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ORIGINAL ARTICLE

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Introduction of a new teaching concept for crown preparation with 3D printed teeth

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Abstract

Introduction: For both students and teachers, it is challenging to learn and teach a correct crown preparation. The purpose of this study was the design, feasibility and evaluation of a 3D printed tooth model with internal preparation for dental education in crown preparation and to analyse the quality of the prepared printed teeth in comparison with prepared standard model teeth.

Materials and methods: A printable tooth was designed and printed by a stereolithographic printer. 38 fourth-year dental students in the first clinical course in prosthodontics were trained in a voluntary course using printed teeth. Different aspects of the printed tooth were evaluated by a questionnaire using German school grades (1 best to 5 worst). The quality of the preparation with the printed teeth and standard training teeth was also rated in an evaluation form done by an expert group consisting of five experienced dentists.

Results: The workflow was feasible and cost-effective for the production of the teeth. The overall rating of the printed tooth was Ø 2.0 ± 0.34 in the questionnaire completed by the students. The students rated the printed tooth model (Ø 2.1 ± 0.85) as significantly better than the standard model tooth (Ø 3.3 ± 0.77; P = .000). The students reported great benefits in the use of this model tooth, for example valuable replacement of a standard model and real teeth, direct control of material loss. The quality of the preparation was evaluated by the expert group as significantly better with an overall mean grade of Ø 2.6 ± 0.37 for the printed teeth compared to Ø 2.9 ± 0.42 for the standard model teeth (P = .000).

Conclusions: The feasibility of this teaching concept was confirmed. The students favoured to work on the innovative 3D-teeth with internal preparation, emphasising the usefulness of this technique in dental education. The expert group confirmed also the significant training effect of this tooth model in contrast to a standard model tooth.

KEYWORDS
3D printing, additive manufacturing, clinical practice, dental education, printed tooth, student training

1 | INTRODUCTION

New 3D printing technologies give us the chance to produce individual teeth models with more anatomical characteristics. Up to now, the main problem for the creation of such models was the characteristics of the printing materials. They were initially designed for visual models for the industry. But today there are new materials available for 3D printers with more usable properties. They enable us to produce functional and individual teeth models at very low cost. Despite these new possibilities, there are only very simple teeth models available for the education of students in important treatment options. One of these is the training of a correct crown preparation in prosthodontics. The teaching and learning of a correct crown preparation is very difficult for the supervisors as well as for the students. The learning effect differs between the supervisors and depends on personal opinions. It has been described previously that a visual recognition at the learning process has great effects on the student`s performance.[1-4]

So far, the great influence of printed 3D models and teeth was investigated in different studies. Soares et al[1] used 3D printed models and virtual models to demonstrate the differences in cavity preparation for teaching students. The quality of the training model was measured by a questionnaire. Students and teachers evaluated the new didactic material compared to a conventional one. They described a positive learning effect for both groups.

Kröger et al[2] used 3D printed models, based on real patients, for the training of students in different treatment situations. Three different models were used in the study. The first model was for veneer preparation, the second was for dental bonding, and the third was for interdisciplinary simulation of caries excavation and crown removement. The different models were evaluated by students in a questionnaire and received a good feedback.

Cantin et al[3] created 3D printable models to study the morphology of permanent teeth. The production process of the models was described. A very important role was expected in the teaching of tooth anatomy, dental form and internal structure for dental students.

Boonsiriphant et al[4] described the production process for 3D printed prepared teeth and the use for education of dental students. They expected significant advantages for real 3D visual recognition and skill acquisition by students in contrast to 2D images in books or lectures.

We established so far two other printed tooth models. The first model was created for the practice of a realistic prosthodontic situation. This includes caries excavation, pulp capping, core build-up and crown preparation. The material combination of the printed tooth was selected to enable the students to control the correct caries excavation and the core build-up under a blue LED light.[5] This printed tooth model received a good evaluation by our students and led to the creation of the second model. With the second printed tooth model, students had the opportunity to train a crown preparation with different material properties in hardness and colour for enamel and dentin.[6]

The aim of the new study was the design of a 3D printable tooth with internal preparation for dental education in preclinical crown preparation. The tooth was designed for supporting self-education and learning. The benefits for education were evaluated by a questionnaire and compared with both a standardised artificial model tooth and a real tooth. The quality of the preparation done by the students was also evaluated by a group of experienced experts.

The hypothesis of this study was that the 3D printed tooth had benefits for education. We assumed that the model performed superior to a standardised artificial model tooth in the training of a crown preparation. Another point was the assumption of a better quality of the tooth preparation, which leads to higher patient safety. We expected also a high cost reduction with this tooth model.

2 | MATERIALS AND METHODS

The study was proved and accepted by the Institutional Review Board.

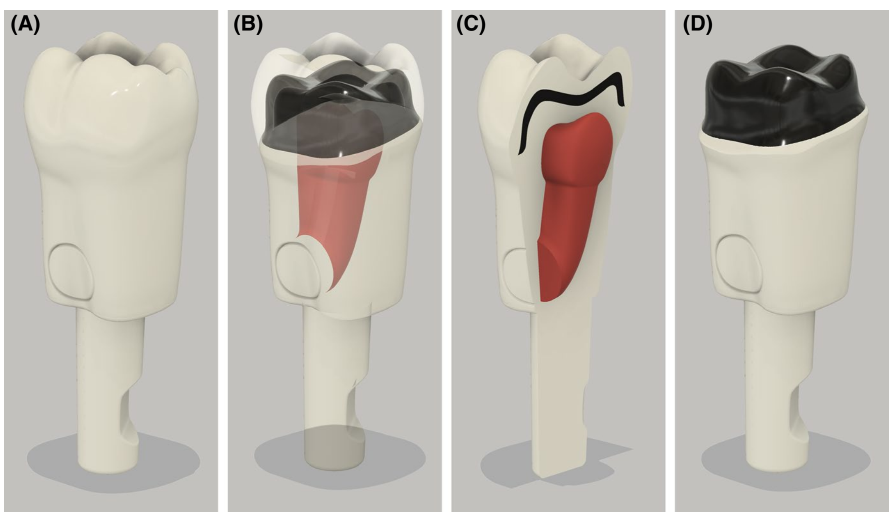

FIGURE 1 The design of the tooth with the internal preparation (A); a transparent look through the design of the tooth with the pulp visible in red and the internal preparation visible in black (B); a cross section of the tooth (C); the tooth after the preparation (D) [Colour figure can be viewed at wileyonlinelibrary.com]

2.1 | Design of the printed tooth

A cone beam computed tomography (CBCT) scan of an extracted first permanent molar was acquired by an Orthophos XG 3D (Dentsply Sirona). These data were used for the reconstruction of the tooth and the pulp geometry. A standard dental study model (KaVo, Biberach an der Riß, Germany) was scanned by an InEos X5 scanner (Dentsply Sirona) with a tolerance of 1.3 µm ± 0.4 (DIN EN ISO12836:2015). Now, the reconstructed data in the standard tessellation language (STL) of the CBCT scan and the model scan were used to design a printed tooth which fits into the standard dental study model. For this purpose, the CAD software Autodesk Inventor 2019 (Autodesk, San Rafael, USA) was used (Figure 1A). A prepared model tooth with an ideal preparation was also scanned (InEos X5 scanner). After scanning the prepared tooth, the resulting STL-data was used to match the prepared tooth with the original tooth. The preparation was minimised by 0.5 mm to generate space for the filling with a contrast material (Figure 1B). The minimised preparation represented the preparation tolerance. If the tooth was prepared over this tolerance the tooth material became visible again and showed the student a too invasive preparation. A cavity for the filling with a pulp material was also included (Figure 1B,C). Finally, the resulting preparation was visualised (Figure 1D).

2.2 | Production of the teeth

After the computer-aided design (CAD) with Autodesk Inventor 2019 (Autodesk), the data were imported into the preparation software of the 3D printer (PreForm 2.19.3, Formlabs Inc) as a Wavefront OBJ-file (OBJ) and printed in a Form2 3D printer (Formlabs Inc). Rigid photopolymer resin (RS-F2-RGWH-01, Formlabs Inc) was used for the print of the tooth model. 30 teeth were produced at one build-platform of the printer in 7 hours and 12 minutes. The automated production time of a single tooth was therefore approximately 15 minutes. The teeth were washed after the production with 95% isopropanol for 20 minutes in the Form Wash unit (Formlabs Inc).

2.3 | Completion of the teeth after print

Afterwards, the cavity for the preparation was filled with Black photopolymer resin (RS-F2-GPBK-04, Formlabs Inc) and cured in the Form Cure unit (Formlabs Inc) for 15 minutes. The pulp cavity was filled with Impregum Penta DuoSoft Light Body (3M Espe, Seefeld, Germany). The material was applicated by an automix syringe and hardened after mixing in the syringe. Duosoft is a polyether impression material and simulated the pulp in colour and consistence. The pulp was closed with a printed cover and sealed with Rigid photopolymer resin (RS-F2-RGWH-01, Formlabs Inc) and cured for 15 minutes. The completion of each tooth was done in approximately one minute. The price for the complete material for one tooth was 0.35$ and for the printer and the printing equipment a total of 4550$. Therefore, the production was not that expensive and time consuming. The design of different tooth models is a single time investment after the establishment of the first model. An experienced CAD designer can construct the tooth after the acquisition of the primary data from the CBCT and scan of the study model in approximately 2 hours.

2.4 | Training on the tooth model

38 fourth-year dental students in the first clinical course in prosthodontics (27 females and 11 males, from 22 to 37 with a mean age of 25) were trained in a voluntary hands-on course with 152 printed teeth. These students were familiar with standardised artificial model teeth, as these teeth were used during their preclinical education. All the participating students had already removed caries and prepared teeth in one clinical course on patients and had also experience on real-teeth-models. They had done at least 10 dental fillings and three endodontic treatments on patients. In the present study, every student had the opportunity to prepare four identical printed teeth and four standard model teeth. Half of the students prepared the four printed teeth first and the other half the standard model tooth. The students mounted the printed tooth into their study model (Figure 2A), and the training was done in a phantom head under simulated clinical conditions. The margin of the preparation was clearly visible, and the black material was also noticeable through the tooth. In Figure 2B,A cross section of the printed tooth is shown. The black material for the ideal preparation and the red material for the pulp are visible. The students started now the preparation and removed the material until the black material was visible. In Figure 2C,A printed tooth with a vestibular preparation is shown. A good discrimination of the different materials is visible. The preparation was than completed until no white material was left (Figure 2D).

2.5 | Questionnaire after practice

The benefits of the 3D printed tooth were evaluated by 38 students using a questionnaire covering several items (Table 1) with respect to the properties of the printed teeth, the real teeth and the standardised artificial model teeth. The digital evaluation was generated with EvaSys (Electric Paper Evaluationssysteme GmbH, Lüneburg, Germany) and validated by the institute of "Medical Teaching and Medical Education Research" of the university. The questionnaire was already tested in a course in endodontic treatment and three printed tooth models.[5,6,7] This questionnaire was also used for this 3D-printed tooth. At the end of the training session, every student received a single key for the digital questionnaire. The questions were designed as closed format rating scale questions divided into school grades (1 = excellent, 2 = good, 3 = adequate, 4 = sufficient, 5 = poor) for a good discrimination. The overall and the mean grade of every question were calculated

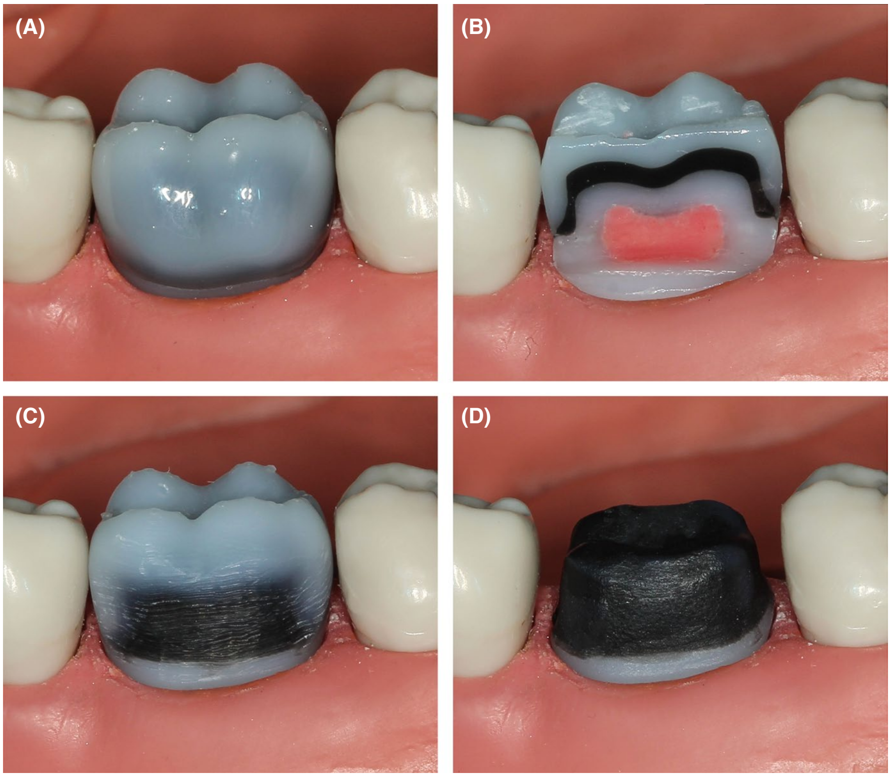

FIGURE 2 The tooth with the internal preparation in the study model (A); a cross section of the tooth with the internal preparation visible in black and the pulp visible in red (B); the tooth with a vestibular preparation (C); the tooth after the complete preparation (D) [Colour figure can be viewed at wileyonlinelibrary.com]

and displayed in a bar chart in Figure 3. Also, the standard deviation was calculated. The quantities of given grades were displayed in percentage. For reliability analysis, Cronbach's alpha was calculated. The last questions were free text questions. The students had to rate the educational effect of the 3D printed tooth, the standard model tooth and real teeth.

The questionnaire was divided into seven main categories with 20 items, including the gender and the age of each student in the first category. In the second category, the printed tooth was compared to a standard model tooth. In this part of the questionnaire, the hardness of the printed tooth was evaluated with the first item. The second question evaluated the realistic impression during preparation. The third item assessed whether the exercise option with the printed tooth is suitable for training. The fourth item evaluated the usefulness of this tooth under examination conditions. The last question of this category rated if the printed tooth is easy to use in the dental study model. The third category compared the printed tooth to a real tooth. In this part of the questionnaire, the hardness of the printed tooth was also evaluated with the first item. The second question evaluated also the realistic impression during preparation. The third item assessed the relevance of this training concept for education. The fourth category was about the special features of the printed tooth with internal preparation. In the first item, the visibility in colour of the internal preparation was evaluated. In the second question, the training effect with the printed tooth was assessed with an attention to the feeling for the right preparation. In the fifth category, the learning outcome was assessed by comparison of the different tooth types. This was assessed in three questions for the model tooth, printed tooth and real teeth. In the sixth category, the learning process with the printed tooth was evaluated. In the first item, the enthusiasm of the students to improve their skills with this tooth model was assessed. The second item was about the introduction of the tooth model before the first treatment of a patient. The third question evaluated the guidance of the printed tooth to improve the preparation. The fourth item assessed the faster achievement and learning of a correct crown preparation. The questionnaire ended with a set of three free text questions. The first question was about the possible improvements to this printed tooth model. The second was about the advantages of the usage of real teeth in education. The third question was about the advantages of printed teeth for dental education.

2.6 | Evaluation of the preparation

The quality of the preparation performed by the students was evaluated by an expert group. This group consisted of five experienced dentists with at least five years of experience in evaluation preclinical model tooth preparations. For a blinded evaluation, the teeth were scanned by an InEos X5 scanner (Dentsply Sirona) to hide optical differences between the models and were randomly numbered. The scanned teeth were rated in a virtual model. The teeth were evaluated in five categories similar to our established evaluation system in the preclinical courses (Table 2). The correct substance loss done by the preparation was evaluated by the item "adequate substance removal." The direction of the preparation in relation to the adjacent teeth was controlled with the item "correct direction of the preparation." The desired conicity of three degrees for each side was

TABLE 1 The questionnaire for the evaluation of the printed tooth. The questions were designed as closed format rating scale questions divided into school grades (1 = excellent, 2 = good, 3 = adequate, 4 = sufficient, 5 = poor)

1. Personal Data
1.1. please enter your gender
1.2. please enter your age
2. Comparison of the printed tooth to a standard model tooth
Rate in school grades
The printed tooth ...
2.1. has a better hardness.
2.2. has a more realistic haptic impression at preparation.
2.3. is a more suitable exercise option.
2.4. is a fair examination condition.
2.5. is easier to use.
3. Comparison of the printed tooth to a real tooth
Rate in school grades
The printed tooth ...
3.1. has a better hardness.
3.2. has a more realistic haptic impression at preparation.
3.3. has a high practical relevance
4. Features of the printed tooth with internal preparation
Rate in school grades
The built-in preparation ...
4.1. was clearly visible in colour.
4.2. made it easy to get a feeling for the right preparation.
5. Assessment of the learning outcome
Rate in school grades
My personal learning outcome ...
5.1. was greatest with the standard model tooth.
5.2. was greatest with the printed tooth.
5.3. was greatest with a real tooth.
6. Assessment of the learning process with the printed tooth
Rate in school grades
6.1. The printed tooth had filled me with enthusiasm to improve my skills in the preparation of teeth.
6.2. In retrospect, I would have liked to practice with the printed teeth first and then treat a patient.
6.3. The printed tooth with the intern preparation helped me to improve my preparation.
6.4. In my opinion the printed tooth made it easier to achieve my goals in the correct preparation.
7. Free text questions
7.1. What could be improved on the printed teeth?
7.2. Which advantages do you see by using real teeth in dental education?
7.3. Which advantages do you see by using printed teeth in dental education?

evaluated by the item "accurate conicity" and controlled with GOM Inspect 2019 (GOM, Braunschweig, Germany) with the corresponding resolution of the InEos X5 scanner. The GOM Inspect software is used by the industry in product development, quality control and production with a focus on alignment and deviation measurement. The software is certified by NIST (National Institute of Standards and Technology) and PTB (Physikalisch-Technische Bundesanstalt, Braunschweig und Berlin). GOM Inspect has been placed in Category 1 with the smallest measurement deviations and was used in many studies.[8-15] Another item was the exact defined preparation margin evaluated by "exact preparation margin." The last category of the questionnaire was the finishing of the surface by the item "smooth finishing of the surface." The five categories were also designed as closed format rating scale questions divided into school grades (1 = excellent, 2 = good, 3 = adequate, 4 = sufficient and 5 = poor). After the evaluation, the preparation quality of every tooth was calculated and summarised to calculate the mean preparation quality of every student.

2.7 | Statistical analysis

The overall and the mean grade of every question were calculated and displayed in a bar chart in Figure 3. Also, the standard deviation was calculated. The quantities of given grades were displayed in percentage. For reliability analysis, Cronbach's alpha was calculated. Significant differences between groups were calculated using the Mann-Whitney U test with the statistical program SPSS (SPSS 25, IBM Corp.). Values under $P = .05$ were considered as significantly different.

3 | RESULTS

The internal consistency of the questionnaire was acceptable, with a Cronbach's alpha of 0.75. No significant effect of the age and gender of the participating students was detectable. The printed tooth was evaluated with an overall grade of 2.0 ± 0.34.

3.1 | Comparison to a standard model tooth

The results of the comparison of the printed tooth with a standardised artificial model tooth are shown in Figure 3 items 2.1-2.6. The printed tooth achieved good results in every item and a very good result (Ø 1.3 ± 0.46) in item 2.3. The students evaluated the printed tooth as a more suitable exercise option than the standard model tooth. The answers in the free text section at the end of the questionnaire showed that most of the students were interested to include the printed tooth into their exercise training.

3.2 | Comparison to a real tooth

The results of the comparison of the printed tooth with a real tooth are shown in Figure 3 items 3.1-3.3. The printed tooth achieved good

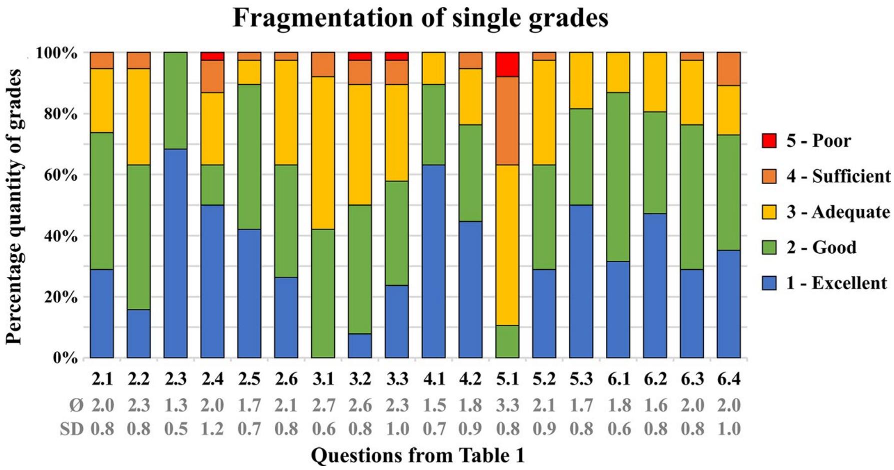

FIGURE 3 The results of the evaluation were visualised as a bar chart. The quantities of given grades were displayed in percentage, the mean values and the standard deviations are under the concerning questions. The questions were designed as closed format rating scale questions divided into school grades (1 = excellent, 2 = good, 3 = adequate, 4 = sufficient, 5 = poor) [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Categories for the evaluation of the preparation. The questions were designed as closed format rating scale questions divided into school grades (1 = excellent, 2 = good, 3 = adequate, 4 = sufficient, 5 = poor)

Evaluation of the tooth preparation
1. adequate substance removal
2. correct direction of the preparation
3. accurate conicity
4. exact preparation margin
5. smooth finishing of the surface

to satisfying results in every item. The answers in the free text section at the end of the questionnaire showed that a lot of students appreciated the printed teeth as a valuable replacement for a real tooth in the study.

3.3 | Special features of the printed tooth

In the next part of the questionnaire, the new features of the printed tooth were evaluated (Figure 3, items 4.1-4.2). These features were the clear visibility of the intern preparation and the possibility to get a feeling for the right preparation. The printed teeth achieved very good to good results.

3.4 | Assessment of the learning outcome

In the next part of the questionnaire, the learning outcome of the students was evaluated for a standardised artificial model tooth, the printed tooth and a real tooth (Figure 3, items 5.1-5.3). Of course, the real tooth achieved the best result. The standard model tooth had the worst result (Ø 3.3 ± 0.77) and the printed tooth (Ø 2.1 ± 0.85). This finding was significant different (P = .000). A real tooth (Ø 1.7 ± 0.76) and the printed tooth (Ø 2.1 ± 0.85) were closer together. This finding was also significant different (P = .032).

3.5 | Assessment of the learning process

In the last part of the questionnaire, the learning process of the students was evaluated (Figure 3, items 6.1-6.4). The printed teeth achieved good results in every item and were very good to good rated (Ø 1.6 ± 0.84) for the use before real patient treatment (Item 6.2.).

3.6 | Evaluation of the preparation

The printed tooth was evaluated by the expert group with an overall mean grade of 2.6 ± 0.37 compared to 2.9 ± 0.42 for the standard model tooth. This finding was significant different between both groups (P = .000). Also, every single category (Table 2) was significant different. The adequate substance removal was evaluated with 2.6 ± 0.47 for the printed tooth and 3.0 ± 0.53 for the standard model tooth (P = .000). The correct direction of the preparation received a grade of 2.4 ± 0.35 in contrast to 2.6 ± 0.45 for the model tooth (P = .000). The accurate conicity of the preparation was evaluated with 2.6 ± 0.45 for the printed tooth in contrast to 3.0 ± 0.62 for the standard model tooth (P = .001). The preparation margin received a grade of 2.6 ± 0.51 in contrast to 2.9 ± 0.53 for the model tooth (P = .003). The printed tooth received a grade of 2.7 ± 0.57 in contrast to 3.0 ± 0.61 for a smooth finish of the surface (P = .001).

4 | DISCUSSION

The questionnaire for the evaluation of the printed tooth model was based on a questionnaire primary developed and validated by the institute of "Medical Teaching and Medical Education Research" of the university. The questionnaire was already tested in a course in endodontic treatment and two other printed tooth models.[5,6,7] At a former publication, the questionnaire was tested on reliability between students and an expert group and proved its consistency.[6]

According to the results of the analysis of the questionnaire, the 3D printed teeth with the intern preparation were rated as useful in learning a correct crown preparation. The tooth model was evaluated with an overall grade of 2.0 ± 0.34 in the questionnaire. But there were some points to discuss. The printed tooth model received the worst results in the third part of the questionnaire (Figure 3). This part was about the comparison to a real tooth. Admittedly, this was and still is a great challenge for the creation of a printed tooth model. In comparison with a real tooth there, were some shortcomings in hardness (Ø 2.7 ± 0.62, Item 2.1) and haptic impression at preparation (Ø 2.6 ± 0.85, Item 2.2). This was also mentioned in the free text section of the questionnaire. New materials for our 3D printer, with optimised material properties (such as hardness), will be introduced soon and may overcome this problem.

On the other hand, there were some interesting results. The students evaluated the printed tooth as very good for training (Ø 1.3 ± 0.46, Item 2.3), and the tooth was better than the standard model tooth (Ø 2.1 ± 0.85 vs. Ø 3.3 ± 0.77, Item 5.1-2). In the free text section, the good learning effect was addressed. The direct control of the material loss during preparation was often mentioned as very useful. Many students wanted the printed tooth to be included in their education earlier. They requested different teeth and preparation forms for the future.

The good results of the questionnaire and the interest of the students in printed tooth models were also confirmed by the expert group in their evaluation of the preparation. Even after the training with this low number of four printed teeth, there was a significant difference detectable ($P = .000$). The quality of the preparation was rated with an overall grade of 2.6 ± 0.37 for the printed tooth model and 2.9 ± 0.42 for the standard tooth model ($P = .000$). The training success was greatest at the categories "substance removal" with 2.6 ± 0.47 vs 3.0 ± 0.53 ($P = .000$) and "correct conicity" with also 2.6 ± 0.45 vs 3.0 ± 0.62 ($P = .001$) (Table 2). The differences were admittedly not very much, but it must be considered that only four teeth were prepared by the students. Another point was that the students were in their fourth-year, very experienced in tooth preparation and each group was only consisting of 19 students. Students in their first course in tooth preparation would probably benefit more from this printed tooth model. The test of the introduced model with a larger and less trained group of students would be interesting for another study.

Due to the limitation of this study being conducted at a single dental school, its results may not be generalisable to students in other programmes. However, our hypothesis was confirmed: the 3D printed artificial tooth with internal preparation had benefits for education compared to a standard model tooth in the training of full coverage crown preparation.

We used so far two other printed tooth models. With our first model, students had the opportunity to practice a realistic prosthodontic situation. This includes caries excavation, pulp capping, core build-up and crown preparation. The material combination of the printed tooth was selected to enable the students to control the correct caries excavation and the core build-up under a blue LED light.[5] With the second printed tooth model, students had the opportunity to learn a correct crown preparation on a printed tooth with different material properties in hardness and colour for enamel and dentin. Also, a realistic pulp was simulated by this model and a printed teaching model was included.[6] With the third tooth model students had the possibility to learn a correct dentin post treatment. The printed tooth enabled the students to get experience before patient treatment.[7] At the moment is a so far unpublished tooth model in process which is called the "Painting by Numbers Method" for education of students in crown preparation. For the future are two new trainings concepts under development in periodontology, and the training model with the "Painting by Numbers Method" will be adapted to other tooth forms.

With the before mentioned printed tooth models, the here described model and projects in the near future, we will have a new teaching concept, which is affordable and will probably enhance the education at our and other universities.

To establish this new teaching concept with printed teeth, it is important to analyse the feasibility. At our university, the students need model teeth for three preclinical courses. They use on average 60 teeth for each course. The price for standard model teeth with none of the features of our printed teeth models is 2.10$, so they spend approximately 378$ for all model teeth during their preclinical studies. Our more advanced tooth can be produced for 0.35$ resulting in a total price of 63$ for each student. Each course has approximately 50 students and two are at the same time, so 6000 teeth are needed every semester. This means a production time of approximately 63 days for all teeth. With five 3D printers, the teeth can be produced in 13 days. The printers and equipment are a single investment of 17 500$, and the price difference between the model teeth and the printed teeth is 10 500$. After one year, the investment of the printers is more than amortised. But this project can even be done with less 3D printers. Because all teeth can be produced in the three months of semester break and even during the semester.

If the printed teeth model is compared with other available solutions, the price difference is even more different. Comparable tooth models with different layers for the enamel, dentin and an included pulp are around 11.20$ for each tooth. But these teeth have no discrimination in hardness and consistency between the layers and are optical less advanced. To establish a teaching programme with these teeth, students had to spend 2016$ for their preclinical studies. This would result in a price difference to our printed tooth model of 65 100$ each semester.

We expect a great reduction of conventional model teeth in the future and a shift onto individual new teaching concepts. Printed teeth can be produced individual and a lot of different training situations are possible. Furthermore, the printed teeth can be produced very cheap and we think that a lot of other dental schools will maybe produce them at no charge for the students. The printing of the teeth can even be included directly into the curricula and the students gain new experience with printing technology. They have also the chance to finish the tooth models on their own and acquire with this more knowledge in tooth anatomy.

An affordable Form2 3D printer (Formlabs Inc) was chosen to print the teeth. Other more advanced printers were available on the market (eg from Stratasys, Rehovot, Israel) that allow to print multiple materials in one step. The teeth need with these printers almost no post-production. Such a printer (Objet 30 Prime, Stratasys) was also available for our department, but we had chosen to show this method, which was not cost intensive and would be available to many academic dental institutions. Nevertheless, with this printer the time for completion of the tooth after printing was within one minute and thus not time intense. The primary advantage of this affordable printer is the great diversity with up to now 18 different materials. The materials are easy to use and in contrast to other printers they have very interesting features. Most of the other more advanced printers offer only different colours and have no material with acceptable hardness. We used a rigid material (Rigid photopolymer resin, RS-F2-RGWH-01, Formlabs Inc) for the creation of our tooth model. This material has several advantageous characteristics for preparation, for example its hardness and the lucency, very close to real tooth substance. There are also new ceramic materials available for the printer, for example (Ceramic Resin 1RS-F2-CEWH-01, Formlabs Inc) with even stronger and more toothlike characteristics in hardness. But they need more post-production, because they must be sintered to achieve the full hardness. Anyhow, this material would be very interesting for models in the future.

Only a limited number of comparable studies were available so far on this topic. A commonly used tool for the control of a crown preparation is CEREC prepCheck (Dentsply Sirona).[14-17] prepCheck had different features for analysing a correct preparation, for example the taper and undercut tools. The analyse was very accurate and precise and revealed a lot of information for the students. However, the process was both cost and time intensive for the CEREC units. After the preparation, the tooth has to be scanned every time to control the preparation. Thus, several devices have to be available for the students to avoid long waiting times. Furthermore, a simultaneous control during the preparation was not available. In contrast, our printed tooth model enabled the student to control the material loss directly during the preparation. Additionally, the material and production costs were very low. However, it might be useful to combine the advantages of both methods. This would enable the students to control the material loss during preparation directly with the printed teeth and check the preparation in detail after finishing it with prepCheck.

Another approach to control a correct crown preparation is the usage of virtual reality training systems with integrated feedback systems. Wang et al[18] compared different training systems and discussed the technical challenges of such systems. They proposed the idea of an ideal dental training system. An example for such a training system is the MOOG Simodont dental trainer® (Moog Dental Simulation). 3D models for this system were described by de Boer et al.[19-21] Real patient situations can be simulated. The virtual reality is useful to train different situations but was still in development so far. Furthermore, this method was very cost intensive, as each student needs a simulation unit. As the printed teeth enable the students to gain realistic experience during preparation also, the use of printed teeth might be a less cost intensive alternative which could be used ubiquitous.

5 | CONCLUSION

The feasibility of this teaching concept was confirmed, and the workflow was cost-effective for the production of the teeth. With the printed teeth, the students had the possibility to learn a correct crown preparation with a standardised tooth with internal preparation. The printed tooth enabled the students on the one hand to control the crown preparation directly on their own and on the other supported the self-education and learning. The results of the questionnaire showed the great interest of the students in the printed tooth model. The students rated the printed tooth model as significantly better than the standard model tooth. The expert group confirmed the usefulness of this method in their evaluation. The training effect with the printed tooth was significantly better than the standard model tooth in all categories. These were the adequate substance removal, direction of the preparation, correct conicity, preparation margin and smooth surface.

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CONFLICTS OF INTEREST

The authors have no conflicts of interest to disclose.

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