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Evaluation of maximum overhang angles for the support-free additive manufacturing of calcium phosphate cement structures

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Abstract: The paper examines the process parameters of 3D printing for the manufacturing of implant structures made of calcium phosphate cement, taking into account different overhang angles. The aim of the investigation is to ensure a dimensionally stable manufacturing of overhangs that meets the requirements of individual implants. To this end, samples with and without an outer contour were printed at different angles (20° to 48°) and with different numbers of layers (16, 24, 32, 40) and analyzed metrologically. The methodology included a systematic variation of relevant parameters to investigate the influence of the overhang angle and the number of layers on the shape deviations. The results showed that samples without an outer contour still exhibited sufficient dimensional stability up to an overhang angle of 38°, while significant dimensional distortions were observed in samples with an outer contour from an angle of 30°. In both cases, a layer count of 24 proved to be optimal for high overhang quality.

Keywords: calcium phosphate cement, additive manufacturing, individual implants, overhang angle

1 Introduction

Among the various materials explored for manufacturing of individual implants, calcium phosphate cement (CPC) stands out due to its biocompatibility, osteoconductivity, and ability to resorb and osseointegration [1]. These characteristics make CPC ideal for manufacturing patient-specific implants tailored to meet individual anatomical needs [2].

A critical aspect of additive manufacturing in the context of individual implants is the dimensional stability of printed structures, especially in regions with overhanging geometries. The design of such implants must accommodate the complex morphology of bone defects while ensuring structural integrity and precision in fit. Overhangs, which are common in implant geometries, pose a significant challenge as they can lead to deformations, material collapse, or inaccuracies during the printing process if not properly controlled.

Unlike polymer- or metal-based additive manufacturing, CPC exhibits unique rheological and curing characteristics that influence its printability and stability [3]. The ability to manufacture overhanging features without additional support structures is essential for achieving high-precision implants that conform to the patient-specific bone structure [4]. However, the critical overhang angle at which shape deviations occur remains a key limitation in the support-free printing of CPC.

This study investigates the process parameters influencing the manufacturing of overhang structures in CPC-based 3D printing. Specifically, it evaluates the effect of different overhang angles and layer counts on the dimensional stability of printed samples, both with and without an outer contour. By systematically analyzing these factors, the study aims to define optimal printing conditions that enable dimensionally stable implant structures suitable for clinical applications.

2 Materials and methods

2.1 Design and process parameters

The test specimen was designed as an inverted trapezoidal prism (Figure 1) with a constant base area of 10 × 10 mm. The height of the specimen varied depending on the number of

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printed layers, while the overhang angle was systematically adjusted to evaluate its influence on dimensional stability.

Based on the findings of a preliminary investigation, parameters relevant to the printing process were defined. The needle diameter, the system pressure, the filling density and the filling pattern are considered constant parameters.

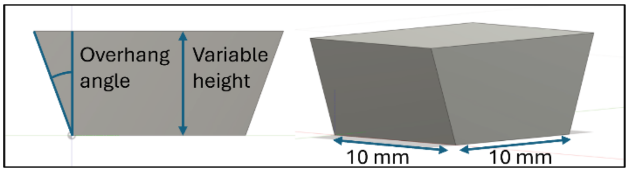

Figure 1: Design of the specimen with default parameters

The filling density describes the percentage of material in the volume of a 3D-printed object. Accordingly, a value of 100% corresponds to a completely filled inner structure, while lower values indicate a partially hollow inner structure (closed porosity). The infill pattern is defined as the specific geometric structure used to occupy the inner area of a 3D-printed object. A higher filling density increases the mechanical strength of the printed structures, but can affect porosity and thus biological integration. On the other hand, a lower infill density leads to higher porosity, which promotes cell colonization and tissue ingrowth. In terms of filling pattern, regular patterns such as linear structures provide uniform load distribution and controlled porosity. More complex patterns can produce specific mechanical properties, but require careful adjustment of the printing parameters. [5, 6]

The further fixed parameters were defined as follows:

- needle diameter: 0.41 mm, which corresponds to an estimated layer height: 0.307 mm
- system pressure: 0.35 MPa
- fill distance: 0.95 mm (pore size 0.54 mm) to achieve best possible filling density (approx. 30 %) according to [7]
- filling pattern linear with a filling profile of -45° x 45° (achievement of an open porous outer structure for better osseointegration)

The variable parameters to be examined are the overhang angle, the number of layers and the use of an outer contour (outline). This means that an additional closed outer contour is printed in addition to the filling pattern to achieve more stability in the boundary area.

Viscosity was not considered as an independent parameter, but rather assumed to be constant. This decision is based on the current lack of a standardized or widely accepted metric that adequately captures the rheological behavior of CPC during the printing process. CPC typically exhibits shear-thinning, non-Newtonian flow characteristics, with its apparent viscosity being highly dependent on factors such as shear rate, nozzle geometry, extrusion speed, and temperature. During the extrusion phase, CPC is in a paste-like, flowable state, which transitions into a solid during setting, accompanied by a significant change in viscosity. [8]

2.2 Planning the series of experiments

As part of the planning, a systematic variation of the overhang angle, the number of layers and the use of an outer contour is selected (Table 1). In general, a maximum permissible overhang angle of 45° is communicated in the field of additive manufacturing without the need for support structures [9]. Therefore, a range for the maximum overhang angle of up to 48° is defined. As the overhang angle increases, the risk of the overhang losing its shape also increases. For this reason, a finer gradation was selected in the range from 38°.

Table 1: Planned and finally printed variants

Overhang angle (°)	Number of layers	Height (mm)	With/without outer contour
20	16-40	4.912-12.28	w/wo
30	16-40	4.912-12.28	w/wo
34	24-40	7.368-12.28	wo
38	24-40	7.368-12.28	wo
40	24-40	7.368-12.28	w
42	24-40	7.368-12.28	wo
44	24-32	7.368-9.824	w/wo
46	24-32	7.368-9.824	w/wo
48	24-40	7.368-12.28	w

Four different layer counts were defined: 16, 24, 32, and 40, corresponding to structure heights ranging from 5 mm to 12 mm. This range was selected to reflect the typical thickness of cranial bones, which represent a common application area for CPC-implants in patient-specific bone reconstruction [4].

2.3 Manufacturing and measurement

The specimens were designed using the CAD software *Fusion 360* (Autodesk, USA). This was followed by the slicing process using the *SliceIt!* (Chair of Virtual Product Development, Dresden, Germany) slicing software. CPC paste from *INNOTERE* (Radebeul, Germany) was used as the printing material. CPC specimens are produced with a self-build laboratory printer using direct ink writing. This is an extrusion-based printing technology in which a paste or viscous material is used as a starting form and is applied in the form of strands through a needle in layers. Figure 2 shows some examples of printed test specimens.

The printed components were examined geometrically to compare the target design specifications with the actual state. The *Zeiss Scancobot 3D scanner* (Carl Zeiss GOM Metrology, Braunschweig, Germany) was used for this purpose. The data obtained was converted into STL format and imported into the *Blender* (Blender Foundation, Open Source) software.

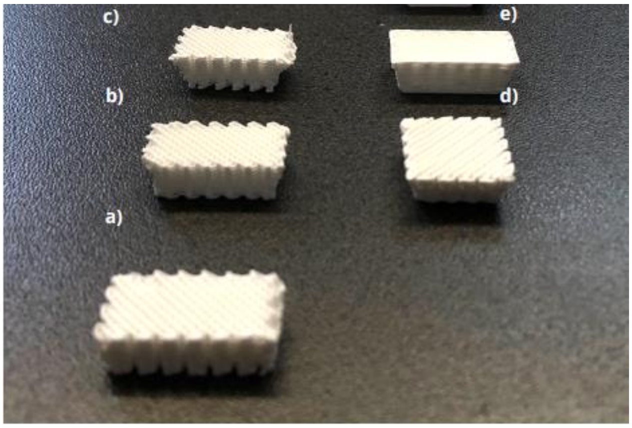

Figure 2: Examples of printed test specimens with different parameterization (a-e)

Three measurements were then carried out on each sample in Blender (Figure 3): One measurement on the left side of the sample (deviation-L, Figure 3 Nr. 3) and one measurement on the right side of the sample (deviation-R, Figure 3 Nr. 2). The base plane served as the basis for the measurement, from which a target plane (green) was drawn as a function of the specified overhang angle. A parallel red plane is placed from the green target plane, which represents the point furthest away from the original design (actual plane). The curvature at the upper edge of the component was recorded by the third measurement (deviation-T, Figure 3 Nr. 1). The green target plane corresponds to the actual height of the sample and the red actual plane corresponds to the end of the curvature caused by the CPC pasty state. This allows the pure deformation on the outer sides due to sagging to be determined, whereby the overall deformation (sagging over the entire surface) of the structure is not taken into account in the measurement.

In all cases, the target plane serves as the zero point from which the distance to the actual line is determined and evaluated as an absolute value.

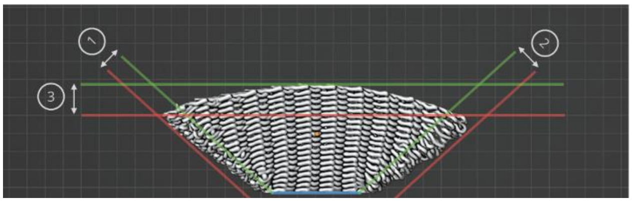

Figure 3: Representation of the measurements on the aligned test specimen (blue: target base area, green: target angle or actual height, red: actual angle or deformation) with 1) measurement on the left, 2) measurement on the right, 3) measurement at the top

3 Results

All printed test specimens were measured using the measurement scheme shown. The results for test specimens with and without outer contours are shown separately in Figure 4 and Figure 5. For some variants, several test specimens were produced with the same parameter settings. This is shown in the diagrams with the respective final digit (-1 to -3) when naming the test specimens on the x-axis.

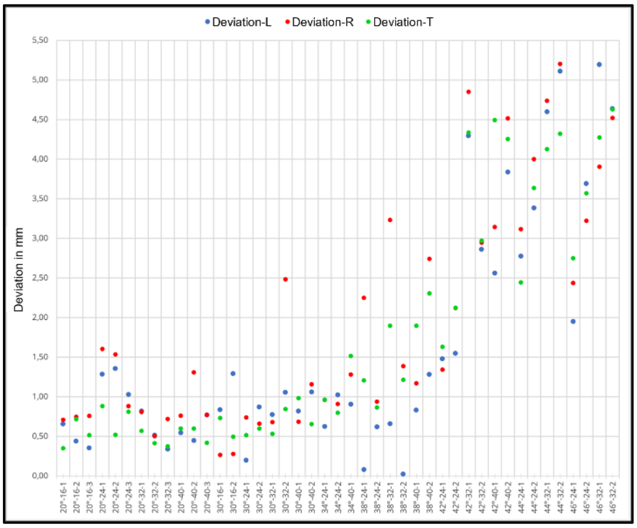

Figure 4: Visualization of measurement results for test specimens without outer contour

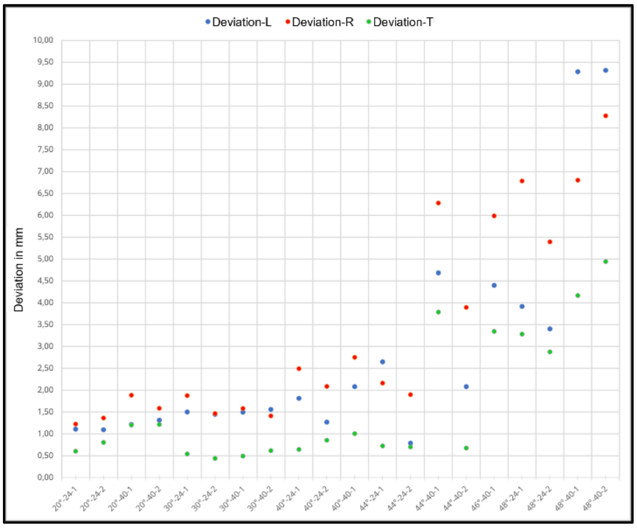

Figure 5: Visualization of measurement results for test specimens with outer contour

4 Discussion and conclusion

A maximum form deviation (regardless of direction) of 1.0 mm is considered tolerable (S - suitable). In addition, a deformation of up to 1.5 mm was defined as partially suitable (PS), while larger deviations are classified as critical (US - unsuitable). This limit is based on literature, which in most cases considers a maximum gap of 1.0 mm, in some cases up to 2.0 mm, to be tolerable for bone ingrowth at the bone-implant interface [10, 11].

Based on the data obtained, several conclusions can be drawn for the 3D printing of CPC structures with overhangs (Table 2). A reliably printable range for overhangs without an outer contour is obtained up to an overhang of 30°, regardless of the number of layers. A conditionally suitable range results for overhang angles between 34° and 38°, which also requires a particularly careful choice of parameters. Here too, smaller numbers of layers (16 and 24) are preferable in order to ensure dimensional stability. From an angle of 42°, however, overhangs are problematic. This applies all the more if a high overhang angle is combined with a high number of layers. Dimensional stability can hardly be achieved in this range.

Table 2: Evaluation of usability of parameter combinations (S - suitable, PS - partially suitable, US - unsuitable)

Without outer contour					With outer contour		
Angle/ Layer	16	24	32	40	Angle/ Layer	24	40
20°	S	S	S	S	20°	PS	PS
30°	S	S	S	S	30°	PS	PS
34°	S	S	PS	PS	40°	US	US
38°	S	S	PS	PS	44°	US	US
42°	US	US	US	US	46°	US	US
44°	US	US	US	US	48°	US	US
46°	US	US	US	US			

It was found that the presence of an outer contour has a negative influence on the stability of the overhang. An outer contour leads to an increase in shape deviations. This effect encourages critical deviation values to be reached earlier, as the additional material on the outer contour tends to increase mold instability. The process window for reliable manufacturing results is restricted by the outer contour, which must be taken into account during design and manufacturing planning.

In conclusion, it is recommended to design overhangs up to a maximum of 38° for complex geometries without an outer contour in order to ensure sufficient stability of the overhangs. If larger overhang angles are unavoidable, a significant loss of quality in terms of dimensional accuracy must be expected. Especially if 40 or more layers are to be used. For samples with an outer contour, on the other hand, designs with angles over 30° should be avoided as far as possible or secured by additional measures (e.g. support structures), as otherwise significant deviations will result even with medium component heights.

Author Statement

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