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3D printed versus commercial models in undergraduate conservative dentistry training

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Abstract

Introduction: The treatment of carious lesions is one of the most fundamental competencies in daily dental practice. However, many commercially available training models lack in reality regarding the simulation of pathologies such as carious lesions. 3D printed models could provide a more realistic simulation. This study provides an exemplary description of the fabrication of 3D printed dental models with carious lesions and assesses their educational value compared to commercially available models in conservative dentistry.

Materials and Methods: A single-stage, controlled cohort study was conducted within the context of a curricular course. A stereolithographic model was obtained from an intraoral scan and then printed using fused deposition modelling. These models were first piloted by experts and then implemented and compared against commercial models in a conservative dentistry course. Experts and students evaluated both models using a validated questionnaire. Additionally, a cost analysis for both models was carried out.

Results: Thirteen dentists and twenty-seven 5th year dental students participated in the study. The 3D printed models were rated significantly more realistic in many test areas. In particular, the different tactility and the distinction in colour was rated positively in the 3D printed models. At 28.29€ (compared to 112.36€), the 3D printed models were exceptionally cost-efficient.

Conclusions: 3D printed dental models present a more realistic and cost-efficient alternative to commercial models in the undergraduate training of conservative dentistry.

KEYWORDS
3D printing, 3D rapid prototyping, conservative dentistry, dental education, simulation training

1 | INTRODUCTION

In daily dental practice, a wide variety of theoretical, practical and psychosocial competencies must be mastered at a very high level. Thus, the training of these competencies is a central component in dental education to impart what is required for later practice.[1–3] One of the most important competencies in dentistry is to adequately diagnose and treat carious lesions which is also reflected in the German national competency-based learning objectives catalogue in dentistry (Chapter Z, 23a ff., Level 3).[4]

Traditionally, in undergraduate dental education students are taught complex procedural skills like the excavation of a carious lesion or the preparation of a cavity with the help of simulation training. This has a long history reaching back to the invention and fabrication of the first phantom heads and models in 1940.[1,3] Compared to more traditional learning methods like William Halsted's famous "See One, Do One, Teach One"[5] which is often used in surgical education, simulation training enables the training of complex procedural skills in a safe environment and moreover leaves room for mistakes. This helps to learn and master a complex skill without the pressure of the operating room or dental chair and ultimately contributes to a better and safer treatment. Despite these advantages, most phantom models today lack reality, especially when it comes to the simulation of pathologies such as carious lesions. Even though the industry is recently selling individualised models for the training in conservative dentistry,[6] these models are very expensive and do not provide the necessary differences in tactility to realistically mimic a carious lesion.

Additive manufacturing also known as 3D printing is a rapidly developing technology with a wide scope of applications in medicine and dentistry.[7] Today, there is a large variety of open-source software solutions as well as affordable consumer market 3D printers which enables an intuitive and easy to learn transfer from volumetric data into surface data models using the standard tessellation language (.stl) format. Especially, the now widely spread fused deposition modelling (FDM) technique allows the production of very cost-efficient, multi-material printed models. In the FDM technique, thermoplastic filament (plastic wire) is melted by heat, and the component is build up layer by layer through a nozzle that can be moved in three axes (Figure 1). If such a printer is equipped with several nozzles, printing with different materials is possible simultaneously. This process is very inexpensive, both to purchase and to use which makes it interesting for medical and dental educators.

There are some studies that sought to investigate the educational benefit of 3D printed models in dentistry and maxillofacial surgery.[8–16] To train the excavation of a carious lesion and the preparation of a cavity Kroeger et al. used the PolyJet technique to 3D print individualised tooth models which received positive feedback from students. However, students criticised the missing differentiation in colour between the carious lesion and the healthy tooth structure. Furthermore, the missing gingival mask was rated as negatively. Studies from Höhne et al.,[12–15] Marty et al.[16] and Soares et al.[9] used the dual-light processing technique to print individualised tooth models and added pathologies such as carious lesions digitally in a computer aided design method. Compared to commercial KaVo (KaVo, Biberach an der Riß, Germany) models, these models were rated positively by students and experts. However, these models also did not provide a satisfactory differentiation in colour and tactility to distinguish between the carious lesion and the healthy tooth structure.

To our knowledge, there is no study that investigated the production of individualised tooth models that used the fused deposition modelling technique. Accordingly, the aim of the present study was to describe the production workflow of multi-material 3D printed individualised tooth models fabricated with the fused deposition modelling technique and to compare these models within a curricular framework to commercially available models regarding their simulation reality and educational value. Our null hypothesis was that both types of models were equal regarding their perceived educational value and experience. A Secondary aim was to analyse the production costs of 3D printed individualised tooth models compared to commercially available models.

2 | MATERIALS AND METHODS

2.1 | Conception and production

An intraoral scan (TRIOS 3, 3Shape A/S) of the upper jaw of a 23-year-old male patient was used as the basis for the conception of the model. In the following, the 3D model was reworked using the

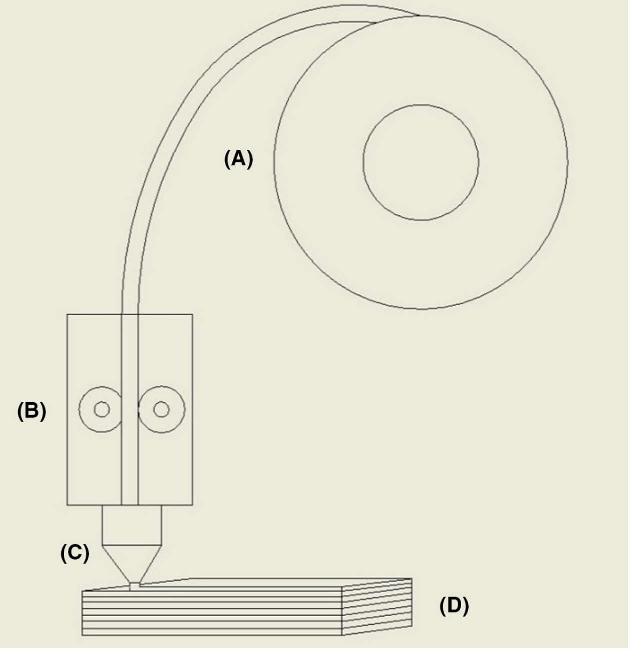

FIGURE 1 Principle of an FDM 3D printer. Thermoplastic material from a spool (Filament) (A) is melted in the extruder (B) and added to the printed object (D) through the nozzle (C). The extruder and the nozzle can be moved in three axes to build up the printed part

DentalCAD® software (Exocad GmbH) to create a model in which each tooth could be exchanged using a precise plug-in mechanism. Using the freely available software Meshmixer® (Autodesk inc.), a base plate was added to the model, which allowed to mount the model into a Phantom head (PK-1 TSE, Frasaco GmbH). In addition, a carious lesion was digitally modelled into both first molars of the model. This was done by creating a cavity, which was then provided with a defined density using a lattice structure (Figure 2). The virtual model was then converted into the .gcode file with the freely available software ideaMaker® (Raise 3D technologies inc.) and printed on a dual-extruder 3D printer (Raise E2, Raise 3D technologies inc.) with the following printing parameters: layer height 0.05 mm, trays 16, filling density 20%, support only touch platform, extruder temperature 240°C, heating bed temperature 100°C, printing speed 30 mm/s, fan off. The printing material used was acrylonitrile-butadiene-styrene (ABS), which is a synthetic and amorphous polymer that belongs to the group of thermoplastics. White and black ABS filaments (TEQStone, Shenzhen Pinmei Wangluo Keji Co., Ltd.) were used to print the healthy tooth structure and the carious lesion at the same time. Moreover, a gingival mask was digitally designed based on the intraoral scan using the Meshmixer® software (Autodesk inc.). The resulting.stl file was prepared for 3D printing with freely available Chitubox® slicer (Chitubox) with the following settings: layer thickness 0.2 mm, exposure time 20 s. The gingival masks were then printed using the dual light processing (DLP) technique. In the DLP technique, a UV light source cures a photopolymerising resin layer by layer into a component (Figure 2). This manufacturing technique is relatively inexpensive, starting at 150€ for a consumer market printer. The gingival mask was then printed with the Anycubic Photon (Anycubic) printer using NextDents® flexible gingiva mask resin (NextDent B.V.). Afterwards the printed gingival masks were glued to the base model and finally, the finished models were mounted in the phantom heads (Frasaco GmbH) with a suitable threaded plate (Figure 2).

2.2 | Study participants

The study participants were selected from two groups. The first group consisted of licensed dentists from the Department of Operative Dentistry (Carolinum Dental School, Goethe University, Germany) with multiple years of working experience which were regarded as experts. The second group consisted of dental students in their final (5th) year which from the 3rd semester onwards, were

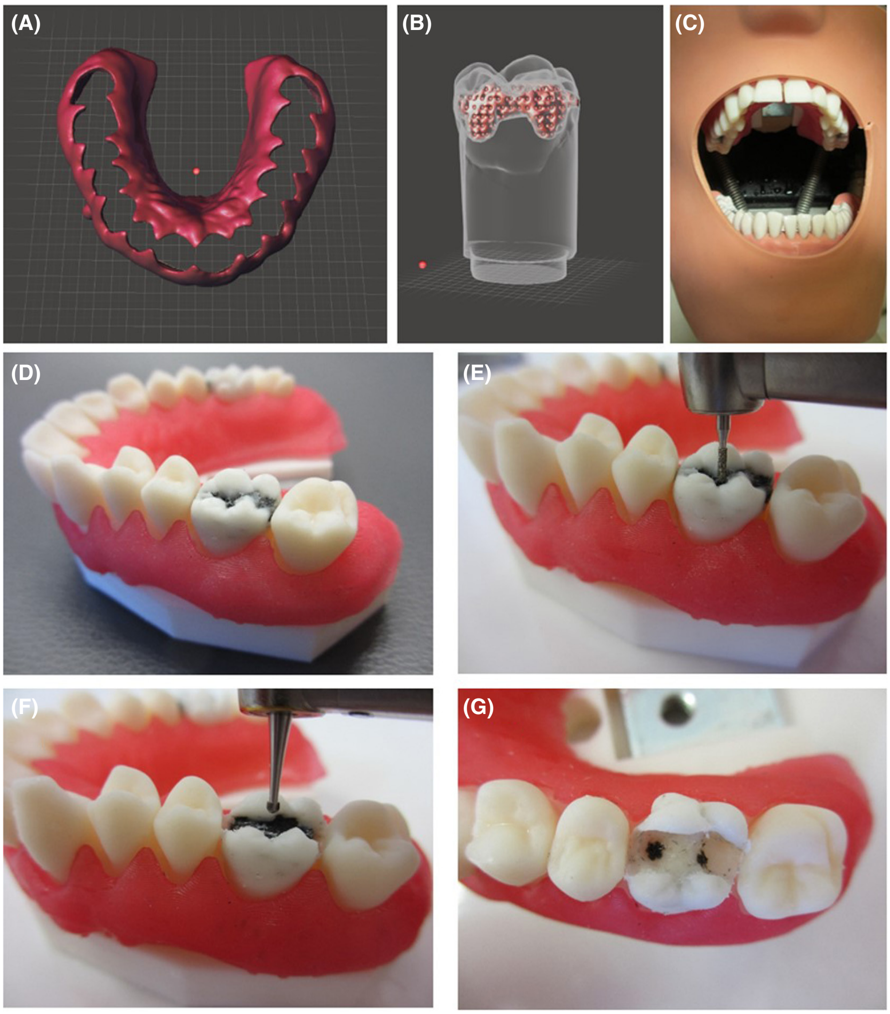

FIGURE 2 Design, fabrication and curricular implementation of the 3D individualised patient model. (A) Design of the gum; (B) design of the decayed tooth inserting a lattice structure to the caries cavity; (C) models (3D and KaVo) screwed into the patient simulator; (D) to (F) caries removal steps; (G) selective caries removal to protect the pulp

intensively involved in the subject of tooth preservation, starting with the training on standardised phantom models, followed by the clinical treatment of real patients with carious lesions, they can thus be considered rather experienced.

Participation in the study was voluntary after written and informed consent, which could be revoked at any time. Basic data on the study participants' gender, length of study and years of professional experience were recorded using a questionnaire.

A total of 27 out of 39 students took part in the survey, which corresponds to a participation rate of 69%. In case of the experts 12 out of 13 took part in the survey, which corresponds to a participation rate of 92%.

2.3 | Study conduction

The study was carried out in the simulation laboratory of Goethe Universities dental school (Carolinum Dental School). The 3D printed tooth models were mounted in phantom heads as the upper jaw, whilst the commercial tooth models (KaVo GmbH) were mounted as the lower jaw (Figure 2). First, the expert group evaluated and compared both models using a standardised questionnaire to pilot them before curricular integration. After this pilot evaluation, the 3D printed tooth models were integrated in a curricular conservative dentistry course. Each study participant from the dental student group received comprehensive task, including a detailed explanation of the course's learning objectives, an exemplary patient history as well as x-rays in the bitewing format that showed a D2 carious lesion in the first molars that matched the 3D printed tooth models. Students then excavated the carious lesions, performed a cavity preparation and restored the defect according to the principles taught in prior semesters. To simulate the carious lesions on the commercial KaVo models, the lesions were drawn on the tooth with a felt-tip pen, as it was the usual procedure in the conservative dentistry course at the time of the study conduction. The same task was performed on both models in order to enable a direct comparison. During the entire duration of the course (120 min), questions could be asked at any time, and the study participants were supported if necessary.

2.4 | Model evaluation

The models were evaluated using a previously designed and published questionnaire,[11] which was translated and adapted into the German language by a native English speaker. Moreover, the content of the questionnaire was validated and adapted to the learning objectives of the conservative dentistry course by a group of medical education experts ($n = 5$). The questionnaire (Table 1) contained eleven items which could be rated on a Likert scale from 1 (=not applicable) to 10 (=fully applicable). Additionally, the questionnaire contained free text fields for personal feedback related to the 3D printed tooth model.

2.5 | Data analysis

Data analysis and graphical display of data were conducted using Microsoft Excel 2016 (version 2110) and GraphPad Prism (version 9.1.1 (225)). In addition to descriptive analysis, the ordinally distributed data were checked for significance using the Mann–Whitney *U*-test.

2.6 | Cost analysis

For the cost analysis, the working hours of a student assistant (15€/h) for the creation of the 3D printed tooth models, as well as the material costs per model were included. In addition, we have included the running costs and the maintenance costs for the printers. The developing costs (15€/h) for the printing files also were considered in the calculation. The calculation is subdivided into outlay (Table 2) and ongoing (Table 3) costs for each model. The amount of material and the printing time used were calculated using the software ideaMaker (version 4.0.1., Raise3D Technologies Inc.) and the software Chitubox® slicer (version 1.6.3, Chitubox). The acquisition costs of the required printers (Raise E2 (2969.00€ as of 6 June 2021, 3D-Technologie Hörth GmbH, www.3d-printmaster.de) and Anycubic Photon (145€ as of June 6, 2021, Anycubic, www.anycubic.com)) were apportioned to the models in the calculation. The calculation was based on 50 models per semester and a production period of 5 years. For the commercial KaVo model, the new purchase price for the entire model plus preparation time for marking the caries was used for comparison.

3 | RESULTS

3.1 | Study participants

A total of 27 out of 39 (participation rate of 69%) dental students (female $n = 16$, male $n = 11$) and 13 out of 13 (participation rate of 92%) experts (female $n = 6$, male $n = 7$) took part in the study. All student questionnaires and 12 of the experts' questionnaires were included in the analysis. One questionnaire had to be excluded because incompletion in the dental experts group.

3.2 | Model evaluation

In comparison to the commercial KaVo tooth models the 3D printed tooth models were rated significantly better in the student group in nearly all items tested (Table 1 and Figure 3) with the only exception being the simulation reality of the 3D printed gingival mask which was rated as equally realistic and the assessment of the degree of difficulty. In particular, the differences between the healthy tooth structure and the carious lesion in relation to colour and tactility stood out. Moreover, the subjective learning effect and the

TABLE 1 Questionnaire and evaluation results from dental students and conservative dentistry experts

	Students					Experts					Students versus Experts	
	KaVo		3D			KaVo		3D			KaVo	3D
Questionnaire	*M*	SD	*M*	SD	*p*-value	*M*	SD	*M*	SD	*p*-value	*p*-value	*p*-value
1. The idea of the model is good.	7.44	1.50	9.19	1.04	<.001	8.5	1	9.75	0.45	<.001	.040	.062
2. The model offers a good learning effect.	6.70	1.32	8.48	1.12	<.001	7.42	0.67	8.92	1.08	0.010	.027	.100
3. The model is helpful in preparing for clinical courses.	6.59	1.76	8.37	1.21	<.001	7.58	1.31	8.58	1.62	0.056	.045	.184
4. The model enables a realistic simulation.	5.26	1.56	7.67	1.41	<.001	5.58	1.08	6.92	1.24	0.007	.248	.074
5. The removal rate is realistic.	5.07	1.88	7.19	1.66	<.001	5.42	1.38	6.42	1.51	0.126	.206	.085
6. The simulation of caries is helpful.	2.63	2.11	8.85	1.77	<.001	2.25	2.01	8.92	1.00	<.001	.278	.236
7. The gum mask is realistic.	6.48	1.89	7.04	1.65	0.169	5.75	1.86	5.58	1.51	0.818	.154	.010
8. The tactile simulation of the caries is realistic.	1.37	0.79	7.30	1.51	<.001	1.08	0.29	6.83	1.75	<.001	.236	.192
9. The colour simulation of the caries is realistic.	1.52	1.19	7.22	1.37	<.001	1.17	0.58	7.42	1.44	<.001	.251	.298
10. The simulation of the approximal area is realistic.	6.41	1.95	7.81	1.75	<.001	5.50	1.93	6.42	1.51	.258	.048	.004
11. Assessment of the degree of difficulty. (10 = difficult; 1 = easy)	5.04	1.53	5.33	1.57	.215	3.83	1.64	4.75	2.14	.313	.021	.140
Experience	Semester: *M* 10 │ SD 0					Working years: *M* 17.46 │ SD 13.20						

Abbreviations: *M*, mean; SD, standard deviation.

TABLE 2 Outlay costs for the 3D printed tooth models compared to KaVo models

	3D			KaVo	
	Used per model		Cost per model	Used per model	Cost per model
New purchase price					111.86€
ABS Filament	66.9 g (19.99€/kg)		1.34€		
Resin (gum mask)	5.99 ml (260.05€/kg)		1.56€		
Bonding	1/30 Bottle (6.90€/Bottle)		0.23€		
Personnel costs	15 min (15€/h)		3.75€	2 min (15€/h)	0.50€
Printer acquisition apportioned to the models	50 per Semester in 5 years		6.23€		
Running costs printers	Electricity costs 0.30€/kWh (FDM = 250W) (DLP = 30W)		2.78€		
	Wear parts 0.15€/h (printing time)		5.65€		
Maintenance costs	15 min per print (15€/h)		3.75€		
Printing time	DLP 44 min	FDM 36 h 56 min	Included in running costs		
Developing time for the print files	Approx. 100 h (15€/h) divided by 50 models per Semester in 5 years		3.00€		
	Total price per model		28.29€		112.36€

TABLE 3 Ongoing costs for the 3D printed tooth models compared to KaVo models

	3D			KaVo	
	Used for 32 teeth		Cost for 32 teeth	Used for 32 teeth	Cost for 32 teeth
New purchase price				2.20€/tooth	81.00€
ABS Filament	43.0 g (19.99€/kg)		0.86€		
Resin (gum mask)	Not needed				
Bonding	Not needed				
Personnel costs	10 min (15€/h)		2.50€	32 min (15€/h)	8.00€
Printer acquisition apportioned to the models	Included at outlay cost				
Running costs printers	Electricity costs 0.30€/kWh (FDM = 250W) (DLP = 30W)		1.69€		
	Wear parts 0.15€/h (printing time)		3.38€		
Maintenance costs	15 min per print (15€/h)		3.75€		
Printing time	DLP not needed	FDM 22 h 30 min	included in running costs		
Developing time for the print files	Included at outlay cost				
Total price for 32 teeth			12.18€		89.00€

simulation reality were rated significantly better in the 3D printed tooth models (Table 1 and Figure 3).

In the expert group, only the soft tissue mask of the 3D printed tooth models was rated worse than that of the KaVo model. In all other questioned items, the 3D printed tooth model was rated better than the KaVo model. Some items were even rated significantly better (Table 1 and Figure 3).

Furthermore, it is noticeable that the students rated the 3D printed tooth models better than the experts in most cases with regard to the reality of the simulator, but only the gingival mask and the simulation of the approximal area were rated significantly better (Table 1).

In the free text comments (Table 4), it was highlighted positively that the degree of hardness of the caries lesion could be clearly

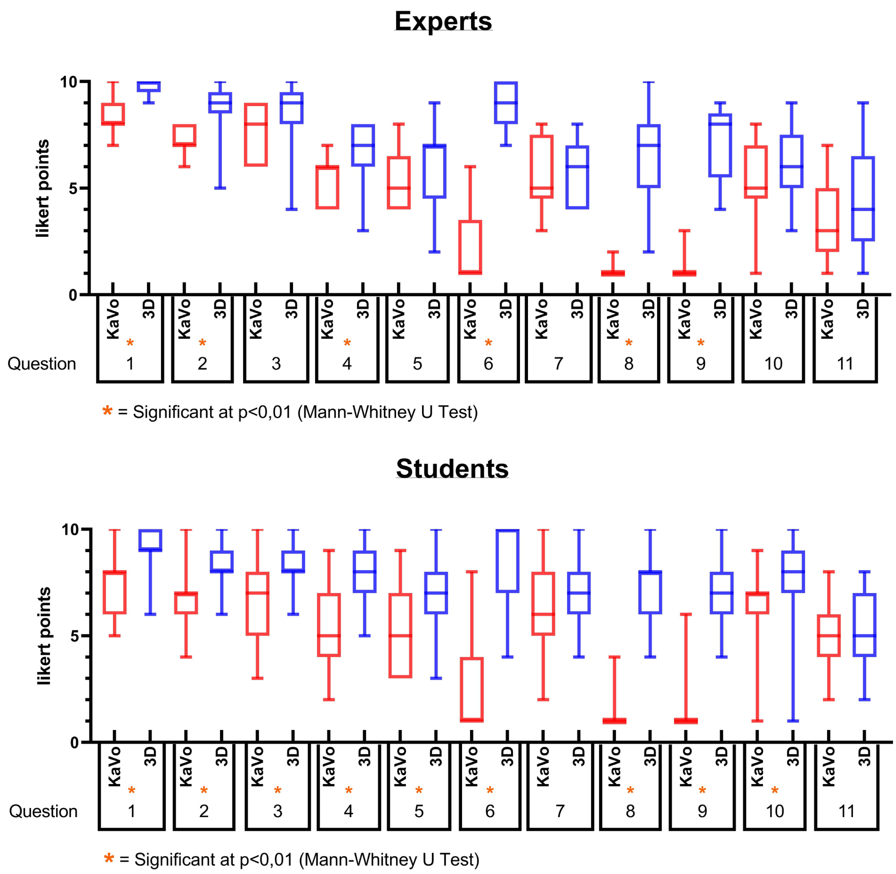

FIGURE 3 Evaluation results from dental students ($n = 27$) and conservative dentistry experts ($n = 12$) comparing KaVo and 3D printed models. Questions are listed in Table 1

TABLE 4 Individual student and expert evaluation of the 3D printed models

Positive
- Colour difference "caries and healthy tooth structure." ($n = 13$)
- falling into the caries with the rose drill. ($n = 2$)
- Shining through of the caries. ($n = 2$)
- Difference in hardness between caries and dentin. ($n = 12$)
- Realistic representation of a cavity. ($n = 10$)
- Transferring the situation from the x-ray image to the model. ($n = 2$)
- Selective caries excavation possible. ($n = 2$)
- Positional anomalies of the teeth in the model. ($n = 1$)
- Realistic representation of caries extension and depth. ($n = 13$)
- Sustainable model due to exchangeable teeth. ($n = 2$)
Negative
- The diamond burs clog a little with the material and the material fibres slightly. ($n = 15$)
- The gingival mask does not completely fill the approximal space. ($n = 1$)
- Possibility of selective caries excavation would exist. ($n = 1$)
Suggestions for improvement
- The healthy dentine could be a little harder to better feel the difference compared to the caries. ($n = 8$)
- A pulp would make the model even better. ($n = 4$)
- Different consistencies within the caries would be noticeable. ($n = 4$)
- Optimise caries colour, especially at the transition from caries to dentin. ($n = 1$)

distinguished from healthy tooth structure which helped to realistically mimic a carious lesion. However, it was criticised that the dentin was still a little too soft compared to a real tooth and the material frays too easily when preparing the cavity with a diamond-coated grinding tool. This was the most frequent suggestion for improvement with regard to the properties of the 3D printed tooth model.

3.3 | Cost analysis

The total costs of producing a 3D printed tooth model (upper jaw, 14 replaceable teeth and a gingival mask) mounted up €28.29 (Table 2). The acquisition costs for a fully toothed KaVo model (KaVo GmbH, Biberach an der Riß, Germany) are €112.36 including marked caries and VAT per model (as of 17 March 2021, HenrySchein, www.henryschein-dental.de).

The running costs were calculated on the average of 32 teeth and amount to €12.18 for the 3D printed tooth models, compared to €89.00 for the KaVo model (32 teeth: €81.00; as of 21 November 2021, HenrySchein, www.henryschein-dental.de).

According to our estimates, the base plate can be used for at least one semester. Additional research would be needed to evaluate the actual durability of the baseplate.

4 | DISCUSSION

The aim of the present study was to develop cost-efficient, multi-material, 3D printed individualised tooth models fabricated with the fused deposition modelling technique and to compare these models within a curricular framework to commercially available models regarding their simulation reality and educational value. For this purpose, the 3D printed tooth models were first piloted by conservative dentistry experts and then implemented as part of a curricular course. Moreover, the manufacturing workflow of the 3D printed tooth models was presented in detail, and a cost analysis was carried out. Overall, the 3D printed tooth models were rated significantly better in many properties by both experts and dental students. In particular, the realistic colour distinction and the tactile feedback of the carious lesion in the 3D printed tooth models were consistently rated positively, and the perceived learning effect was rated higher. The evaluations of the students and experts do not differ significantly in most cases, which could be due to the fact that the students are considered to be relatively experienced with regard to their previous experience of caries excavation.

There are only a few studies that investigated the simulation of a carious lesions with the help of different 3D printing techniques and nearly all chose different technical approaches to manufacture such models. Kroeger et al.[11] used the PolyJet printing technique which is similar to that of an inkjet printer, and which applies light-curing material in layers and cures by photopolymerisation after each layer. This principle enables very precise simultaneous printing with different materials and accordingly also material properties.[17] The main disadvantage of this printing process is the initial cost of the printer, which is far higher (around 15 times) than the cost of the dual-extruder FDM 3D printer that was used in this study. Furthermore, the printing process is easy to access and can be replicated at low costs. The models investigated in the study from Kröger et al.[11] were rated very positively; however, the missing distinction between healthy tooth structure and the carious lesion and the missing gingival mask were often criticised.[11] Both aspects were taken up and improved in our 3D printed tooth models. In a similar study Marty et al. investigated and compared commercial KaVo models with self-designed 3D printed tooth models which received positive feedback from study participants regarding their simulation reality.[16] Just like the models Kröger et al.[11] fabricated these models did not have an interdental space, as they were printed in one piece and did not provide a colour differentiation nor a gingival mask. Due to the plug-in mechanism in our 3D printed tooth models, the realistic representation of an interdental space was possible, which is also reflected in the study participant's evaluation. Furthermore, the models investigated in Marty et al. and Kroeger et al. studies were reduced to a single use, as they were printed in one piece without interchangeable parts. In our 3D printed tooth model, each tooth could be replaced, which enables the majority of the model to be reused and thus saves costs and material in the long term. Höhne et al.[15] followed a similar cost-efficient approach and designed a fabricated single tooth with a carious lesion and a pulp chamber that could be inserted in a commercial KaVo tooth model. Their tooth model and the simulation reality of the carious lesion also received very positive feedback by the study participants. However, their 3D printed tooth model was printed in multiple parts and some components such as the filling of the pulp chamber and the carious lesion had to be added by hand after printing which made the manufacturing relatively time and labour consuming. In contrast, we described a fully automated manufacturing process, which saves working time and thus costs.

4.1 | Limitations

The rather small number of study participants and participation rate of 69% in the case of students and 92% regarding the experts group (27 students, 12 experts) might be a limitation to the statistical power of our study. Furthermore, for practical reasons the model took place in different jaws (3D printed tooth model as the upper jaw, commercial KaVo model as lower jaw), which could possibly influence the comparability. In addition to that, the evaluated data are based on perceived experiences and not a subjective assessment of educational value. This study only evaluated and piloted newly developed 3D printed tooth models. Differences in objective growth of competence were not tested and should therefore be investigated in future studies. Furthermore, the properties of different materials should be subject of further research.

5 | CONCLUSION

In summary, our 3D printed tooth models were rated more realistic by dental students and conservative dentistry experts regarding the simulation of a carious lesion compared to the up to this day most often used commercial KaVo models to train caries excavation and tooth restoration. In the case of students, even significantly better in most items asked. The group of experts rated the 3D printed model significantly better on most questions about realism. The main areas for improvement in our 3D printed tooth models remain the integration of a pulp chamber, to realistically train the selective excavation lesions in close proximity to the pulp, the optimisation of the caries colour and the improvement of the material properties of the dentin of our teeth. Due to the constant, further technological development of 3D printing techniques and materials, we assume that even better and cost-efficient simulation models will soon be able to be produced.

CONFLICT OF INTEREST

All authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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