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# Quantitative Evaluation of Caries Removal on 3D-Printed Molars Using Volumetric Analysis

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# Quantitative Evaluation of Caries Removal on 3D-Printed Molars Using Volumetric Analysis

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## Keywords

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## Abstract

This study evaluates the reliability and validity of caries removal for educational purposes using volumetric analysis on 3D-printed molars. Fifty mandibular first molars with included realistic carious lesions were treated by dental students. After treatment CBCT and 3D surface scans were performed to generate digital models for investigation. The volume of the residual caries and overexcavation were determined by segmentation software and compared to a reference model. Results showed significantly more residual caries left on mesial and distal surfaces in comparison to buccal and occlusal surfaces. In contrast overexcavation was not significantly different. This study demonstrates the potential of 3D-printed teeth and CBCT as a tool for standardized, objective assessment of caries removal in dental education.

## Introduction

In modern conservative and prosthodontic dentistry, accurate removal of carious tissue is the basis for adequate restorative dental practice [1–3]. The ability to detect infected dentin and remove it adequately is a key skill that requires theoretical and manual training. Traditionally, the only possible solution for dental students is using extracted human teeth to practice on [3]. This approach has several shortcomings: ethical concerns about donorship, hygienical aspects, availability of tooth material, variability in tooth anatomy and lesion size, deeply destroyed unrealistic teeth due to extraction origin [4].

The adaptation of industrial technologies and widespread usage - particularly in 3D printing, cone-beam computed tomography (CBCT) and computer-aided design (CAD) and manufacturing (CAM) - allowed new possibilities for dental education and research [5–7]. These tools made it possible to generate anatomically accurate, reproducible tooth models with simulated carious lesions [8,9]. This offers a standardized platform for educational training. Moreover, the new possibilities of digital imaging and volumetric analysis can overcome the former subjective visual and tactile assessments.

Computed tomography in combination with segmentation and volumetric analysis has been used only in a few studies to assess the efficiency of caries removal. But this was solely utilised for real teeth and not for educational purposes. For example, Neves et al. [10–12] used micro-CT to quantify residual caries and overexcavation in extracted teeth. However, using a micro-CT is not generally accessible because of its high cost and limitations in clinical usage. Also, digital imaging is very time consuming and has a high radiation dose [13]. In contrast CBCT is increasingly available in dental practice and offers a broad spectrum of clinical usage with acceptable costs. It provides fast digital imaging and a sufficient resolution for hard tissue [14–17].

Our idea of combining 3D-printed teeth with CBCT volumetric analysis is a promising method for educational and research purposes. By simulating reproducible and realistic carious lesions and by using digital tools for the assessment of treatment outcomes, educators can give students consistent training experiences and objective feedback. Also, this method makes it easier to research factors influencing caries removal efficacy, lesion location and operator techniques.

This study is built upon this idea by evaluating the reliability and validity of caries removal on realistic standardized 3D-printed teeth using volumetric analysis. In specific we investigated the efficacy of caries removal dependent on the treatment surface. Our findings are useful for the development of new competency-based curricula and contribute to digital innovations in dental education.

# Methods

## Study Design and Sample Preparation

This in vitro study evaluated the efficiency of caries removal on realistic 3D-printed teeth. A total of 50 identical mandibular first molars were printed using stereolithography (SLA). The printed model is based on a CAD model generated from a CBCT scan of a natural human molar. Afterwards it was modified to fit into

a standard dental study model (KaVo, Biberach an der Riß, Germany). The carious lesion was multi-surface including mesial, distal, buccal and occlusal surfaces. The whole production process was described in a preliminary study [8].

The teeth were printed with a high-resolution SLA 3D printer (Form2, Formlabs Inc., Somerville, MA, USA) using a suitable photopolymer resin (RS-F2-GPWH-04, Formlabs Inc.). After printing, the teeth were post-processed according to the manufacturer guidelines. This includes cleaning with isopropanol and UV curing. The simulated carious lesions were filled with a soft material (Dentalon, Heraeus, Hanau, Germany). This material is radiolucent and mimics the consistency and radiographic image of carious dentin.

**Caries Removal Procedure**

A total of 50 fourth-year dental students (31 women and 19 men; mean age 25) in their first clinical prosthodontics course participated in a voluntary hands-on training course using 50 3D-printed teeth. During their preclinical education, these students practiced on standard typodont models All participants had clinical experience, including caries removal and tooth preparation on patients, as well as work on real teeth models. Each student had done at least ten dental fillings and three root canal treatments on patients.

The printed teeth were mounted into their corresponding models and used in simulation units (KaVo, Biberach an der Riß, Germany). Each student performed caries excavation using standard rotary instruments under visual and tactile guidance, simulating clinical conditions. After the excavation a restoration of the cavities followed by the use of dual-cure core build-up material (Rebilda DC White, VOCO), which is radiopaque and distinguishable in CBCT imaging.

## Imaging and Data Acquisition

After restoration, digital imaging was done by two methods:

- 3D Surface Scanner: inEos X5 (Dentsply Sirona, Bensheim, Germany), using structured light projection with a scanning accuracy of 1.3 µm ± 0.4 µm.
- CBCT: Orthophos XG 3D (Dentsply Sirona, Bensheim, Germany), voxel size 100 µm, field of view 5 × 5.5 cm, 85 kV, 6 mA, 14.4 s exposure.

To guarantee a correct positioning during imaging, a custom-designed radiographic holder was used (Fig. 1). This holder has three titanium spheres with a diameter of 5 mm for alignment. Also, in each radiograph a reference block made from the same core build-up materials was included to calibrate the threshold. The dimensions of this block are 3x6x9mm.

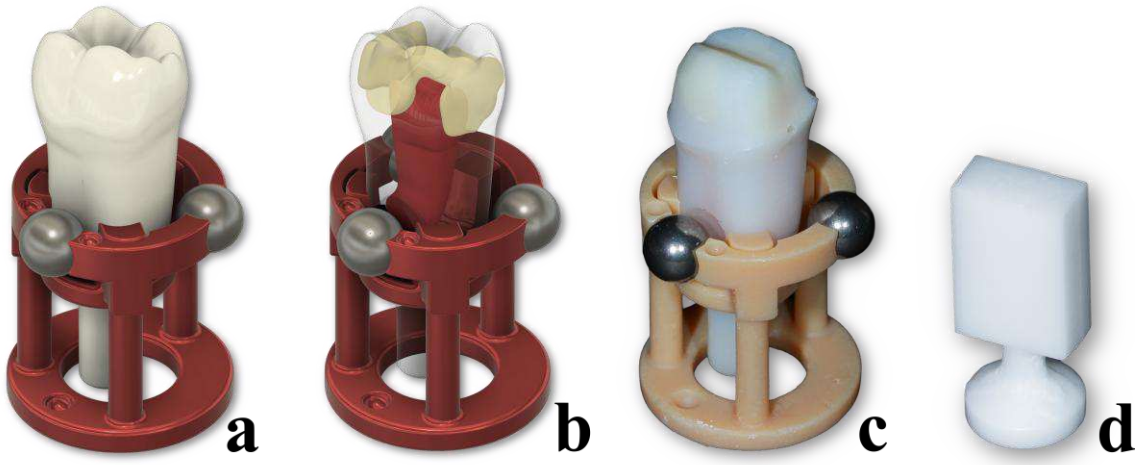



**Fig. 1.** (a) Design of the radiographic holder with printed tooth. (b) Digital see-through of printed tooth. The pulp is visible in red and the carious lesion in yellow. (c) Printed holder and tooth after caries excavation and core build-up. (d) Reference block for threshold calibration.

## Image Processing and Segmentation

For postprocessing purposes CBCT data were exported into DICOM format and imported into 3D Slicer (version 4.10.2). This is an open-source medical image

processing software. By using the “Segment Editor” module, the core built-up material was segmented (Fig. 2a). This was based on grayscale thresholding in relation to the reference block to ensure consistent values for every sample. After this the segmented volumes were exported as STL files (Fig. 2b).

Also, the 3D surface scans were exported as STL format (Fig. 2c). Both datasets, the segmented CBCT and surface scan, were aligned to the original CAD model of the printed tooth (Fig. 2d). For this GOM Inspect software was used (GOM, Braunschweig, Germany). The alignment process was performed by a combination of positioning and best-fit registration based on the titanium spheres.

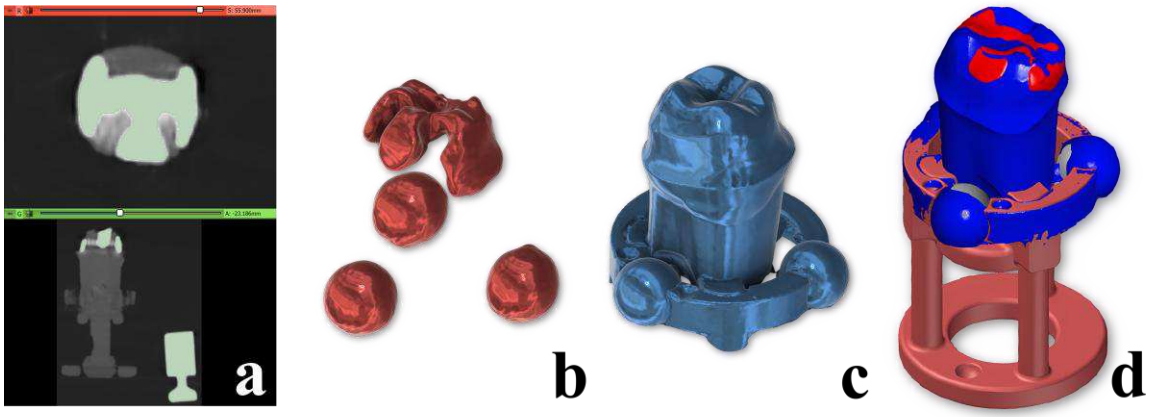



**Fig. 2.** (a) Segmentation of the core built-up material in different viewing directions. In the bottom picture is the reference block visible. (b) Exported STL file of the segmentation. (c) Surface scan in STL format. (d) Alignment of the segmentation and surface scan.

## Volumetric Analysis

Autodesk Fusion (Autodesk, San Rafael, CA, USA) was used for volumetric comparisons. The segmented volumes were converted into solid bodies using boundary representation (BRep) modeling. These solid bodies were then compared to the reference lesion (Fig. 3).

Calculated volumes:

- Residual caries: volume not filled by the core material
- Overexcavation: volume of core material extending beyond lesion

After this each volume was subdivided by tooth surface into mesial, distal, buccal and occlusal portions.

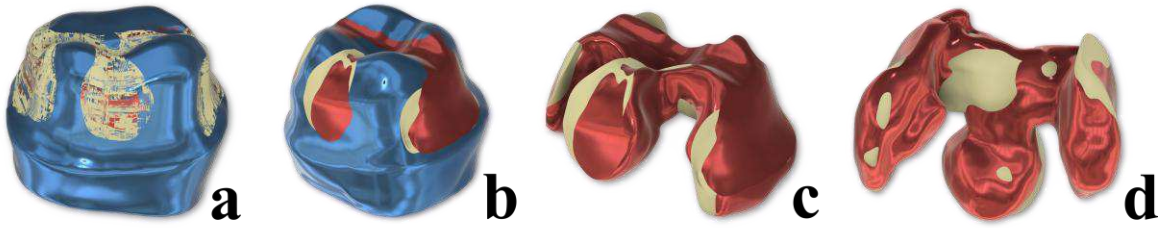



**Fig. 3.** (a) Superimposition of solid bodies. Complete tooth after treatment in blue, core built-up material in red, carious lesion in yellow. (b) Solid bodies after boolean operations. Built-up material in red and remaining carious lesion in yellow frontal (c) and bottom (d) view.

## Statistical Analysis

All volumetric data was analyzed using SPSS (Version 25; IBM Corp., Armonk, NY, USA). The results were non-normal distributed, confirmed via Kolmogorov-Smirnov test. Because of this non-parametric tests were used:

- Kruskal-Wallis test: for assessing differences in residual caries and overexcavation across surfaces.
- Mann-Whitney U test: for pairwise comparisons between surfaces

The statistical significance was set at $p < 0.05$. For visualization boxplots were generated.

# Results

## Residual Caries Volume

Significant differences were revealed for residual caries depending on the tooth surfaces. The median volume was highest on the distal surfaces, followed by mesial, occlusal and buccal surface (Fig. 4).

- Mesial surfaces had significantly more residual caries than buccal surfaces ($p = 0.002$), but not significantly more than occlusal surfaces ($p = 0.530$).
- Distal surfaces had significantly more residual caries than buccal ($p < 0.001$) and occlusal ($p = 0.014$) surfaces.

Summarizing, the removal of caries was less effective on proximal surfaces. The boxplot confirmed greater variability and right-skewed distribution for residual caries on mesial and distal surfaces. The interquartile range (IQR) was notable wider for these surfaces. This indicates inconsistent performance among students on these surfaces.

## Overexcavation Volume

In contrast to residual caries the overexcavation volumes were not significantly different between tooth surfaces ($p = 0.256$). Also, pairwise comparisons showed no significant differences (all $p > 0.05$). This indicates that students tended to leave more caries on proximal surfaces, but they did not compensate by removing more healthy tissue in these areas. The median overexcavation remained below 4 $mm^3$ but IQR was remarkable wider for the distal and even more for the occlusal surfaces. This indicates inconsistent performance among students on these surfaces.

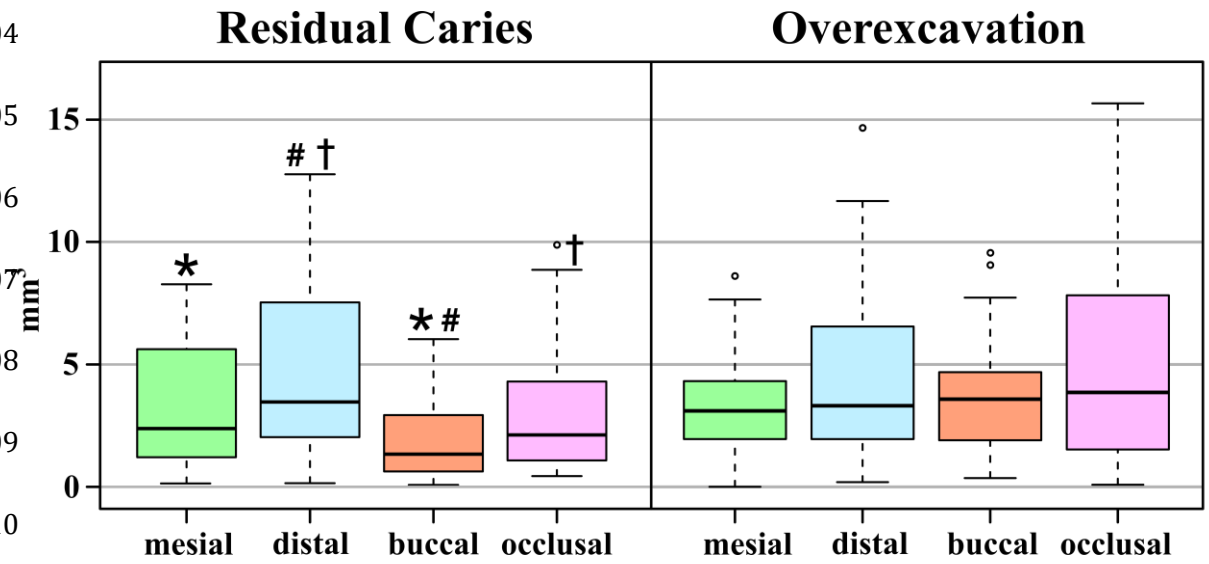



**Fig. 4.** Boxplot for illustrating the results of residual caries and overexcavation. Significance values: * p = 0.002 mesial vs. buccal, # p < 0.001 distal vs. buccal, † p = 0.014 distal vs. occlusal

## Discussion

In this study the feasibility and value of using 3D-printed teeth in combination with CBCT-based volumetric analysis to investigate the effectiveness of caries removal was evaluated. Another aspect was to determine whether removal efficiency varied by tooth surface. By measuring both residual caries and overexcavation volumes, we were able to identify significant differences in excavation efficiency across tooth surfaces. It was found that residual caries volumes were significantly higher on proximal surfaces – particularly distal – in contrast to buccal and occlusal surfaces. In comparison, overexcavation was not significantly different between surfaces. These findings offer important insights into challenges of caries excavation and potential of integrating new digital tools into dental education.

## Interpretation of Findings

Increased residual caries was found on mesial and distal surfaces. This reflects probably the difficulty of accessing and visualizing these areas during treatment. Proximal surfaces are in general obscured by adjacent teeth and require tactile feedback and indirect vision. This can compromise precision, especially for students with less developed clinical skills. This was also described by Hoffmann and Kielbassa and Ulrich [18,19]. It was also showed with a retrospective study regarding the renewal of dental fillings that secondary caries were located 1.23 times more frequently under extensive restorations in the distal cavity areas than in the mesial ones [20]. The missing significance in overexcavation suggests that students did not try to compensate for this difficulty. They were not removing more healthy tooth structure but rather remained carious tissue.

This conservative treatment approach was in accordance with the training at our university. Modern minimally invasive dentistry principles emphasize the preservation of healthy tooth substance. However, it also underlines the need for new improved training assessment tools that help to identify and remove carious lesions. This might be especially important for challenging anatomical regions.

Our results are in accordance with research by Neves et al. [10–12]. They used micro-CT to analyse residual caries and overexcavation in extracted teeth. They also found differences in excavation outcomes, but their study did not analyse differences in tooth surfaces. Their focus was not on educational purposes, and they used real teeth in contrast to additive manufactured ones. Comparable, Arnold et al. showed the feasibility of 3D reconstruction for measuring carious lesions [21–23]. In contrast their work focused on lesion characteristics rather than treatment outcomes. Also, the teeth were cut into slices to analyze the volumes.

Our study builds on these findings by combining additive manufactured teeth with CBCT-based volumetric analysis. CBCT offers a scalable, cost-effective, less time-consuming and clinically relevant alternative to micro-CT with acceptable resolution.

## Educational Implications

The combination of 3D printing and digital volumetric analysis into dental education offers several advantages:

- **Standardization**: Every student is working on identical models. This eliminates variability in lesion size, location and tooth anatomy.
- **Objectivity**: Quantitative assessment replaces subjective visual inspection, reducing inter-examiner variability.
- **Feedback**: Students can receive detailed, surface-specific feedback on both under- and over-excavation, supporting self-directed learning.

These advantages align to the objectives of competency-based education, which has the focus on measurable results and personalized learning paths. Also, the ability to show a three-dimensional reconstruction of the residual caries and overexcavation may enhance the spatial understanding and clinical reasoning of students. Moreover, the here described method has potential applications beyond education. This includes research on excavation techniques, material performance and clinical decision making.

## Limitations

Some limitations should be recognised. The study was in vitro using simulated lesions under idealised conditions. The 3D-printed teeth mimic closely natural tooth anatomy, but they do not replicate the full complexity of a clinical scenario. This includes patient movement, saliva, soft tissue and for the mandible tongue interference.

The segmentation accuracy may be affected by CBCT resolution and exact differentiation of the core build-up material at the margins. Even with a reference block for calibration, minor segmentation artifacts are possible.

The study was done on a single tooth type and with a single cohort of students. In the future other tooth types, lesion configurations and experience levels of the students should be considered. Additionally, the incorporation of augmented reality or haptic feedback system could enhance realism. This will further enhance the educational value of this method.

## Conclusion

In summary, digital volumetric analysis of caries removal on 3D-printed teeth is an advancement in dental education and research. It represents a new more precise method and data-driven approach for clinical skill development. The main findings were that residual caries was significantly higher in proximal surfaces but overexcavation was not significantly different.

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## Author Contributions

Christian Höhne: Conceptualization, Methodology, Data curation, Formal analysis, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing; Tamer Kurum: Investigation, Formal analysis, Data curation, Validation, Visualization, Writing – review & editing; Johannes Schrenker: Methodology, Validation, Writing – review & editing; Gabriel Krastl: Project administration, Resources, Supervision, Validation, Writing – review & editing; Marc Schmitter: Project administration, Resources, Supervision, Validation, Writing – review & editing.

## Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

## Ethics approval and consent to participate

The study and the experimental protocol were approved by the Institutional Review Board of the University of Würzburg (2026-1-ka). All students that participated in the voluntary course were thoroughly informed and no personal data was collected. An informed consent to participate was obtained from all of the participants in the study. All methods were performed in accordance with the named guidelines, regulations and Declaration of Helsinki.

## Competing interests

The authors declare no competing interests.

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