3D PRINTING OF CALCIUM PHOSPHATE CEMENT FOR CRANIOFACIAL BONE RECONSTRUCTION

Laboratório de Biomateriais, Universidade Federal do Rio Grande do Sul  
Av. Bento Gonçalves, 9500, CEP: 91501-970, Porto Alegre, RS, Brasil  
*liciane.bertol@ufgrs.br

ABSTRACT

In the current scenario of flexible manufacturing processes, the 3D printing shows up as an alternative to generate individual parts with complex geometries. Moreover, the development of the 3D printing machines, software and parameters allows the manufacture of parts in some materials suitable for implantation. In this way, this study investigates the feasibility of the production of patient-specific craniofacial implants in calcium phosphate cement. The implant was previously generated in CAD environment based on the patient’s tomographic data. The fabrication of the implant was carried out in a commercial 3D powder printing system and the chosen powder was an alfa-tricalcium phosphate (α-TCP). The accuracy of the 3D printed implant was measured by three-dimensional laser scanning. The printed part showed adequate accuracy.

Key-words: Craniofacial implants, 3D printing, calcium phosphate cement

INTRODUCTION
Currently, the surgical procedures to craniofacial reconstruction still demand efforts due to the difficulty to shape the implant and restore the bone defect. The definition of the geometry of the implant is the first challenge, once each patient has an individual anatomy and each bone defect has a specific shape. The implant must have a geometry that fits properly in the original structure and consist of a biocompatible material. Furthermore, the selected manufacturing process must enable the production of single pieces, in order to produce patient-specific implants. In the current scenario of flexible manufacturing processes, the tree-dimensional printing (3DP) is highlighted since it allows the production of geometric complex parts directly in the material to be used for implantation.

Bone cements, more specifically those based on calcium phosphates, are attractive due to their chemical similarity to the mineral phase of human bone. For this characteristic, it can be considered to be a bioactive material – that stimulates ingrowing of host bone tissue and osteointegration. The great advantage of this cements (α-tricalcium phosphates, α-TCP) is the reaction of formation of crystals of calcium-deficient hydroxyapatite (CDHA) during its setting, similar to the biological hydroxyapatite. The entanglement of the hydroxyapatite crystals increases the mechanical strength of the cement. Some studies point to the great potential of the manufacture of 3d powder printing of calcium phosphate parts \(^{1-9}\). Such approach permits the preoperative fabrication of implants that fit precisely to the patient’s anatomy, leading to the optimization of the aesthetical results, reduction of risks and surgery time.

The manufacture of customized implants became of great interest for Biomedical Engineering. The main benefits of the use of patient-specific implants are the reduction of the surgical time, more predictable aesthetic results and the reduction of risk of infections. However, the manufacture of implants according to the demands of each specific patient still require efforts to develop the process chain and its equipment, parameters, material and software. Bearing in mind the potential of the 3D powder
printing of customized implants and the lack of information available about the technique, this study aims to evaluate the feasibility and the accuracy of the manufacture of patient-specific implants in calcium phosphate cement for craniofacial bone reconstruction.

MATERIALS AND METHODS

**Implant Design**

A case of bone defect in the frontal-orbital region of the skull was selected to define the design steps to produce the patient-specific implant. Computed tomography (CT) scans of the skull were carried out. The software Invesalius (Medical Imaging Public Software, CTI, Brazil) was used to generate the 3D virtual model based on a sequence of the 2D files acquired in the CT (DICOM files, Digital Imaging and communications in Medicine). These files were saved as STL (Stereolithography) exported to a 3D modeling software (3ds Max, Autodesk, USA). All implants were designed in CAD software and imported into the 3D printing software in the STL format. The bone defect and the designed implant are shown in Figure 1.
Figure 1: Virtual representation of the skull. a) Cranial defect. b) Designed implant for the skull reconstruction.

Powder and binder solution formulations

The synthesis of the $\alpha$-TCP was performed as described previously in the literature $^{[10]}$. Initially, $\gamma$-calcium pyrophosphate ($\gamma$-CPP, $\text{Ca}_2\text{P}_2\text{O}_7$) was obtained through the calcination of dicalcium phosphate dihydrate (DCPD, $\text{CaHPO}_4$) for 5 hours at 550°C in a muffle furnace. After sieving (200 mesh, 74μm), the calcinated powder was mixed to calcium carbonate ($\text{CaCO}_3$, 35.43 wt.%) for 20 minutes and sintered at 1500°C for 3 hours. After synthesis, the powder was crushed in a mortar and pestle and subsequently sieved. The particle size distribution was measured with the 1180 Cilas Analyser using isopropyl alcohol as liquid phase. A Phillips XPert diffractometer MPD with copper tube ($\text{K}a$ radiation = 1.5418 Å), voltage and current of 40 kV and 40 mA, respectively, was used to obtain the X-ray diffraction patterns and identify the crystalline compounds of the obtained powder.

Powder-based 3D Printing
A commercial 3D powder printing system Z Printer Z310 plus (Z-Corporation, USA) was used to print the designed parts (Figure 2) at room temperature. The prepared α-TCP powder was distributed on the feed area of the printer and diluted sodium phosphate (Na$_2$HPO$_4$, 5 wt.%) was used as liquid binder phase. Although different definitions for the term “binder” exist, in this paper we refer to the sodium phosphate solution as “binder”.

In 3DP, the solid is created by the reaction of a liquid, selectively sprayed onto a powder bed. During the printing process, a roller places a thin layer of powder on the build area (Figure 3). The inkjet head prints droplets of the binder on the powder bed and thus locally solidifies part of the solid cross-section. The process was repeated for every layer until the 3D structure of the hole implant is printed. After this steps, the printed part was taken from the building area and the remnants of loose powder were removed using compressed air of the powder recycling station (depowdering step). In order to complete the setting of the cement, the printed parts were immersed in the binder (sodium phosphate solution) for the post-hardening.
Figure 2: 3D printing system – 3D printer (right) and powder recycling station (left).
No adaptation of the commercial 3D printer was needed, once the used binder solution does not affect the fluid lines and binder container. The liquid/powder ratio was set as 0,19 (shell)/0,09 (core) in the ZPrint™ software. The binder solution was delivered by thermal inkjets (HP10, Hewlett-Packard, USA) to selectively bind the powder. After printing, the samples were post-processed by dipping in Na₂HPO₄ solution and then washed in deionized water to improve surface binding.

The dimensional precision of the implant was verified with three-dimensional laser scanning and by comparing the designed parts with the printed one. For this purpose, the surface of the built part was scanned using a three dimensional laser scanning system with a 10mm lens, whose accuracy is 0,015μm (Figure 4). The model was digitized with a resolution (distance between the points) of 0,2mm.
RESULTS AND DISCUSSION

Powder Characterization

The particle size distribution of the α-TCP powder is shown in Figure 5a. The particle size distribution of \( d_{10} = 1.15 \mu m \); \( d_{50} = 8.19 \mu m \); \( d_{10} = 20.93 \mu m \) and medium particle diameter of 9.18\( \mu m \) was found. Figure 5b shows the X-Ray Diffractometry pattern of the obtained powder. The most intense and sharp lines are observed in the 2θ angle range between 20 and 40°. These lines are coincident with the lines of the XRD
spectrum reported in JCPDS 09–0348 and 29-0359 files, which corresponds to alfa-tricalcium phosphate.

Figure 5: Characterization of the obtained α-TCP powder. a) Particle size distribution; b) X-Ray diffractometry.

**3D Printing Dimensional Accuracy**

In order to validate the dimensional precision of the 3D printing, the printed parts were scanned and compared with the original designed models, as shown in Figure 6. The values of maximum distance, average distance and standard deviation found for the printed part are shown in Table 1.
Figure 6: Three-dimensional comparison (in mm) between the physical models, produced through the laser sintering process, and the CAD original 3D model. a) Front side; b) back side.

Table 1: Dimensional deviations found for the printed part in the front and in the back side.

<table>
<thead>
<tr>
<th>3D comparison</th>
<th>Front</th>
<th>Back</th>
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<tbody>
<tr>
<td>Maximum Distance (mm)</td>
<td>positive + 1,01</td>
<td>positive + 1,16</td>
</tr>
<tr>
<td></td>
<td>negative - 1,08</td>
<td>negative - 0,86</td>
</tr>
<tr>
<td>Average Distance (mm)</td>
<td>positive + 0,13</td>
<td>positive + 0,14</td>
</tr>
<tr>
<td></td>
<td>negative - 0,13</td>
<td>negative - 0,11</td>
</tr>
<tr>
<td>Standard Deviation (mm)</td>
<td>0,16</td>
<td>0,17</td>
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As it can be seen from the evaluation of the dimensional deviations of the 3D printed part compared to the designed model, the average distance is around 0.02mm. According to Klammer et al. [6], such dimensional accuracy is adequate for the production of craniofacial structures. A greater difference can be noticed at the margins of the part, partially explained by the fact that, during the depowdering step, some thin regions of the part may be removed when reached by compressed air. On the other hand, the regions at the margins that present a positive deviation could represent overlapping areas. However, in this case, the improvement of the fit can be achieved by smoothing with a gypsum burr.

CONCLUSIONS

In this study, a commercial 3D printer was used to create patient specific geometries to replace bone structures. While other studies have focused on parameters related to the powder and binder formulations, the current study evaluated the dimensional accuracy of the process and its feasibility for craniofacial reconstruction applications.

Structures generated from computer tomography data, displaying implants for real applications, were producible. The designed part could be 3D powder printed in α-tricalcium phosphate with accuracy adequate for craniofacial structures. No adaptations in the 3D printer were necessary.

REFERENCES


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