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3D printed replicas for endodontic education

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Abstract

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Aim To assess the feasibility of producing artificial teeth for endodontic training using 3D printing technology, to analyse the accuracy of the printing process, and to evaluate the teeth by students when used during training.

Methodology Sound extracted human teeth were selected, digitalized by cone beam computed tomography (CBCT) and appropriate software and finally reproduced by a stereolithographic printer. The printed teeth were scanned and compared with the original ones (trueness) and to one another (precision). Undergraduate dental students in the third and fourth years performed root canal treatment on printed molars and were subsequently asked to evaluate their experience with these compared to real teeth.

Results The workflow was feasible for manufacturing 3D printed tooth replicas. The absolute deviation after printing (trueness) ranged from 50.9 to 104.3 μm. The values for precision ranged from 43.5 to 68.2 μm. Students reported great benefits in the use of the replicated teeth for training purposes.

Conclusion The presented workflow is feasible for any dental educational institution who has access to a CBCT unit and a stereolithographic printer. The accuracy of the printing process is suitable for the production of tooth replicas for endodontic training. Undergraduate students favoured the availability of these replicas and the fairness they ensured in training due to standardization.

Keywords: 3D printing, artificial teeth, education, endodontics, feasibility study.

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Introduction

There is a demand for realistic, extensive and repetitive hands-on training in pre-clinical settings to prepare students to carry out their first dental treatment on patients. In Endodontics, a large range of manual competencies are expected to be executed by dentists, for example accessing the pulp chamber, identifying the canal orifices as well as shaping and filling the root canals (de Moor *et al.* 2013). For training, performing these steps on extracted human teeth has been the standard practice in pre-clinical courses for decades. Extracted teeth remain the most realistic training tools; however, their use has several drawbacks that have come to the fore in recent years (DeWald 1997, Tchorz *et al.* 2015): availability is difficult, selection of suitable teeth is time-consuming, ethical considerations must be taken into account, there are concerns over cross-infection and they have a nonstandardized anatomy for test situations (student assessments). As a result, simulated canals in plastic blocks were introduced for endodontic training that was meant to overcome these disadvantages (Spenst & Kahn 1979). Although they allow the individual treatment steps to be visualized, they do not imitate an entire root canal system but rather a single root canal, thus they are not realistic enough for repetitive training measures. Subsequently, artificial teeth have been promoted as possible alternatives (Nassri *et al.* 2008). They are realistic and standardized, visualization is possible when transparent and most of the teeth are radiopaque. However, their

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disadvantages include high costs, limited selection of tooth types and delivery times must be considered with a dependency on a manufacturer. The manufacturing process of 3D printing has evolved over the last few decades, and various applications of 3D printing technology exist in medicine, dentistry as well as Endodontics (Anderson *et al.* 2018). These include guides for access opening (Krastl *et al.* 2016) and root-end surgery (Ahn *et al.* 2018), printed replicas for determining the correct size of autotransplantation fields (Cousley *et al.* 2017) and educational models (Reymus *et al.* 2018).

There are a number of 3D printing technologies in use today. Fused deposition modelling (FDM) is most common especially for private use as it is relatively inexpensive, although less accurate (Kim *et al.* 2016). MultiJet Printing and PolyJet Printing devices are more precise but are more expensive (Van Noort 2012). Digital light processing (DLP) and stereolithography (SLA) both work with the polymerization of photosensitive resin from the bottom of a tank (Groth *et al.* 2014). The DLP technology uses a projector which exposes an entire layer, whereas SLA works with a laser which polymerizes single points rather than an entire image.

New devices working with these technologies have been introduced as the expiry of the patent of SLA technology held by 3D Systems (Rock Hill, SC, USA). They are in general user-friendly and require no prior knowledge of their handling; as they are highly cost-effective, they have become a reasonable alternative for dental educational institutions.

The aim of this study was to overcome the disadvantages of commercial tooth replicas for endodontic training by manufacturing artificial teeth within the limited technical borders of a dental educational institution using SLA printing technology.

The workflow to achieve tooth replicas was intended to be simple, user-friendly and time and cost-effective as well as being transferable to other educational institutions. The generated teeth were meant to be suitable for practising access opening, for canal instrumentation, radiographic length control and root filling, thus fulfilling all the requirements for educational use in pre-clinical student courses. The final goal was to create artificial teeth that were realistic and represented an alternative to extracted human teeth and commercial replicas for endodontic training. The trueness and precision of printed teeth were measured to evaluate the accuracy of the printing process. Finally, students having performed root canal treatment on a printed molar were asked to evaluate their experience.

Materials and methods

Suitable extracted human teeth were selected. The exclusion criteria were previously determined for root canal treatment: incomplete root growth, extensive loss of tooth structure, radiographically undetectable root canals along their entire length and an anatomy presenting a degree of difficulty too great for pre-clinical student courses, for example obliteration and high curvature. To ensure the patency of the apical part of a root canal, a retrograde preparation of the apical 5 mm with hand files up to size 10 was conducted. With teeth having narrow root canals along their entire length, a small access cavity opening was prepared, and the root canals were manually prepared with hand files up to size 20, rinsed with sodium hypochlorite and dried with papers points. Subsequently, a cotton pellet was inserted into the pulp chamber and the cavity was closed with a radiopaque filling material. A three-dimensional radiograph of the selected teeth was taken using a CBCT with a small field-of-view (Kodak 9300; 5 × 5 × 5 cm; 78 kV; 6.3 mA; 20 s; Kodak, Rochester, NY, USA; Fig. 1). The generated data were exported as single DICOM-files and imported to the application Invesalius for Mac 3.0 (Centre for Information Technology Renato Archer, Amarais, Brazil). It converts a sequence of 2D images, such as the single DICOM-files, in volumes or surfaces as meshfiles, that is standard triangulation language (STL; Fig. 2). The generated STL-files were subsequently imported to the software Meshmixer for Mac 11.0 (Autodesk, San Rafael, CA, USA) which allows further investigation, processing and selection of the digitalized teeth. The final STL-files (master file) were imported to the software Preform for Mac (Formlabs, Sommerville, MA, USA), in which the support structure, required for printing, was added and the file was prepared for the printing process. Finally, the replicas were printed with a stereolithographic printer (Form 2; Formlabs) using the resin of the manufacturer (Grey V3 FLGPGR03; Formlabs; Fig. 3). To achieve radiopacity, 10 g of barium sulphate powder was mixed with 100 mL of resin keeping in mind that the radiopacity of the replicas had to be revaluated after each manufacturing process as the printer constantly adds fresh resin into the printer's reservoir.

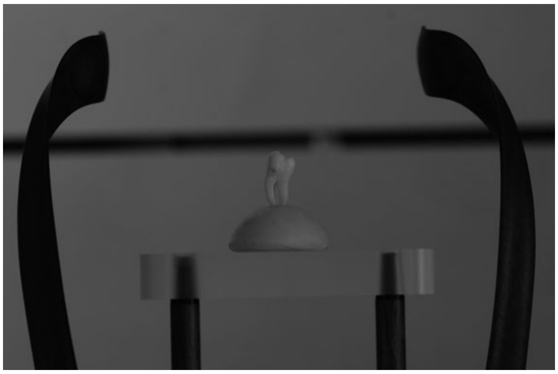

Figure 1 Real tooth within the CBCT unit for digitalization.

Figure 2 Digitalized tooth within the software Invesalius.

After having been manufactured, the replicas were separated from the support structure and cleaned with alcohol for 2 min in an ultrasonic bath. Subsequently, the replicas were inserted into a centrifuge (Allegra X-15R; Beckmann-Coulter Life Science, Indianapolis, IN, USA) for 10 min at 3500 revolutions per minute to free the canals from uncured resin.

Figure 3 Printed replicas directly after the reproduction process on the printer's platform.

Finally, the replicas were post-cured for 15 min (LC 3DPrint Box; Next Dent, Soesterberg, the Netherlands).

To evaluate the trueness and precision of the printing process, a replica of a first maxillary premolar was printed ten times in the following settings:

1. layer thickness of 25 μm with the axis of the tooth positioned horizontally to the print platform (25 μm_hor)
2. layer thickness of 25 μm with the axis of the tooth positioned horizontally to the print platform, resin mixed with barium sulphate powder (25 μm_hor_bs)
3. layer thickness of 25 μm with the axis of the tooth positioned vertically to the print platform (25 μm_ver)
4. layer thickness of 25 μm with the axis of the tooth positioned vertically to the print platform, resin mixed with barium sulphate powder (25 μm_ver_bs)
5. layer thickness of 100 μm with the axis of the tooth positioned horizontally to the print platform (100μm_hor)
6. layer thickness of 100 μm with the axis of the tooth positioned horizontally to the print platform, resin mixed with barium sulphate powder (100 μm_hor_bs)
7. layer thickness of 100 μm with the axis of the tooth positioned vertically to the print platform (100 μm_ver)
8. layer thickness of 100 μm with the axis of the tooth positioned vertically to the print platform, resin mixed with barium sulphate powder (100 μm_ver_bs)

The surfaces of the replicas were scanned (Activity 888, Smart Optics, Bochum, Germany) to obtain STL-files for each replica. The single STL-files were compared to the printable master file representing the trueness and to another in each group representing the precision of the printing process. For this comparison, the open-source software CloudCompare (www.cloudcompare.org) was used. In this application, the two STL-files to be compared were first aligned to each other manually by picking four equivalent point pairs and then superimposed by means of best-fit superimposition by the software. The STL-files were subsequently converted to point clouds with 50 000 points each, and the absolute distances of corresponding points were measured. To eliminate outlier values resulting from this method, the 10% and 90% percentiles of absolute distances of each superimposition were calculated. The values under 10% and over 90%, respectively, were excluded and the remaining values summarized. For each group, the mean, standard deviation and 95% confidence interval were calculated (Table 1) using SPSS 23 (IBM, Armonk, NY, USA).

Students in the third and fourth year having either trained with extracted human teeth or performed a root canal treatment on a patient, had to perform the following treatment steps on a printed mandibular molar: creation of the access cavity, manual negotiation of the root canals, radiographic length control, rotary preparation (Mtwo; VDW, Munich, Germany) and root canal filling (Thermafil, VDW). Subsequently, the students were asked to evaluate the printed replicas in comparison with an extracted human tooth. The questionnaire consisted of eleven multiple-choice questions comparing the anatomical similarity, the individual treatment steps (performing the access opening, finding the root canals, manual and rotary preparation, obturation), radio opacity and mechanical properties. Finally, the students were asked to identify what they thought was the greatest advantages of printed replicas in comparison with real teeth.

Results

The digitalization of human teeth through a CBCT scan with the subsequent application of suitable software solutions and the reproduction by a stereolithographic printer enabled the manufacturing of tooth replicas.

Sufficient radiopacity was achieved by mixing barium sulphate powder into the uncured resin (Fig. 4). The printed replicas are realistic in comparison with natural teeth as seen in Fig. 5. The material property of the resin was suitable for its preparation with diamond dental burs and various endodontic instruments (e.g. Gates Glidden burs as well as manual and rotary files). The values of the absolute distances between the corresponding point clouds of the teeth were not normally distributed for both the fine print and the fast print group according to the Shapiro–Wilk test. Regarding trueness, the mean of the absolute distances between the original STL-file and the printed teeth ranged from 50.9 μm (25 μm_hor) to 104.3 μm (100 μm_ver_bs). Regarding precision, the mean of the absolute distances between the teeth within each group ranged from 43.5 μm (25μm_hor) to 68.2 μm (100 μm_ver_bs). All results are listed in Table 1.

The questionnaires from 105 students were analysed. The anatomic similarity of the replicas was mostly judged as being very comparable (60%) or rather comparable (34%) to real teeth. The preparation of the root canals, however, was considered as being easier in comparison with extracted human teeth (Fig. 6). Correspondingly, the impact of the hardness of the resin was seen as the reason why preparation was easier (71%). In contrast, the filling

Table 1 Mean, standard deviation (SD) and 95% CI of absolute distances for trueness and precision (in μm)

Print method	Trueness		Precision	
	Mean (SD)	95% CI	Mean (SD)	95% CI
25 μm_hor	50.9 (13.3)	[50.8; 50.9]	43.5 (11.1)	[43.6; 43.7]
25 μm_hor_bs	51.7 (21.8)	[51.6; 51.8]	44.2 (12.3)	[44.1; 44.3]
25 μm_ver	54.4 (14.9)	[54.4; 54.5]	44.7 (21.4)	[44.6; 44.7]
25 μm_ver_bs	62.5 (17.6)	[62.4; 62.6]	45.2 (22.0)	[45.1; 45.1]
100 μm_hor	53.5 (14.3)	[53.4; 53.6]	53.1 (15.3)	[52.9; 53.0]
100 μm_hor_bs	56.3 (16.5)	[56.2; 56.3]	55.3 (16.2)	[55.2; 55.3]
100 μm_ver	68.9 (20.7)	[68.7; 68.9]	65.7 (21.6)	[65.6; 65.7]
100 μm_ver_bs	104.3 (16.0)	[103.6; 104.9]	68.2 (22.1)	[68.1; 68.3]

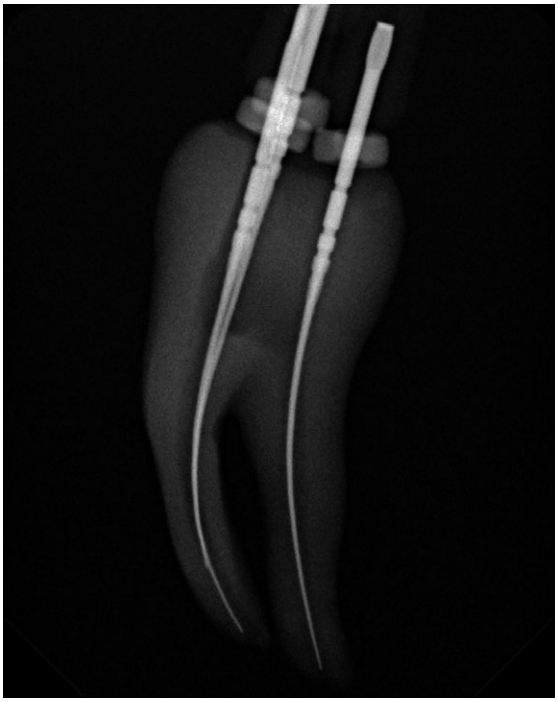

Figure 4 Radiopacity of printed replica.

Figure 5 Final appearance of printed replicas: real tooth and corresponding replicas in grey, white and transparent resin (with red colour in root canals).

of the replica root canals was judged as being very comparable (64%). Regarding the benefits of self-created artificial teeth, students especially favoured the availability and fairness due to the standardization of the teeth (Fig. 7). Hygiene, however, had less importance for them.

Discussion

A number of new innovative models for endodontic education have been proposed by dental schools. They ranged from teaching the use of apex locators (Tchorz *et al.* 2013) to a model for revitalization procedures (Widbiller *et al.* 2017). Recently, 3D printed models based on real patients have been proposed (Kröger *et al.* 2017) for dental education even though they have been known in general medicine for several years (McMenamin *et al.* 2014, Vaccarezza & Papa 2015). With the costs for 3D printing technology constantly declining, the initial investment costs are no more an obstacle. Its great advantage is not only justified by the possibility of exercising direct influence on the design and manufacturing process but also in the immediate availability of the product. For dental schools, 3D printing offers unexpected possibilities for the development of new, individual training models that are either not yet available on the market or are too expensive to purchase in high quantities. Moreover, there is a wide selection of different printers and manufacturers to choose from. Although MultiJet Printers are considered more accurate in comparison with SLA or DLP printers (Ishida & Miyasaka 2016), their investment costs are significantly higher. For a dental school, the most efficient solution seems to be a device which is suitable for creating educational models as well as for the production of applications in patient's care. The presented workflow demonstrates a practical and highly cost-effective way of producing tooth models while being transferable to other educational institutions in the possession of a CBCT and a stereolithographic printer. A micro-CT is an excellent alternative to a CBCT unit in regard to the quality and accuracy of the scan. However, the limited access to Micro CTs as well as the large amount of data generated by each scan may restrict their application in endodontic education.

All software applications used in this study are available online free of charge. They are easy and intuitive to use, and there are several online tutorials giving accurate instructions; neither special training nor specific prior knowledge is required. An operator should therefore be able to work with these applications within 2 days. The replicas are suitable for various aspects of endodontic training, and they show a good comparison to real teeth and exceed commercial replicas in various criteria: they are less expensive, the selection of different teeth is not limited, they have good radiopacity and are available in sufficient numbers at the right time. Nevertheless, fine structures, such as lateral root canals, small isthmuses or very narrow root canals, cannot yet be reproduced with a 3D printer such as the one used in this study.

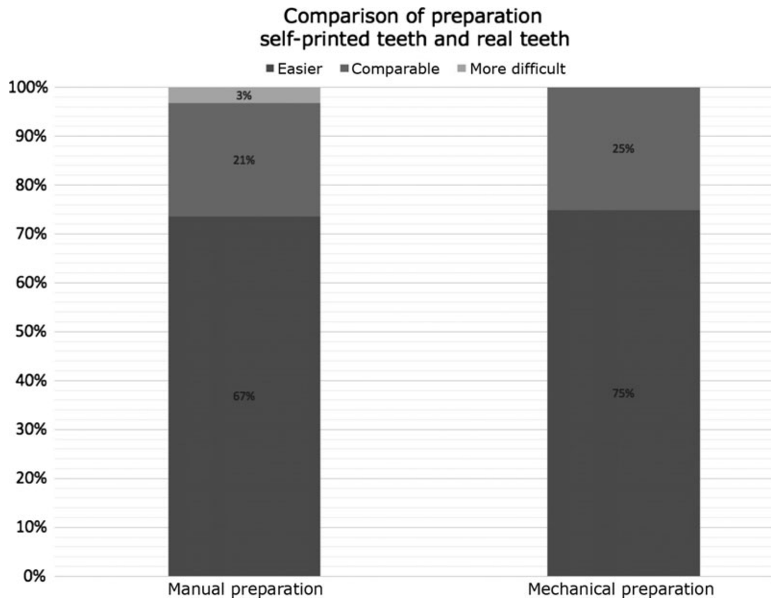

Figure 6 Comparison of root canal preparation of printed replicas to real teeth.

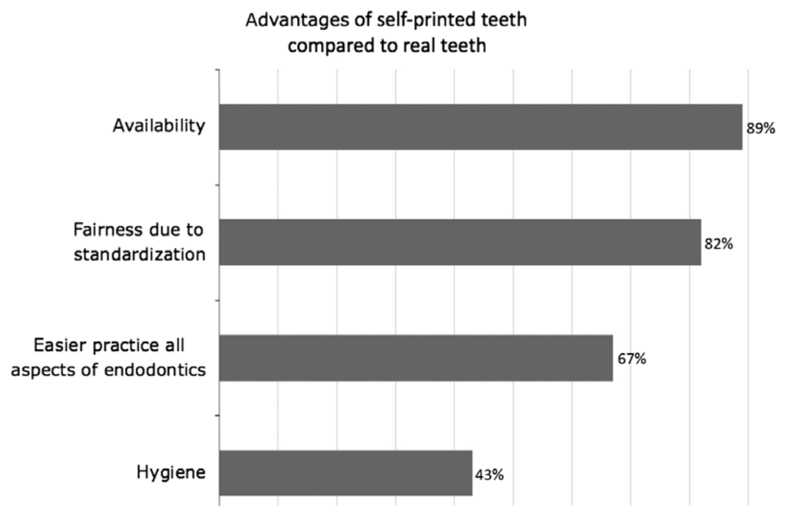

Figure 7 Advantages of printed replicas compared to real teeth (multiple answer).

For such special training measures, commercial replicas are still the first choice. Conventional resin for 3D printing is not able to reproduce the physical properties of a biological material such as dentine. Regarding the stiffness of the resin used in this study, it is considerably less than human dentine (2.8 GPa vs. 20–25 GPa) and so is the ultimate tensile strength (65 MPa vs. 104 MPa; Materials Data Sheet by Formlabs, Version 01/27/2017; Sano *et al.* 1994, Kinney *et al.* 2003). This fact is indeed a drawback of the resin. A new approach based on 3D printing using a microporous hydroxyapatite-based matrix (Robberecht *et al.* 2017) as printing material seems to be promising for correctly imitating dentine. Not surprisingly, the students assessing the replicas found that their hardness was less comparable to real teeth.

The workflow presented in this study can be adapted to the technical possibilities of any institution. Therefore, the digitalization of extracted teeth could be achieved with a micro-CT as well. The authors of this study encourage other institutions to copy and further develop the workflow hoping that they share their experiences. Within this workflow, the selection of suitable extracted human teeth is still the most time-consuming part. With dental schools being increasingly in financial competition, the availability of staff members and their time is the most important asset of any institution. In the future, an online platform where educational institutions could share their printable files to profit from each other would be a considerable benefit for the entire educational community. Artificial teeth have the potential to replace natural teeth in endodontic training (Nassri *et al.* 2008). They overcome their disadvantages, such as potential of cross-infection, ethical considerations of their origin and nonstandardized anatomy. Although they are suitable for imitating all aspects of endodontic treatment and prepare students sufficiently for their first treatment on a real patient (Bitter *et al.* 2016), natural teeth still remain the gold standard in terms of comparison of the situation on a patient.

To assess whether the manufacturing process with a low-cost desktop printer such as the one used would be applicable for repeatable production of such replicas, trueness and precision were evaluated. As the best results regarding trueness and precision were achieved for the specimens manufactured in the fine print method and horizontal positioning, these settings are recommended for achieving the best print results. Mixing the resin with barium sulphate powder only had minor effects on recorded precision and trueness. This is especially true for horizontal positioning. Although it was only possible to investigate the outer surface of the teeth, one can assume that the results correspond to the inner anatomy as well. However, uncured resin remaining in the reproduced root canals is an obstacle for their patency as the resin will polymerize in time and block them. To overcome this disadvantage, centrifugal force was applied to the replicas directly after the manufacturing process to remove the uncured resin out of the canals. To do so, the root canals have to be patent at the apical foramen. That is why a retrograde preparation of the apical part of the root canals of the extracted human teeth was conducted with hand files before digitization. As an alternative to this method, the root canals can be edited digitally to either change the width or the curvature of the canal to adapt to the morphology of the student. This, however, requires special computer-aided-design (CAD) software applications for which specific computer skills are a prerequisite. As the aim of this study was to present a simple workflow which can be copied by other dental schools, this procedure is not further described.

Students who trained with the replicas mostly judged them as being very comparable to real teeth in terms of anatomic design. The preparation of the root canals, however, was easier on the replicas than on real teeth, according to the students. This is probably due to the reduced hardness of the resin compared to real teeth. Radiopacity of the replicas could be gained by adding barium sulphate powder to the resin making radiographic control possible. However, the replicas are still less radiopaque than dentine. Future projects should seek to find resin with physical properties that are more similar to dentine in terms of hardness and radiopacity. 3D printing resin for the manufacturing of temporary crowns and bridges might be such an alternative.

Conclusion

The presented workflow will enable dental educational institutions to manufacture their own tooth replicas for endodontic training. For this purpose, teeth with certain desired anatomic characteristics can be selected to reduce redundancy in endodontic education. The accuracy of the printer is suitable for the production of realistic replicas. Students appreciate the short-term availability of the replicas and their standardization which results in better comparability and thus leads to greater fairness in the training simulation.

Conflict of interest

The authors have stated explicitly that there are no conflict of interest in connection with this article.

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