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ORIGINAL ARTICLE

Effectiveness of a 3D Printed Training Kit for the Preparation of Access Cavities in Calcified Teeth: A Pilot Study

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ABSTRACT

Objective: This study aimed to evaluate the effectiveness of a 3D printed training kit for the preparation of endodontic access cavities in calcified teeth.

Methods: The root canal system of a micro-CT scanned premolar was digitally processed to create an endodontic training kit containing 10 teeth with ten different progressive degrees of pulp canal calcification. A tooth variant with a medium calcification degree (5/10) was printed in three copies using opaque resin. Additionally, a set of 10 transparent training teeth with red-colored pulp was produced using PolyJet 3D printing technology, which was used to train the access cavity preparation in a controlled manner due to the transparency of the teeth. Undergraduate students (n=27) and dentists (n=10) each prepared a total of 13 (one pre-training, two post-training) access cavities. Substance loss was quantified by CBCT, and user satisfaction was evaluated by questionnaire. Paired t-tests were used to compare the means for substance loss and procedure time for pre- and post-training conditions. Unpaired t-tests were used to compare differences between students and dentists. The level of significance was set at α=0.05.

Results: Mean substance loss before and after training decreased for both students (71.4 versus 54.68 mm^3; p=0.069) and dentists (67.3 versus 51.1 mm^3; p=0.633), but the difference was not statistically significant. The average preparation time decreased with training for students (420 versus 275 seconds; p=0.100) and dentists (336 versus 158 seconds; p=0.054), but not significantly. Root perforation rates also decreased (students: 6/27 versus 4/27; dentists: 1/10 versus 0/10) . Participants rated the training model as very realistic and useful, despite the difference in material texture.

Conclusion: The proposed 3D printed training kit appears to be a suitable tool for undergraduate dental students, which could expand their opportunities to practice the preparation of endodontic access cavities in calcified teeth.

Keywords: Endodontic education, pulp canal calcification, pulp obliteration, substance loss

HIGHLIGHTS

- 3D printed teeth are valuable for endodontic education.
- Endodontic access cavities were less invasive after using a 3D printed training kit.
- Preparation time for endodontic access cavities decreased after using a 3D printed training kit.

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INTRODUCTION

Although root canal treatment is a standard procedure in daily practice, it often presents major challenges for dentists (1). The first invasive step of root canal treatment is the preparation of an endodontic access cavity, which should be performed as minimally invasive as possible to increase fracture resistance (2). The presence of pulp canal obliteration (PCO) further complicates this procedural step and is associated with an increased failure rate (3, 4). PCO can result from various causes, including physiological dentine apposition in the elderly and the formation of tertiary dentine due to pathological conditions such as caries or trauma (5, 6).

Although it has been shown that experienced specialists can successfully detect calcified root canals, albeit sometimes with significant time and effort (7), inexperienced dentists frequently cause perforations when attempting to do so in teeth with PCO (8). This reduces the prognosis for tooth survival and increases the risk of extraction.

Therefore, preclinical training with such challenging teeth can be of great value in dental education by helping students improve their practical skills.

Dental students typically perform their first root canal treatment during the preclinical curriculum. However, the lack of suitable extracted teeth limits their training opportunities. Teeth with PCO are challenging to obtain and vary in complexity. Therefore, the potential for using alternative training materials has been explored for quite some time. Spenst and Kahn (9) pioneered the use of acrylic materials, which were limited to root canal preparation, irrigation and obturation, but were not suitable for access cavity preparation.

Advances in digital technology have opened up new opportunities, such as computer-aided design and manufacturing (CAD/CAM). In recent years, 3D printing has become more widely available and affordable, allowing dentists and dental students to explore new training options (10).

Teeth with the desired morphology can be digitally designed and manufactured using micro-CT and CBCT scan data and appropriate software (8).

The use of 3D printed teeth in endodontics has been shown to improve training and test fairness (11). Another study also showed that 3D printed teeth can enhance preclinical endodontic training, although students preferred extracted teeth due to their superior physical characteristics (12).

To the best of our knowledge, there are no studies addressing the use of 3D printed teeth to train students in the preparation of access cavities in teeth with calcified root canals at the preclinical stage of the dental curriculum.

Therefore, the aim of this work was to evaluate the effectiveness of a 3D printed endodontic training kit regarding root canal detection rate, amount of substance loss, and educational suitability for access cavity preparation training in teeth with varying degrees of calcification.

MATERIALS AND METHODS

Fabrication of the Training Kit

The ethics committee of Northwestern and Central Switzerland approved the use of irreversibly anonymized teeth from donors who provided informed consent to the use of their extracted tooth/teeth for research purposes (Ethical approval number: EKNZ UBE-15/111). Informed consent was obtained from all subjects and/or their legal guardian(s). This study was conducted in accordance with the Declaration of Helsinki.

A micro-CT-scanned mandibular first premolar, extracted for reasons unrelated to this study, was used to design three-dimensional training models of the tooth. The root canal system was modified using 3D creation software (Blender 2.79; Blender Animation Study, Amsterdam, The Netherlands). First, the pulp was virtually separated from the tooth surface and modified to create an idealized version of a juvenile tooth with a large pulp volume (version 1; Fig. 1a). From this version, the pulpal lumen was trimmed by 10% in the vertical direction and then contracted by 10% in diameter. Nine additional versions with a constant and standardized calcification were created in this way, by a 10% downsizing compared to the previous version. (versions 2–10, Fig. 1b-j). In order to ensure that the following fabrication by 3D printing proceeded without errors, care was taken to ensure that the diameter of the pulp was not less than 200 micrometers in the horizontal plane during downsizing. This resulted in calcification occurring exclusively in the vertical direction in versions h to j.

These ten versions were exported as STL files and printed using a PolyJet printer at a resolution of 16 µm (Objet 500 DS, Stratasys, Edina, MN, USA).

Resin materials of different hardness and color were used to differentiate pulp tissue from dental hard tissue. A soft, red material with Shore A30 hardness was used to simulate pulp tissue (IORA FLX, Stratasys).

The hard tissues of versions 1–10 were printed with a transparent material (Vevo clear, Stratasys). The hard tissues of version 5 were additionally printed with an opaque resin (Med690, Stratasys) to simulate moderate calcification. All replicas were polished to a high gloss after printing (Fig. 2).

For each access cavity, diagnostic radiographs were provided. The original radiograph of the premolar was edited using GIMP (version 2.10.14) to create mesio-distal and bucco-lingual projections for all ten versions, reflecting the respective dimensions of the obliterated pulp (Fig. 1).

Mandibular models were fabricated for mounting the 3D printed (opaque) premolar in a dental dummy to simulate clinical conditions (Fig. 3). A different mounting system was designed for the transparent teeth, which were processed extraorally.

Each study participant received three replicas of the opaque version 5 and one replica of each transparent version 1 to 10 (details for the study workflow are presented in Fig. 4).

Access Cavity Preparation and Questionnaire

The 37 participants were divided into a test group and a control group. The test group consisted of 27 undergraduate students (mean age: 23.1 years, range 20 to 26 years) in their third preclinical year. Nineteen were female, seven were male, and one identified as non-binary. Participation was voluntary and ungraded, and nonparticipation did not affect their academic ratings. All students had received prior hands-on training in endodontics on resin blocks and extracted teeth.

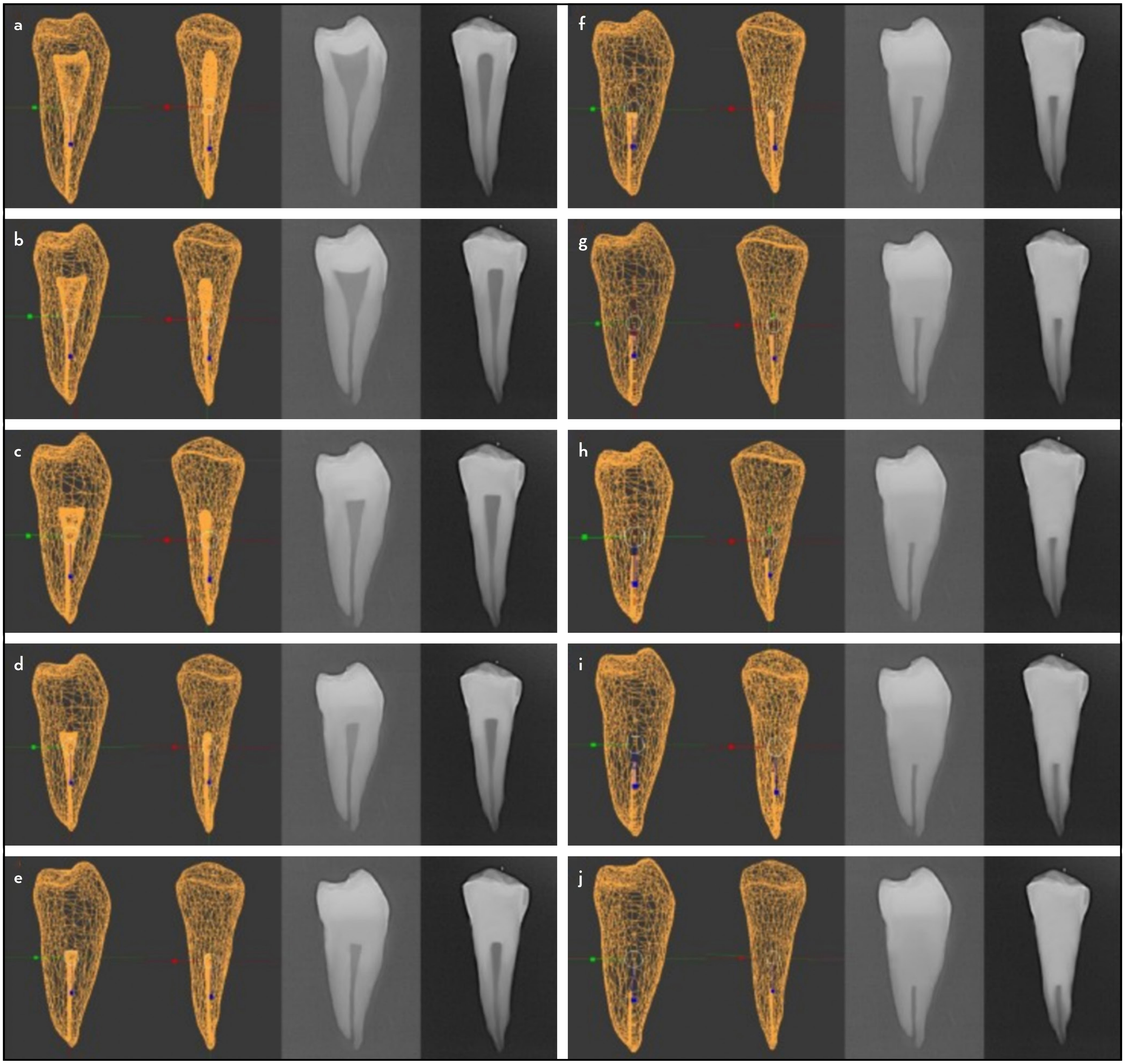

Figure 1. Digital modification of the pulp in versions 1-10: Version 1 (a) simulated a juvenile tooth with a large pulp, gradually reduced in length and diameter in 10% increments to produce versions 2 to 10 (b-j). The labial and proximal views of the teeth are shown in the software and the corresponding diagnostic radiographs

The control group consisted of 10 fully trained dentists with different levels of experience in different areas of dentistry. Three of the dentists were female, and seven were male. They had a mean of 3.4 years of work experience (range: 1 to 14.5 years). Four dentists specialized in endodontics, three in periodontics, and three in general dentistry. The mean age of the dentists was 28.8 years.

All participants received a brief explanation of the procedure before beginning the training exercises and were provided digital radiographs of respective tooth versions. Access cavity preparation was performed using a high-speed contra-angle handpiece (1:5, KaVo Master Series; KaVo Dental GmbH, Biberach, Germany) with a standard cylindrical diamond bur with rounded edges and a diameter of 1.0 mm (837 KR; Intensiv SA, Montagnola, Switzerland). Operators in both groups were allowed to use conventional optical magnification aids, with the exception of dental microscopes, since undergraduate students had no previous experience or instructions with microscopes. The training procedure was as follows:

Before training, access cavity preparation was performed "intraorally" on an opaque tooth (version 5) mounted in a dental dummy (tooth #0). During training, the same procedure was performed extraorally on the transparent teeth (teeth #1 to #10) in chronological order. After preparation, root canal detection was

Figure 2. Transparent and opaque 3D printed replicas with varying degrees of pulp canal obliteration

Figure 3. Opaque training tooth placed on the model, which was mounted in a dental dummy for access cavity preparation

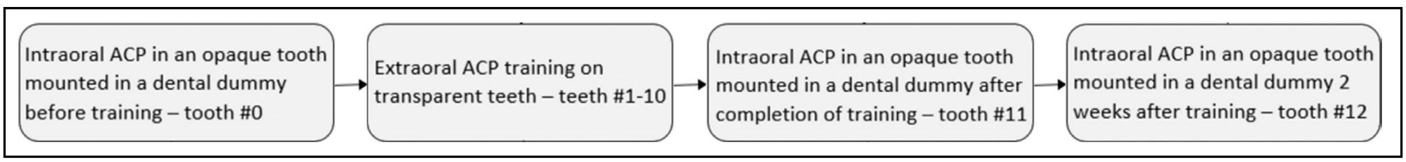

Figure 4. Training workflow

ACP: Access cavity preparation

Gender: ______

Age: ______

Was it easy to find enough extracted teeth for the practical course? ☐ Yes ☐ No

Training with the 3D-printed teeth on the mounting and dental dummy was: ☐ useful ☐ unnecessary

Compared to the extracted teeth, the printed teeth are:

harder ☐	identical ☐	softer ☐
more suitable for training ☐	identical ☐	less suitable for training ☐
fairer for exams ☐	identical ☐	less fair for exams ☐
easier to handle ☐	identical ☐	more difficult to handle ☐

Comments:

Figure 5. Questionnaire administered at the end of the study

confirmed with an ISO 10 K file (VDW, Munich, Germany). After completion of training (teeth #1–10), the intraoral access cavity preparation was repeated on another opaque tooth (version 5) in the dental dummy (tooth #11). Two weeks later, intraoral preparation of another opaque tooth (version 5) was performed under simulated clinical conditions (tooth #12). Preparation time was evaluated based on the time required to prepare the opaque tooth (#0, #11, #12). The training workflow is shown in Figure 4.

At the end of the study, the participants received an anonymous questionnaire (Fig. 5) asking them to rate and compare the 3D printed teeth to extracted teeth. It also contained a free text comments section where they could express their opinions freely.

Calculation of Substance Loss

The prepared opaque teeth (#0, #11, #12) and one non-prepared tooth were mounted in silicone and scanned with a CBCT scanner (Accuitomo 170; Morita Manufacturing Corp, Kyoto, Japan) in preparation for substance loss measurements. Images were acquired with the following settings: 70KV, 6 mA, voxel size: 125 µm, field of view: 6x6 cm. The images were converted to DICOM format for further analysis.

TABLE 1. Results (mean and 95% confidence intervals (CI)) for the volume of tooth structure removed (in mm^3) during the preparation of teeth #0, #11, and #12 by students and dentists

Level	Mean #0	Lower 95%-CI	Upper 95%-CI	Mean #11	Lower 95% CI	Upper 95% CI	Mean #12	Lower 95% CI	Upper 95% CI
Student	71.4	58.21	84.58	67.41	56.11	78.71	54.68	45.4	63.96
Dentist	67.3	36.23	98.37	62.79	43.83	81.74	51.1	34.72	67.48

CoDiagnostiX software (Dental Wings Inc., Montreal, Canada) was used to measure substance loss. Grayscale thresholds were identical for all scans. Access cavities were automatically determined by the software, the volume of the remaining tooth substance was calculated and the differences between the preoperative value of a non-prepared tooth and postoperative values used for further statistical analysis. The postoperative CBCT scans were also used to evaluate perforations occurred during access cavity preparation of teeth #1, #11 and #12.

Statistical Analysis

Descriptive statistics were generated using SPSS version 26 (IBM Corp, Armonk, NY). Prior to conducting further statistical analyses, the normality of the data was assessed using the Shapiro-Wilk test.

Mean values of tooth substance loss and procedure time and their 95% confidence intervals (CI) were calculated. The mean values for tooth #1, #11 and #12 were compared using paired t-tests. The level of significance was set at $\alpha=0.05$. To compensate for type I error due to multiple comparisons, p-values were adjusted using the Bonferroni correction method.

Independent t-tests with a significance level of $\alpha=0.05$ were used to compare the mean values for substance loss and procedure time between students and dentists.

RESULTS

Substance loss and procedure time were normally distributed, as assessed by the Shapiro-Wilk-Test ($p>0.05$).

Substance Loss

Evaluation of substance loss in the prepared opaque teeth (#0, #11, #12) before and after training (T0, T1, T2) showed that the performance of both students and dentists improved with training. For the students, the average volume of tooth substance removed before training was 71.4 mm^3 (tooth #0), then decreased to an average of 67.41 mm^2 at the end of training (tooth #11) and was even lower (54.68 mm^2) two weeks later (tooth #12). However, the differences between the mean values were not statistically significant in the student group ($p=0.069$).

Similar results were observed in the control group (dentists). The dentists' access cavity preparations also became more minimally invasive with training (teeth #0 to #12). However, no statistically significant differences were observed ($p=0.633$). A detailed breakdown of the substance loss results is presented in Table 1.

Both students and dentists showed significant improvement in procedure time after completion of training (tooth #0 vs. #11; students: $p<0.001$; dentistst: $p=0.004$). Two weeks after training (tooth #12), procedure times were slightly longer than at the end of training (tooth #11). Procedure times were still shorter than at baseline (tooth #0), yet without statistically significant differences (students: $p=0.100$; dentists: $p=0.054$). A detailed breakdown of the procedure time results is presented in Table 2.

Independent t-tests revealed that the differences between dentists and students for substance loss and procedure time were not statistically significant (Volume: $p=0.541$; Time: $p=0.084$).

Perforation and Root Canal Detection Rates

During access cavity preparation before training (tooth #0), 25 out of 27 (93%) students successfully located the pulp/ root canal and six (22%) caused a perforation. After completion of training (teeth #1–10), 24 students (89%) successfully located the pulp/ root canal with a total of four perforations (15%). Two weeks after the first training, all 27 students (100%) detected the root canal system successfully (four perforations occurred (15%)). Fourteen students (52%) did not perforate any of the 3D printed teeth during the entire training exercise. Among the dentists, one (10%) periodontist perforated tooth #0.

Questionnaire Findings

Of the 27 students surveyed, 7 (26%) reported difficulty finding suitable extracted teeth for the undergraduate endodontic course. Overall, 22 students (81.5%) and all dentists (100%) rated training with the 3D printed teeth in a dental dummy as very useful.

When asked to rate the material hardness of 3D printed teeth compared to extracted teeth, 40.7% of students rated the printed teeth as "harder", 22.2% rated them as "identical", and 37% rated them as "softer". Among dentists, 60% rated the hardness of 3D printed teeth as "softer", and the rest rated it as "identical" to extracted teeth.

Regarding the suitability of the extracted teeth for training, most dentists and students found the printed teeth to be as good as or better than the extracted teeth. In addition, 85.2% of the students rated the test fairness of the 3D printed teeth as equal to or better than that of the extracted teeth.

Detailed summaries of the survey responses are presented in Tables 3 and 4.

Approximately half of the students provided additional feedback in the free-text comments section. Many students (n=14) praised the educational value of the transparent teeth and the mounting of the teeth in a dental dummy. One student mentioned the lack of odor as an advantage. Several students (n=8) suggested that the endodontic training kit exercises be included in the regular curriculum. None of the dentists left comments.

TABLE 2. Results (mean and 95% confidence intervals (CI)) for the time required (in seconds) for the preparation of teeth #0, #11, and #12 by students and dentists

Level	Mean #0	Lower 95%-CI	Upper 95%-CI	Mean #11	Lower 95% CI	Upper 95% CI	Mean #12	Lower 95% CI	Upper 95% CI
Student	419.56	323.29	515.82	161.15	125.5	196.8	274.52	203.94	345.1
Dentist	336	210.23	461.77	134	91.03	176.97	157.8	80.35	235.25

TABLE 3. Questionnaire responses from students (n=27)

	n	%
Harder	11	40.7
Identical	6	22.2
Softer	10	37
More suitable for training	6	22.2
Identical	15	55.5
Less suitable for training	6	22.2
Greater fairness	13	48.1
Identical	10	37
Less fairness	4	14.8
Easier to handle	9	33.3
Identical	11	40.7
More difficult to handle	7	25.9

TABLE 4. Questionnaire responses from dentists (n=10)

	n	%
Harder	0	0
Identical	4	40
Softer	6	60
More suitable for training	3	30
Identical	7	70
Less suitable for training	0	0
Greater fairness	7	70
Identical	3	30
Less fairness	0	0
Easier to handle	2	20
Identical	7	70
More difficult to handle	1	10

DISCUSSION

This study showed that both students and dentists could benefit from a novel 3D printed training kit for the preparation of endodontic access cavities in calcified teeth. During the tests, the access cavities became more minimally invasive, and both procedure time and perforation rate decreased. The students rated the 3D printed teeth as a helpful training exercise and an excellent alternative to extracted teeth. However, it was found that the decrease in substance loss was not statistically significant. This lack of statistical significance can be attributed to the relatively low number of participants in this pilot study. The loss of substance obviously varied relatively widely from participant to participant and outliers in both directions were observed. An increase in the number of participants would reduce the impact of these outliers and lead to a reduction in the range of the measurable confidence intervals. Thus, if this pilot study progressed with an increased number of participants, statistically significant differences could also be expected. An increase in the sample size would improve the robustness and generalizability of the findings.

Root canal treatment is generally considered a challenging task for dental students and newly graduated dentists (1). In this pilot study, the control group consisted of dentists with different specializations and different levels of expertise. In future studies, individual groups with certain specializations and defined levels of work experience could show more precisely for which group of dentists such training kits could be particularly suitable and answer the question of whether only inexperienced dentists could benefit from them or whether experienced dentists could also improve their performance. In this study, the mixed control group was selected to address the general question of whether such training kits are useful at all within postgraduate training or whether their use should be restricted to undergraduate training.

Puryer et al. (13) showed that students lacked confidence in performing a full root canal treatment on anterior and posterior teeth and that the level of confidence was related to the number of teeth treated. Students surveyed cited the limited availability of extracted teeth as a reason for the lack of practice opportunities. As a result, the training for simple endodontic treatments was deemed insufficient, making it difficult to gain experience with more complex cases, which were often referred to specialists. The study also found a positive correlation between the number of teeth treated and treatment safety. This underscores the importance of providing dental students with adequate practice opportunities to improve their skills and increase the safety of root canal treatment.

The European Society of Endodontology (ESE) is aware of the deficiencies in endodontic education and has stated that some of the lack of knowledge in endodontics among general practitioners may be related to the acquisition of basic knowledge and skills during undergraduate training, where standards are highly variable (14). Current guidelines for undergraduate education emphasize the teaching of techniques for the treatment of access obstructions, such as secondary and tertiary dentine (14). Since the standardization of training is difficult due to the lack of suitable extracted teeth for practice and the varying degrees of difficulty, providing alternative learning tools could help meet the established learning standards.

For this study, a novel training kit was designed to address the shortcomings of the undergraduate programme.

Access cavity preparation training was performed both intraorally on a dental dummy (opaque teeth) and extraorally (transparent teeth). The extraoral training with transparent teeth was designed to help participants gain a better understanding of the location of the calcified pulp, and the intraoral training with opaque teeth mounted in the dental dummy was designed to simulate clinical conditions. Preoperative radiographs of the corresponding training teeth completed the clinical training setup.

The students in this study had never performed access cavity preparation on teeth mounted in a dental dummy before and had no clinical experience with patients. Evaluation of operating times showed that the majority of the students improved with training. Before training (tooth #0), the students completed the procedure in an average of 5 minutes, and the dentists completed it in only 3.5 minutes. After practicing on the transparent teeth, the average time improved to 2 minutes for students and 1.5 minutes for dentists.

These results significantly differed from the procedure times observed in the study by Kiefner et al. (7), in which an experienced endodontist performed access cavity preparation and scouted 68 root canals in 15 minutes, 30 root canals in 15–30 minutes, 8 root canals in 30–45 minutes, and another 8 in 45–60 minutes. As the majority of participants in our study had limited or no prior experience, longer operating times were to be expected. The lack of a reward for good performance and, conversely, the lack of consequences for poor performance may have lowered the students' concern about causing perforations. Real patient cases would likely have resulted in longer procedure times.

Several studies (12, 15) have found 3D printed teeth to be softer than natural teeth. In this study, there was no consensus among the students as to whether the printed teeth were harder or softer than natural teeth, although most felt that the printed teeth did not match the extracted teeth. The dentists, on the other hand, clearly felt that the printed teeth were similar to or softer than extracted teeth. It is difficult to replicate the hardness of enamel in 3D printing. Therefore, the development of harder 3D printing materials could lead to the production of more accurate replicas.

The lack of color differences between structures in the printed teeth may have limited the ability of study participants to accurately distinguish between specific tooth structures, such as the enamel and dentine layers. These layers can be easily distinguished based on color and texture differences in natural teeth, especially if magnification aids such as the microscopes are used. In this study, it was not possible to reproduce these differences in the 3D printed teeth due to technical limitations and the use of microscopes would have been of questionable benefit. Although the replicas were printed with a softer red material to simulate pulp tissue, a material of uniform color and hardness was used to simulate the enamel and dentine layers, which does not correspond to the structure of human teeth. Therefore, the participants likely relied on the radiographs to determine the preparation length and axis. In addition to increasing the number of participants, more realistic 3D printed teeth would presumably also lead to statistically more significant results. The additive manufacturing process should therefore be improved for follow-up studies in order to obtain multicolored training teeth that are as realistic as possible. Beyond the external appearance and color correspondence with natural teeth, haptic properties also play an important role. In future, additive manufacturing processes could also simulate different degrees of hardness of dental hard tissues in addition to multicolored 3D printing. 3D printing using highly hard resin as the outer enamel layer and softer resin as the inner dentine layer would further improve the degree of true-to-life reproduction of such a training set and should be targeted for future studies.

Despite these limitations, the use of 3D printed teeth offers numerous advantages. All participants recognized the potential benefits of artificial teeth, as evidenced by the positive ratings from most students and dentists. In the free text comments section, some students even commented that this training exercise should be included in the preclinical curriculum. As in previous studies (11, 12) of 3D printed teeth, participants found that the use of standardized teeth provided greater test fairness.

Financial considerations should also not be underestimated if 3D printed teeth were to be used in the field of endodontic education. In two studies from the field of maxillofacial surgery (16, 17), it was shown that 3D printed models had excellent cost-efficiency for educational purposes. Because 3D printing is a rapidly evolving field, the costs of producing models using the 3D printing process are expected to decrease even further in the future.

The proposed workflow provides a practical and versatile method for producing dental models that can be adapted for different exercises. To further expand the possibilities, radiopaque substances such as barium sulfate could be added to the printing materials to improve the X-ray performance. Moreover, only single-rooted teeth with straight root canals were used in this study. Multi-rooted teeth or teeth with curved root canals could be used in follow-up studies. These may cause even greater challenges for practitioners in everyday clinical practice compared to single-rooted teeth. In this pilot study, however, the use was limited to "simpler" calcified single-rooted teeth in order to evaluate the basic suitability of a 3D printed training kit for the preparation of access cavities in calcified teeth by undergraduate students. The calcifications were performed very schematically in this study. In clinical cases, irregularities may occur. In principle, however, it is assumed that calcification proceeds in a coronal-apical direction (4), whereby the last versions of the training kit are intended to represent extreme situations.

The combination of haptic simulators and 3D printed teeth could expand the field of endodontic education in the future. Haptic simulators could lead to an improvement in patient treatment in the sense of personalized medicine (18), but could also become an integral part of academic training in the field of endodontics if such systems lead to an evidently enhanced access cavity preparation.

Future research should further explore the potential benefits and limitations of using printed teeth in dental education. For example, using a randomized educational trial approach could provide more detailed results about the effects of a novel educational approach compared to a standard educational approach in the same population as a test group. This pilot study aimed to evaluate generally the potential use of this novel 3D printed kit training and therefore included also dentists. Based on the results of this study, targeted follow-up studies can be carried out in a specific context, e.g. exclusively in undergraduate education or in postgraduate training.

CONCLUSION

The results of this study indicate that the 3D printed training kit was effective in improving the skills of both students and dentists in preparing access cavities in calcified teeth. Overall, 3D printed teeth can be a valuable tool for undergraduate training in endodontics.

Disclosures

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