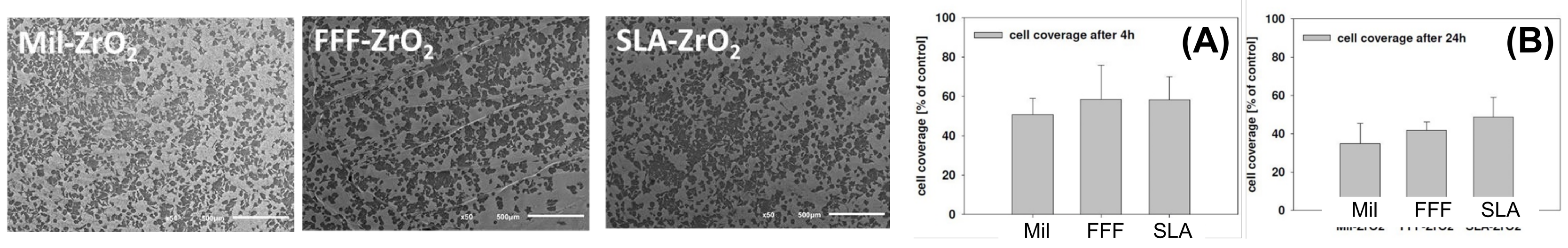


Fig. 4 - Analyses of cell coverage revealed o significant differences between zirconia surfaces.

Marker genes of osteoblastogenic differentiation

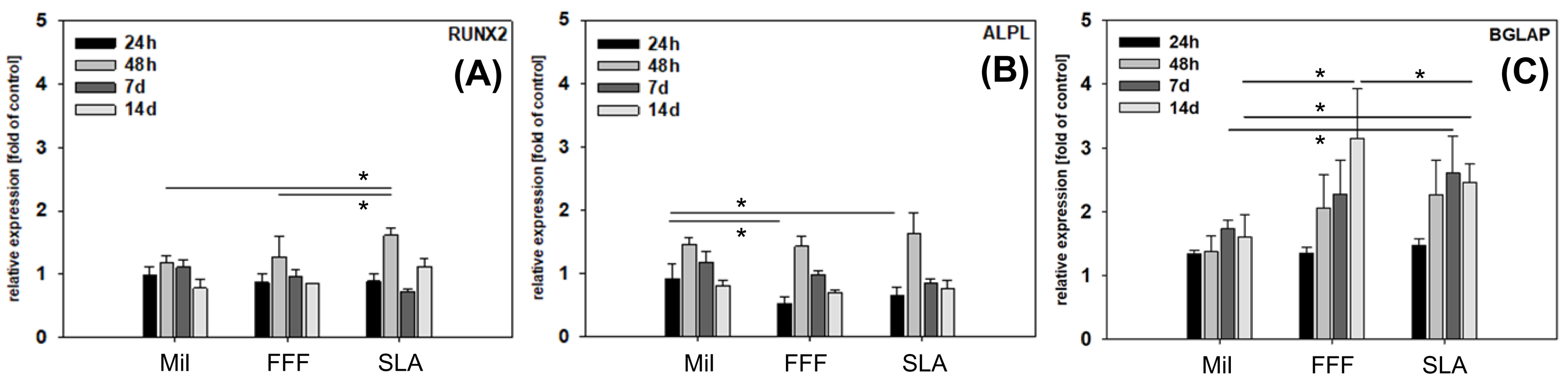


Fig. 5 - The surfaces showed comparable temporal patterns for the early markers RUNX2 and ALPL. However, for the late marker osteocalcin (BGLAP) Mil had the lowest osteocalcin expression, with significant differences at 7 days (SLA vs. Mil) and 14 days (Mil vs. SLA, Mil vs. FFF, and FFF vs. SLA). The highest osteocalcin expression was on FFF at 14 days. * = p < 0.05, indicating clear support of FFF surfaces for terminal osteogenic differentiation.

Challenges

Process-related voids and surface irregularities weaken mechanical properties. Archimedes density measurements and CT images revealed the quantity and location of such voids. Printing conditions were optimized to minimize void formation.

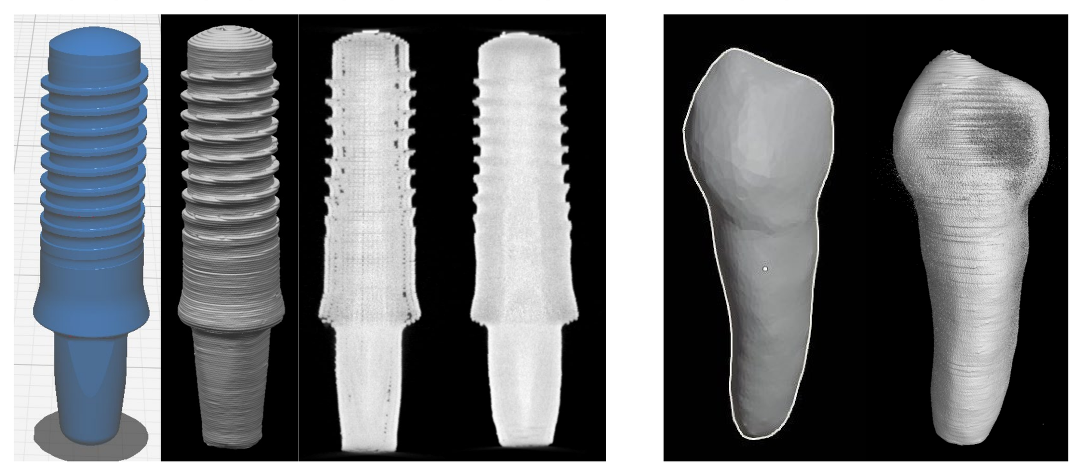


Fig. 6 - FFF-printed implants:
(A) CAD-file,
(B) External structure,
(C) Incomplete filling (inner voids).
(D) Adapted printing conditions (reduced voids),
(E) CAD-file of root analogue implant (ROI)
(F) Printed ROI

Mechanical properties were measured using bi-axial testing according to DIN EN ISO 6872 (Fig. 7). However, surface structures resulted in low mechanical strength of the disk samples (Fig. 8). Currently, we are working on improvements to mechanical stability.

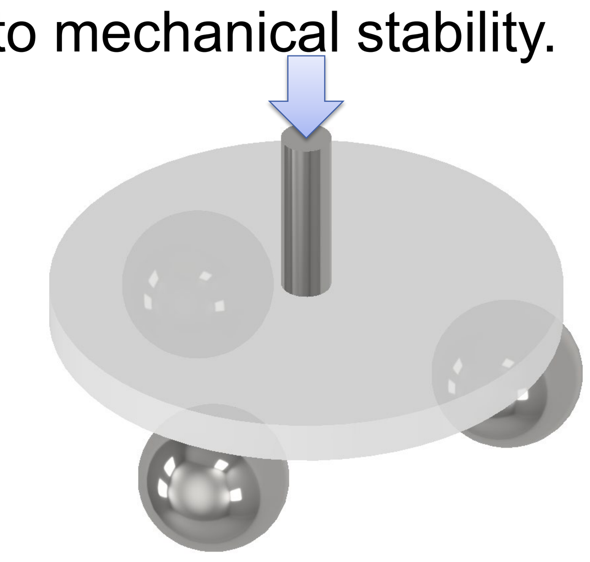


Fig. 7 - Biaxial testing

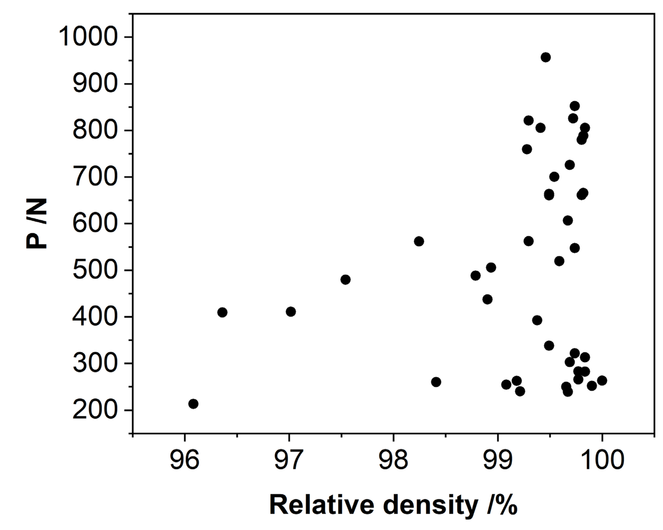


Fig. 8 - Results of Biaxial testing

Interim Conclusion

- FFF-printed ZrO_2 showed favorable cell adhesion of osteoblastic cells and promoted cell proliferation
- Analyses of osteoblastic marker gene expression demonstrated support of terminal differentiation markers.

➔ FFF-printed ZrO_2 could represents a promising bio-material for osseointegration

Future directions

The mechanical properties of the material have not yet reached the desired level of performance, indicating that both the feedstock and the manufacturing process require further optimization.

Additionally, the development of innovative surface topographies is underway with the aim of enhancing the biological properties of the material further.

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