Abstract

**Aim:** The production of individual tooth replicas has two applications in dental practice: tooth autotransplantations and dental root analogue implants. These applications require a particularly high degree of precision. The purpose of this study was to establish and evaluate a method for fabricating individual 3D-printed tooth replicas.

**Materials and methods:** 10 patients requiring extraction of a wisdom tooth and a preoperative cone beam computed tomography (CBCT) scan were included; exclusion criteria were intraoperative fragmentation or fracture of the tooth. 3D Slicer 4.6.2 was used for tooth segmentation and model generation based on CBCT data. The tooth replicas were manufactured by selective laser melting (SLM). The extracted teeth and 3D-printed replicas were scanned and tested for surface deviations in CloudCompare 2.8.1.

**Results:** The mean absolute surface deviation between the 3D-printed teeth and the corresponding extracted teeth ranged from 0.13 to 0.25 mm, with standard deviations of 0.10 to 0.21 mm; 95% of the measured surface points deviated less than 0.474 mm; the surface area was reduced by -6.0% and the volume by -3.4%. The root mean square was 0.238 mm and the mean maximum absolute surface deviation was 0.927 mm. The SLM technique showed a high precision with a mean absolute deviation of 0.045 mm and a standard deviation of 0.04 mm.

**Conclusion:** 3D-printed tooth replicas with a very high accuracy could be produced based on CBCT data. The described method is suitable for manufacturing tooth replicas for use in tooth autotransplantations or for fabricating root analogue implants.

**Keywords:** 3D printing, rapid prototyping, selective laser melting, tooth replicas, cone beam computed tomography, autologous tooth transplantation, root analogue implants, implantology

Introduction

The term 3D printing refers to a wide range of rapid prototyping techniques developed in recent years that are indispensable in many areas of industrial production technology and biomedical engineering.1,2 3D printers represent the most important subclass of additive manufacturers and are used for the production of models and prototypes, especially for workpieces that require only small quantities. The technology is therefore particularly well qualified for the manufacturing of dental workpieces, including ‘biomodels’ for the visualization of anatomical structures, templates for guided surgery, and the production of individual dentures such as 3D-printed implants and prosthetic restorations.3,4 The production of individual and precise tooth replicas has two concrete applications in everyday dental practice: tooth autotransplantations and dental implantology using dental root analogue implants.5,6 Several published studies have proposed different methods for using prefabricated replicas as a template during tooth transplantations, thereby saving the original donor tooth from repeated fitting attempts at the recipient site; this reduces extraoral time and further increases the success rate of tooth transplantations.6-13 The possibility of producing patient-specific root analogue implants by means of the metal laser sintering technique offers new treatment possibilities after tooth extractions.5,14 The first successful case reports show promising clinical results; however, this technology-sensitive method requires a particularly high degree of precision in the production process of the root analogue implants.15-17

The purpose of this study was to establish and evaluate a method for fabricating an individual 3D-printed tooth replica to simplify the surgical procedure and improve the clinical outcome of tooth autotransplantations. Furthermore, the precision of rapid prototyping a tooth analogue based on CBCT data is analyzed with regard to dental root analogue implants.
Material and methods

The study of existing literature and an ongoing analysis performed during the acquisition of patient samples resulted in the inclusion of 10 patients requiring extraction of a wisdom tooth. Inclusion criteria were a planned tooth extraction and a preoperatively required cone beam computed tomography (CBCT) scan for medical indications. Exclusion criteria were intraoperative fragmentation or fracture of the tooth. All the patients participating in the study signed an informed consent document clarifying that the extracted teeth would remain at the study center for study purposes. All patient-related data and materials were stored anonymously and made available to the study investigators only. Ethical approval was granted for conducting this study.

3D replica model reconstruction

CBCT scans were used as source data for the rapid prototyping of the tooth replicas. For all cases, the CBCT scans were taken with 96 kV, 4.0 mA, and a voxel size of 200 μm in the region of interest in a scan position according to the manufacturer’s recommendations (Planmeca ProMax 3D Max; Planmeca Oy, Helsinki, Finland). The scans were exported in Digital Imaging and Communications in Medicine (DICOM) data format. The DICOM data were then imported into 3D Slicer 4.6.2 (revision 25516, built 2016-11-08). Subsequently, the volumes of the whole teeth, including the pulp and apical foramen, were segmented manually in each CBCT slice using the ‘segmentation’ module to ensure a clean demarcation from the surrounding tissue. Finally, the model was generated and exported as a standard triangulation language (STL) file.

3D printing

The virtual STL models of the segmented teeth were processed in CAMbridge software (3Shape, Copenhagen, Denmark) to create supports and printable slices. A high-end selective laser melting (SLM) machine (Mlab cusing R, 100 W fiber laser; Concept Laser, Lichtenfels, Germany) was used to melt 50-μm-high layers of biocompatible cobalt-chrome powder (remanium star CL; Dentaurum, Ispringen, Germany) and finally fabricate the tooth replica. After the successful 3D-printing procedure, the supports were removed and the surfaces of the replicas were sandblasted to obtain a rough, matte, and therefore easily scannable surface.

Optical scan

The wisdom teeth were extracted in toto without damaging the roots or the crown. Subsequently, the extracted teeth were cleaned by removing all soft tissue residues, and stored in 3% hydrogen peroxide for 10 min. For an objective examination of the similarity, the clean extracted teeth and the corresponding 3D-printed replicas were scanned with an optical scanning system (Cerec Omnicam; Dentsply Sirona, York, USA) and exported as STL files.

Matching of extracted teeth and replicas

The virtual models were tested for surface deviations in CloudCompare 2.8.1. The surfaces of two corresponding models were first aligned and superimposed manually, then refined automatically using the iterative closest point registration algorithm to achieve the smallest surface deviation between the surfaces. Consecutively, the following models/teeth were compared: 1) The extracted teeth with the exported STL files of the corresponding segmentations from the CBCT data – evaluating the segmentation precision. 2) The 3D-printed replicas with their original segmentation from the CBCT data – evaluating the 3D-printing precision. 3) The 3D-printed replicas with the corresponding extracted teeth – evaluating the complete process of manufacturing teeth replicas based on CBCT data. The aligned surfaces were compared by calculating the mean differences and standard deviations in the distance between the surface meshes as absolute distances and as signed distances (taking undersizing and oversizing into consideration). For this purpose, the cloud-to-mesh tool in CloudCompare was used. For each of the three groups to be compared, the measured points of all 10 models, 3D prints or teeth were divided into 100 distance classes, depending on the surface deviation, and displayed in a diagram. The number of points in the most common class was normalized to 100 for better comparability. Furthermore, the Hausdorff distance, the total surface area, and the total volume of two corresponding teeth/models were measured and calculated as a percentage change. To illustrate the surface distances of all 10 patient cases in one graph, all measured points on the model surfaces were exported. The descriptive statistical evaluation was performed in Microsoft Excel (Microsoft Office 2016; Microsoft Corporation, Redmond, USA).
Results

CBCT segmentation vs corresponding extracted teeth

In every segmented CBCT model, 3578 to 6578 points were measured as a cloud-to-mesh distance with the corresponding teeth as reference. The mean absolute deviations ranged from 0.13 to 0.25 mm, with standard deviations between 0.11 and 0.20 mm. In all 10 CBCT segmentations taken together, the deviations of 95% of the measured points remained under 0.468 mm, and the mean signed distance was -0.021 mm. Together with a surface area loss of about -4.9% and a volume loss of -2.0%, this suggests a slight underdimensioning of the segmentation process when compared with the actual teeth (Fig 1a). Figures 1b and c summarize the absolute and signed distances between the surfaces of the CBCT segmentations and the corresponding teeth of all 10 patients.
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3D-printed replicas vs original segmentation from CBCT data

In every 3D-printed replica, 28286 to 36242 points were measured as a cloud-to-mesh distance with the CBCT segmentation (STL file) as reference. The SLM technique showed a high precision with a mean absolute deviation of 0.045 mm and a standard deviation of 0.04 mm. In all 10 3D-printed replicas taken together, the deviations of 95% of the measured points remained under 0.119 mm, and the mean signed distance was -0.016 mm. There was a minimal surface area loss of about -1.2%, and a minimal volume loss of -1.4% after the manufacturing process of the 3D-printed replicas (Fig 2a). Figures 2b and c summarize the absolute and signed distances between the surfaces of the 3D-printed replicas compared with the corresponding teeth of all 10 patients.

3D-printed replicas vs corresponding extracted teeth

In total in every 3D-printed replica, 28286 to 36242 points were measured as a cloud-to-mesh distance with the corresponding extracted teeth as reference. The mean absolute deviations ranged from 0.13 to 0.25 mm with standard devia-
tions between 0.10 and 0.21 mm. The mean signed deviations ranged from -0.10 to 0.03 mm with standard deviations between 0.17 and 0.32 mm. In all 10 3D-printed replicas taken together, the deviations of 95% of the measured points remained under 0.474 mm; the surface area was reduced by -6.0% and the volume by -3.4%. The mean signed distance between the surface of the 3D-printed replicas and the extracted teeth was -0.039 mm, and the mean absolute distance was 0.183 mm. The root mean square (RMS) was 0.238 mm and the mean maximum absolute surface deviation (Hausdorff distance) was 0.927 mm (Fig 3a). Figures 3b and c show the distribution of all measured cloud points in the 10 patients as absolute distances and signed distances. In total, 292755 points were calculated and divided into 100 classes of uniformly distributed surface deviations. Considering the absolute distances, most of the points (14459) were in the class between 0.0039 to 0.0079 mm, and the number of these points was normalized to 100. Figure 4a shows a photograph and Figure 4b the optical scans of the 3D-printed tooth replica (left, middle) and the extracted tooth (right) of patient no. 10, as an example. The subjective assessment of shape and dimension of the 3D-printed teeth compared with the corresponding extracted teeth showed a very high degree of similarity, and they appeared practically identical with the
naked eye. Furthermore, Figure 5a shows the scanned replica in a false color representation. The scalar field represents the signed distance of the measured surface points on the replica of patient no. 10 in comparison with its corresponding extracted tooth, in which the blue shades mean additive deviations and the magenta shades mean subtractive deviations of the replica. Figure 5b shows a histogram of the deviations in millimeters, representing the same colors.

Discussion

This study presents a method to produce 3D-printed tooth replicas with a high accuracy. The use of molars in this investigation resulted in minor inaccuracies in the area of the fissures and root furcations due to limitations in the resolution of the CBCT. Previous findings about an increasing inaccuracy of the segmentation process toward the apical region of the teeth leading to difficulties in distinguishing between the tissues could be confirmed. Furthermore, very small defects in the teeth that inevitably arose from the extraction process of retained teeth led to minor deviations mainly in the cervical region. This is in accordance with previous studies evaluating the precision and clinical use of 3D-printed teeth. Examinations similar to the present study were conducted by other groups as in vitro investigations, with the drawback of the use of cadavers. A very high accuracy of the SLM technique could be confirmed. However, there were some minor inaccuracies in the area of the 3D-printing supports. Possibly due to the laser sintering process and post-processing issues such as removal of the supports and sandblasting, a slight decrease in the surface area, volume, and mean
signed distance was experienced. To simplify the surgical procedure of tooth autotransplantations and to minimize the extraoral time and fitting attempts of the donor tooth, various techniques providing a tooth replica have been developed and published. Day et al.27 designed surgical templates based on the usual dimensions of adolescents’ premolars. Ashkenazi et al.28 presented a method of using predesigned, metal, tooth-like templates for adolescent patients, which are good, low-cost solutions that use an autoclavable material without the need for additional irradiation. However, an individual replica of the actual donor tooth has the advantage of a better fit and is especially necessary for transplanting immature teeth.12 In 2001, Lee et al.29 proposed the principle of rapid prototyping of an individual tooth copy based on computer tomography data. This technique has consistently continued to develop due to advances in 3D imaging using CBCT and the development of high-resolution rapid prototyping systems by various study groups.7,8,10-12,21,30 According to the described protocol, 3D-printed replicas with a very high accuracy could be manufactured, proving that the described method is reliable for producing clinically accurate tooth replicas based on CBCT data. Therefore, this method could be used for the production of individual templates for tooth autotransplantations or for fabricating root analogue implants.

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Präzisionsanalyse 3-D-gedruckter Zahnreplikate

Schlüsselwörter: 3-D-Druck, Rapid Prototyping, selektives Laserschmelzen, Zahnreplikate, Digitale Volumentomographie, autologe Zahntransplantation, wurzelanaloge Zahnimplantate, Implantologie

Zusammenfassung


Ergebnisse: Die mittlere absolute Oberflächenabweichung zwischen den 3-D-gedruckten Zähnen und den entsprechen den extrahierten Zähnen lag im Bereich von 0,13 bis 0,25 mm mit Standardabweichungen von 0,10 bis 0,21 mm; 95 % der gemessenen Oberflächenpunkte wichen weniger als 0,474 mm ab; Die Oberfläche wurde um -6,0 % und das Volumen um -3,4 % verringert. Der quadratische Mittelwert betrug 0,238 mm und die mittlere maximale absolute Oberflächenabweichung 0,927 mm. Die selektive Laserschmelztechnik zeigte eine hohe Präzision mit einer mittleren absoluten Abweichung von 0,045 mm und einer Standardabweichung von 0,04 mm.

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