CLINICAL ORAL IMPLANTS RESEARCH

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A novel approach for custom three-dimensional printing of a zirconia root analogue implant by digital light processing

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Abstract

Objectives: This study aimed to explore the feasibility of fabrication of three-dimensional (3D)-printed zirconia root analogue implant (RAI) through digital light processing (DLP) technology.

Material and methods: One partially edentulous mandibular human cadaver was scanned with a cone-beam computed tomography (CBCT) system. The scan volumes and data sets were used to create computer-aided design (CAD) model of the RAI. A high-end DLP 3D printing technology was used to fabricate the RAI from the CAD model. Within this approach, solid 3D objects are built using a DLP projector to translate voxel data so it is reproduced in liquid photopolymer dispersed with a commercial ceramic, thereby light polymerizing the resin to solid. Optical scanning technology was used to measure the tooth and 3D-printed RAI. To validate the accuracy of the printed zirconia RAI, the optical surface model of the original tooth and CAD model were superimposed.

Results: The differences between the optical scans of the RAI and original tooth are most noticeable towards the apical foramen, showing a disparity for the RAI with a maximum deviation of 0.86 mm. When setting a maximum threshold of 0.5 mm for the 3D-printed RAI surface to be deviating from the original tooth model and CAD model, measurements show 1.55% and 4.86% of the surface areas are exceeding the threshold distance, respectively.

Conclusion: With the use of currently available technology, it is well feasible to 3D print in zirconia a custom RAI.

Rapid advancements are being made in the field of three-dimensional (3D) printing processes in the compass of dentistry. Currently, distinctive 3D print processes in combination with different materials are being used for fabrication of patient-specific 3D parts for either prosthetic or surgical reconstruction of the dentally and maxillofacially compromised patient. One of the new applications of 3D additive manufacturing technologies in the area of implantology is the creation of the pre-emptive titanium custom-made root analogue implant (RAI) for immediate implant cases (Anssari Moin et al. 2011; Figliuzzi et al. 2012). Proposed benefits of this RAI approach include uncomplicated immediate implant placement, decreased number of surgeries, less initial bone loss resulting from the absence of the microgap shared with the minimal invasive approach and increasing patient comfort (Pirker & Kocher 2008, 2009; Anssari Moin et al. 2011; Figliuzzi et al. 2012; Mangano et al. 2014). Several studies have proven the feasibility of 3D manufacturing of the RAI by powder bed fusion methods, in the manner of selective laser melting (SLM) and direct metal laser sintering (DMLS) (Anssari Moin et al. 2011, 2012; Figliuzzi et al. 2012 and Mangano et al. 2014).

Growing concerns regarding titanium hypersensitivity and corrosion through gradual material degradation encourage further research into biocompatible alternatives. (Frydman & Simonian 2014; Lawson & Burgess 2014; Wood & Warshaw 2015). Zirconia has been proposed as an alternative implant material to titanium owing to its excellent biomechanical characteristics. Particular advantages of zirconia implants compared to titanium implants include no metal aura (through time) in cases with deficiency of the buccal bone plate and/or thin biotype mucosa with/without recession of the mucosa, corrosion resistance and hypoallergenicity (Van Dooren et al. 2012; Vohra et al. 2015).

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Currently, the widely applied system for fabrication of 3D zirconia parts is by means of computer numerical control (CNC) milling of an unsintered white monoblock and subsequent firing into a sintered high-strength ceramic. Disadvantages of this method are substantial waste of raw material, limited accuracy and time-consuming process (Klocke et al. 1997).

With recent innovations in rapid prototyping technologies, it has become possible to 3D print advanced ceramics. One of such developments is the rise of digital light processing (DLP) technology for 3D printing of ceramics with potential to compete with the current CNC milling techniques of ceramics. The design of this research was based on a previous study by Anssari Moin et al. (2011) in which the possibility of 3D printing a titanium RAI was investigated. The aim of this study was to explore the feasibility of fabrication of 3D-printed zirconia RAI through DLP technology.

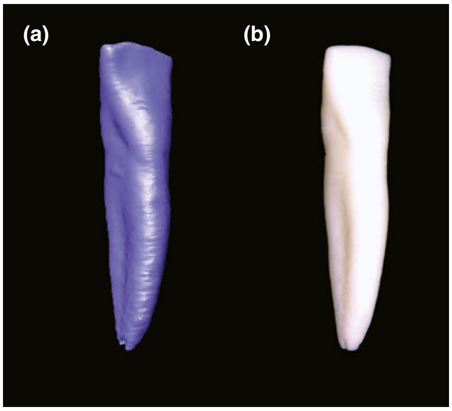

Fig. 1. 3D CAD model of a RAI (a). DLP 3D printed RAI (b).

Material and methods

Sample preparation, radiographic scan and RAI 3D model construction

Based on the previously described method by Anssari Moin et al. (2011), we built a 3D surface model of a RAI. Briefly, human mandibular cadaver with multiple sound teeth, not identified by age, sex or ethnic group, was selected. The mandible was scanned with the 3D Accuitomo 170 cone-beam computed tomography (CBCT) system (Accuitomo 170, 90 kVp, 5 mA, 30.8 s, 4 × 4 cm Field of View (FoV), Morita Inc., Kyoto, Japan). The scan position was with the occlusal plane parallel to the floor following the manufacturer's recommendations. The isotropic voxel size and slice interval were 0.08 mm.

Consequently, the CBCT data set was imported in Amira software for further analysis and image segmentation (v5.3, Visage Imaging, Carlsbad, CA, USA). Threshold-based segmentation techniques were employed to segment a sound lateral lower incisor from its surroundings. The exact procedure for segmenting the tooth was as follows: a region of interest limited to the tooth and surrounding periodontium was first selected. Subsequently, a threshold value based on the histogram analysis, the local grey level value and image gradient was selected to separate the root and crown from the surrounding bone. A manual selection, on basis of the sagittal slides, was added for the most apical part of the root if the threshold-based technique did not confine the entire apex area. The resulting images were processed using interactive processing tools to remove resulting artefacts. The segmented data set was converted to 3D surface model using the marching cube algorithm and saved in the standardized triangulation language (STL) file format. Based on the STL model, a printable 3D RAI mesh has been reconstructed using computer-aided design (CAD) software (SolidWorks 2015 SP3, Dassault Systèmes, Vélizy, France) and stored as a new STL file (Fig. 1a).

3D printing process

A high-end DLP 3D printing technology (under current development by ADMATEC Europe BV, Moergestel, the Netherlands) was used to fabricate the RAI from the CAD STL file. This technology is an additive manufacturing technique in which solid 3D objects are built using a DLP projector to translate voxel data, so it is reproduced in liquid photopolymer, thereby light polymerizing the resin to solid. By altering the pattern of the projection and incrementing the vertical position of the stage, a specific geometry is built up layer by layer (layer thickness varying from 25 μm to 100 μm). To build a solidified ceramic object, the photopolymer used is a dispersion of a commercial ceramic powder (ZrO_2; Formatec Technical Ceramics BV, Goirle, the Netherlands) into a liquid solution of polyacrylate. Subsequently, the residual resin is removed from the solidified object by ethanol and heat treatment and sintered into its final form (Fig. 1b). Due to the current patenting process, further details cannot be provided.

Optical scanning and matching procedure

Optical scanning technology was used to measure the differences between the 3D-printed RAI and the natural tooth that was extracted. The optical system (Atos II SO, GOM GmbH, Germany) uses a fringe projection system in combination with two high-resolution optical cameras to detect the deflection patterns of the projected fringes on the surfaces to be measured. By utilizing a small measurement volume, a high measurement accuracy and resolution were obtained (typical measurement accuracy of 10 microns is achieved in X, Y and Z direction).

To validate the accuracy of the printed zirconium RAI vs. the RAI CAD model vs. the optical scan of the natural tooth, all surfaces were superimposed on the optical scan of the tooth, which served as the gold "reference" standard. The iterative closest point (ICP) registration algorithm was employed to provide maximum alignment. This algorithm brings the two roots to be matched in alignment through minimizing the distance between the two surfaces by calibrating six-degree (three rotation and three translation) transformation parameters (Zhang 1994). The aligned surfaces were compared to each other to establish the difference among the surfaces. The comparison metric was root mean square difference (RMS), which calibrates the mean distance between the two surfaces at anatomically corresponding locations. Additionally, maximum deviation between two surfaces (Hausdorff distance) and the volume was also calculated to provide the maximum deviation among the surfaces.

Results

Comparing the superimposed optical scan surfaces of the original tooth and the CAD model of the RAI to the DLP 3D-printed RAI reveals in most areas a surface distance increase for the DLP 3D-printed RAI (Table 1 and Fig. 2). When setting a maximum threshold of 0.1 and 0.5 mm for the DLP 3D-printed RAI surface to be deviating from the original tooth, measurements reveal 46.38% and 1.55% of the surface areas are exceeding the threshold distances, respectively (Table 1). After repeating this measurement for the DLP 3D-printed RAI surface to be deviating from the CAD model, it is shown that 59.33% and 4.86% of the surface areas are exceeding the threshold distances of 0.1 and 0.5 mm, respectively (Table 1).

Towards the apical foramen, the greatest disparity for DLP 3D-printed RAI compared to the original tooth is noticed with a maximum deviation (Hausdorff distance) of 0.86 mm (Table 1, Fig. 2). The RMS data and surface

Table 1. **Summarized measurements: the optical scan of the 3D printed RAI served as reference standard**

	Optical scan of the tooth vs. Optical scan of the 3D-printed RAI	CAD model of the RAI vs. Optical scan of the 3D-printed RAI
dSurface area %	6.67	7.14
RMS (SD) in mm	0.15 (0.099)	0.18 (0.090)
Maximum errors (Hausdorff distance in mm)	0.86	0.66
% exceeding threshold 0.1 mm	46.38	59.33
% exceeding threshold 0.5 mm	1.55	4.86

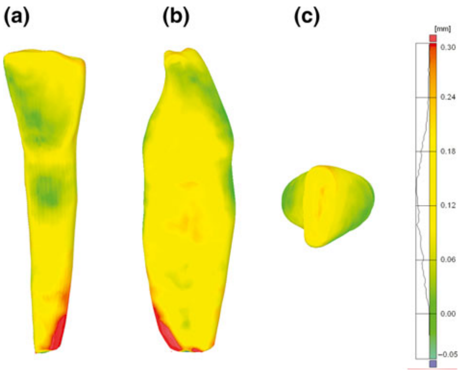

Fig. 2. Superimposed surfaces of the optical scans of the DLP 3D printed RAI and the original tooth. Measurement in millimetres. Frontal (a), sagittal (b) and occlusal (c) views. Notice: optical scan of the tooth served as the reference surface.

area change between the DLP 3D-printed RAI vs. the original tooth and CAD model are measured and summarized in Table 1.

Discussion

This experiment was performed as a first step towards preoperatively 3D printing an individual zirconia root analogue implant. With the combined use of cone-beam CT 3D data and high-end DLP 3D printing technology, it was possible to fabricate a RAI with a certain amount of precision. However, towards the apical area, the divergence increases up to 0.86 mm. This increase in deviation can be explained by the fact that the supporting platform from which this object was built during the printing process was situated at the apex of the RAI model resulting in added material. In addition, previous studies by Anssari Moin et al. 2011, 2012 have shown that during the threshold-based segmentation process from the CBCT, data towards the apical area distinction of root and bone become more difficult in developing a gradual overestimation nearing the apical area. In general, the results show that the printed RAI has a 6.67% larger surface area and 46.38% of the printed RAI has a greater distance than 0.1 mm from the original tooth representing a volumetrically larger copy. Nonetheless, when comparing the printed RAI to the CAD model, measurements show a larger disparity for surface area change (7.14%), percentage threshold surpassing for 0.1 mm (59.33%) and 0.5 mm (4.86%). This shows that the current stage in which DLP 3D printing technology resides provides less accurate models then the commercially available additive manufacturing techniques for metals such as SLM and DMLS (Anssari Moin et al. 2011, 2012). Numerous factors influence the precision of the DLP 3D printing of ceramics, specially the resolution of the digital mirroring device which a part of the DLP printer and the composition of the ceramic photopolymer. Conversely, fine tuning of the DLP 3D printing process for ceramics is an engineering challenge and beyond the scope of this study.

With the advancing possibility to 3D print advanced ceramics for implant dentistry, new possibilities and questions arise. Potential advantages over CNC milling of unsintered ceramics comprise the precise control over spatially grade composition, microstructure design/distribution and (undercut) shape. How 3D-printed zirconia (root analogue) implants with possible (microstructure/porosity) modifications will influence osseointegration and the peri-implant biology needs further research. Nevertheless, we can conclude that with the use of currently available DLP 3D printing technology, it is feasible to pre-emptively fabricate a one-piece zirconia (root analogue) implant.

Conflict of interest

The authors declare that they have no conflict of interests.

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