Evaluating tooth restorations: Micro computed tomography in practical training for students in dentistry

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ABSTRACT

Direct composite fillings belong to widespread tooth restoration techniques in dental medicine. The procedure consists of successive steps, which include etching of the prepared tooth surface, bonding and placement of composite in incrementally built up layers. Durability and lifespan of the composite inlays strongly depend on the accurate completion of the individual steps to be also realized by students in dental medicine. Improper handling or nonconformity in the bonding procedure often lead to air enclosures (bubbles) as well as to significant gaps between the composite layers or at the margins of the restoration. Traditionally one analyzes the quality of the restoration cutting the tooth in an arbitrarily selected plane and inspecting this plane by conventional optical microscopy. Although the precision of this established method is satisfactory, it is restricted to the selected two-dimensional plane. Rather simple micro computed tomography (µCT) systems, such as SkyScan 1174™, allows for the non-destructive three-dimensional imaging of restored teeth ex vivo and virtually cutting the tomographic data in any desired direction, offering a powerful tool for inspection of the restored tooth with micrometer resolution before cutting and thus also to select a two-dimensional plane with potential defects. In order to study the influence of the individual steps on the resulted tooth restoration, direct composite fillings were placed in mod cavities of extracted teeth. After etching, an adhesive was applied in half of the specimens. From the tomographic datasets, it becomes clear that gaps occur more frequently when bonding is omitted. The visualization of air enclosures offers to determine the probability to find a micrometer-sized defect using an arbitrarily selected cutting plane for inspection.

Keywords: *composite polymers, inlay, tooth, micro computed tomography, defect analysis, tooth restoration, dental education.*

1. INTRODUCTION

Adhesive tooth restorations with polymer composites are widespread techniques for replacing existing inadequate or fractured restorations or restoring of caries-affected teeth. The damaged part of the tooth is removed and replaced with the restoration material. To achieve attachment of the composite material to the tooth, the area to restore is first cleaned with water and etched. Subsequently a bonding material is applied to the surface to allow mechanical interlocking between tooth and adhesive restoration. Finally the composite is applied in layers with a spatula.

Direct composites are counted among the permanent type of restorations and show similar annual failure rates compared to other direct and indirect restorations especially in longitudinal studies [1]. However inferior results can be expected when placed in extensive defects [2, 3]. Among the reasons for restoration failure, risk of secondary caries and bulk fracture play an important role [2, 4]. The personal skills as well as the experience of the treating dentist has a strong impact on the recurrence of these phenomena [2, 5]. Improper handling or non-conformity in the bonding procedure often lead to air enclosures (bubbles) as well as to significant gaps between tooth and restoration, impairing the mechanical stability. Crack formation and bulk material failure or detachment of the restoration may result. It is therefore highly desirable to maximize the training of dentistry students to guarantee high-quality restorations even without extended clinical practice.

Among the quality assessment techniques for restoration ex-vivo, cutting the tooth in an arbitrarily selected plane and inspecting this plane to detect air enclosures or gaps is a standard technique [5-7].

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Staining with crystal violet can be applied to facilitate the identification of defects, as the color accumulates on interfaces between tooth hard tissue and polymer as well as inside imperfections. Although the precision of this established method is satisfactory, it is reduced to the selected two-dimensional plane. Defects outside the cutting plane cannot be detected, and the extension of detected defects in the direction perpendicular to the cutting plane is usually inaccessible. Such an analysis can therefore be misleading, as the defect density and extension in the arbitrary cut is not necessarily representative for the whole restoration volume, rendering the evaluation of the students work only partially possible.

It is one of the aims of the present study to figure out if a rather simple micro computed tomography (μCT) system, such as SkyScan 1174™, that is simple to operate, enough for reasonably investigating the restored teeth ex-vivo.

During the dedicated course of dentistry students in Year 3 at the University of Basel, each student prepares a restoration of a previously extracted tooth ex-vivo under predefined conditions. After restoration placement, μCT scans of each specimen are acquired with the SkyScan 1174™ system prior to cutting and staining. The students then have the possibility to evaluate their work based both on microscopy and μCT data. Aim of the training is not only to train the students' restoration placement skills, but also to give them an introduction to state-of-the-art X-ray based tomography, a technique, which is part of the standard clinical routines. Through the comparison of μCT and microscopy the students learn the advantages and disadvantages of a non-destructive 3D imaging technique with high density and spatial resolution in comparison with state of the art clinical methods. They also learn the relationship between image quality and acquisition time related to projection exposure time and number of acquired projections.

A set of 33 restorations, prepared by students at the School for Dental Medicine at the University of Basel were inspected both with μCT and optical microscopy. The restorations were performed on permanent teeth extracted during normal treatment. The comparison of quality assessment results with both techniques shows the advantages of a volumetric 3D analysis over a 2D analysis of an arbitrarily chosen plane.

2. MATERIALS AND METHODS

2.1 Dental restorations/specimen preparation

Slightly carious upper and lower molars, extracted during routine interventions at the School of Dental Medicine of the University of Basel, were cleaned with a toothbrush and disinfected with 100% ethanol after extraction and stored in Ringer's solution prior to placement of the composite restoration (Filtek Supreme XT, 3M/Espe or Tetric Evoceram Ivoclar Vivadent). A part of the specimens presented minor occlusal restorations.

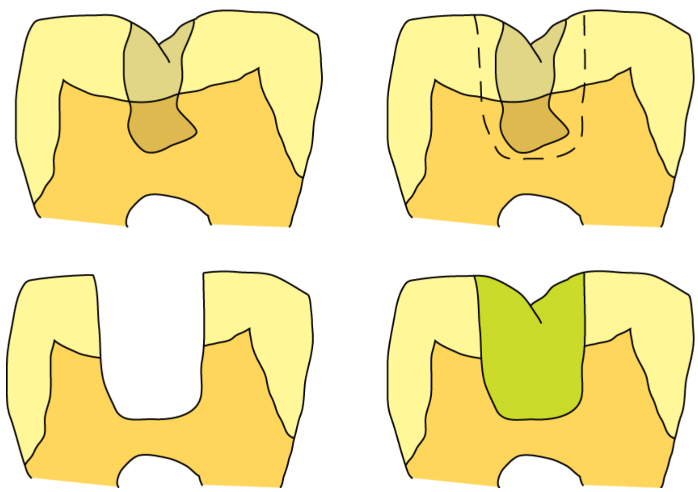

Figure 1. Schematic representation of the restoration placement procedure. The damaged part of the tooth is identified and removed. The cavity is further prepared to allow the placement of the restoration material. After etching, an adhesive is applied. Finally, the cavity is filled in layers with the composite according to the instructions.

A mesial-occlusal-distal (MOD) preparation with beveled margins was performed by the students. After etching, one group of students applied an adhesive, according to the manufacturer's operating manual, to facilitate bonding to the tooth substance, while this step was omitted in a second group. Both groups placed the restoration with a layering technique again according to the supplier's instructions. Each layer was polymerized for a period of 20 seconds. Finally, excess material was removed and the surface polished as done in the clinical practice in vivo.

2.2 Micro-computed tomography

Data acquisition was performed with a SkyScan 1174^{TM} system (SkyScan, Kontich, Belgium) with the maximal acceleration voltage of 50 kV and 800 µA beam current. A 0.5 mm-thick aluminum filter was used to increase the mean X-ray energy and reduce beam-hardening artifacts.

The SkyScan 1174^{TM} allows measuring several specimens serially by shifting the rotation stage in the direction parallel to the rotation axis. 2 to 3 teeth were placed in an Eppendorf container and serially scanned. 900 projections each 1024 × 1024 pixels were acquired over 360° with an exposure time of 3 s per frame, resulting in a total scan time of approximately 55 minutes per tooth. The optical magnification was set to a value that the entire specimen fitted into the field of view. As a result the pixel sizes was between 20 and 28 µm. The data was reconstructed using the producer's software NRecon, based on a modified Feldkamp algorithm, with a correction to reduce ring and beam-hardening artifacts.

2.3 Data evaluation

A qualitative analysis of the restorations was performed on both µCT and microscopy data. For the inspection of the micrographs, the images were displayed on a 19" TFT monitor and searched for visible imperfections in the composite material and for gaps between restoration and tooth hard tissue. The specimens were divided in four groups depending on the size of defects: below 200 µm, between 200 and 500 µm, between 500 and 1000 µm and above 1000 µm.

The µCT data were visualized with the software VGStudio Max 2.0 (Visual Graphics, Heidelberg, Germany). The volumetric datasets were manually aligned with the microscopy pictures and scrolled through in three orthogonal directions. For each dataset, the same classification as for the microscopy images was performed.

2.4 Microscopy

After µCT measurements, the teeth were cut in mesial-distal direction with a Well diamond-string saw (Ebner SA, Le Locle) for light microscopy inspection. The cutting plane was arbitrarily chosen. A 10-times diluted crystal violet solution was dripped on the cut surface with a pipette and dried after 5 s with a paper towel, then rinsed with water. The microscopic images were taken with Leica M7A and Leica DMRM microscopes running the software Leica IM 500, with a DC300 camera.

3. RESULTS AND DISCUSSION

3.1 Defect size recurrence after microscopy analysis

After inspection of the light micrographs, five of the 33 specimens were found to have defects with a maximal linear extension in the cutting plane below 200 µm, 12 specimens showed defects with an extension between 200 and 500 µm, 12 showed defects between 500 and 1000 µm and in 4 specimens defects larger than 1 mm could be found. In the 16 specimens where defects larger than 500 µm were present in the cutting plane, the density of these defects was 1.3 per cut (0.6 std. dev). Only air enclosures and voids between the different composite layers and within the bulk material were considered. Gaps between tooth hard tissue and restoration material, caused by shrinking of the restoration composite polymer and imperfect bonding between tooth and restoration, were not included for this analysis.

3.2 Defect size recurrence after µCT analysis

The inspection of the µCT data showed that all restorations contained imperfections at least 200 µm wide. In 5 specimens 500 µm was found to be the maximum defect size, while 14 specimens also contained defects between 500 and 1000 µm and in the remaining 14 specimens, defects above 1000 µm could be identified. The presence of ring artifacts, imperfect reconstruction near the rotation center as well as loss of image contrast due to beam hardening artifacts in the restoration material bulk complicated the defect detection. A conservative approach to defect analysis was chosen: structures which could not clearly be identified (artifact or defect related) were not considered.

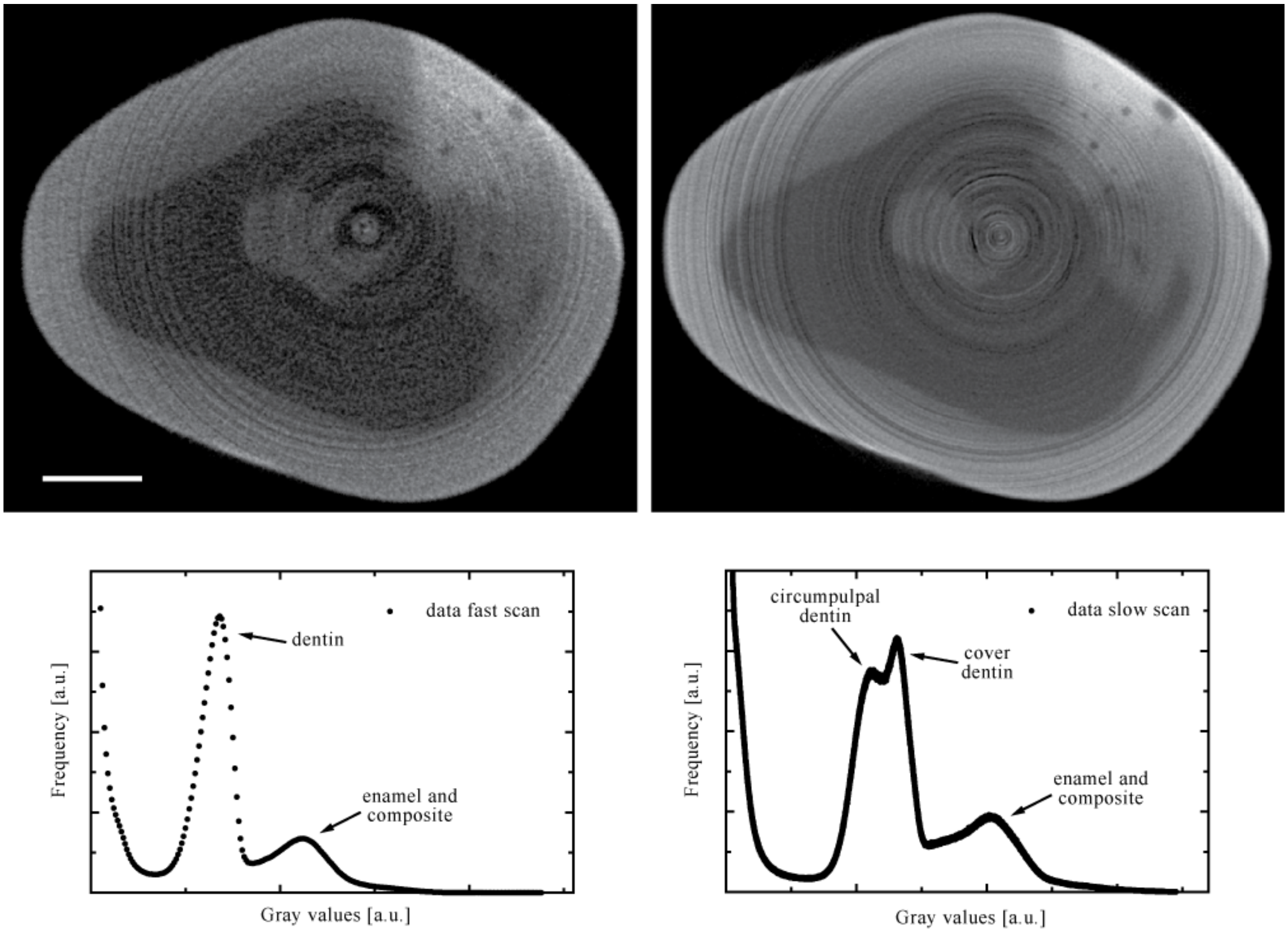

Figure 2. Selected slice from the same specimen, scanned with two different settings: left, fast scan with 900 projections and 3 s exposure time and 8-bit gray value depth; right, slow scan with 1800 projections, 4 s exposure time and 16-bit gray value depth. The length bar corresponds to 2 mm. Below, the corresponding histograms are shown. Note that multiple dentin peaks, corresponding to circum-pulpal and cover dentin, are visible on the left hand side, where only one dentin peak is visible on the right.

3.3 Image quality and acquisition time

Improvement of image quality could be achieved by longer exposure times and increased number of projections per scan, as well as increased magnification. Due to the tight schedule of the dentistry students' education and the further use of the specimens during their trainings, long-term scans could not routinely be performed. To study, however, this issue, one specimen was measured in two height steps with an exposure time of 4 s, 1800 angular steps and 2 projections per step at a pixel size of 14.4 µm. The data was reconstructed with 16 bit gray value depth. In comparison to the standard settings of 900 projections with 3 s exposure time in one height step, the scanning time is increased by over a factor of 8 and the amount of data by a factor of 3.

Figure 2 shows a virtual slice through the reconstructed data of the same specimen with both standard (left hand side) and improved (right hand side) acquisition modes. In both images, air enclosures in the upper right hand side of the slice can be identified. In the right image, a larger number of defects can immediately be spotted, and the defect shape can be clearly discerned. The smaller air enclosures can only hardly be spotted in the left image. Clearly, an increase in image quality is obtained by enhancing the acquisition parameters, as can also be seen in the histograms of the two datasets. In the longer scan, the cover dentin and the less calcified circum-pulpal dentin lead to distinct peaks, which are not observed with the standard measurement settings. However, the increased requirements to scanning time and storage space do not allow examining all specimens with longer exposure times and higher number of projections.

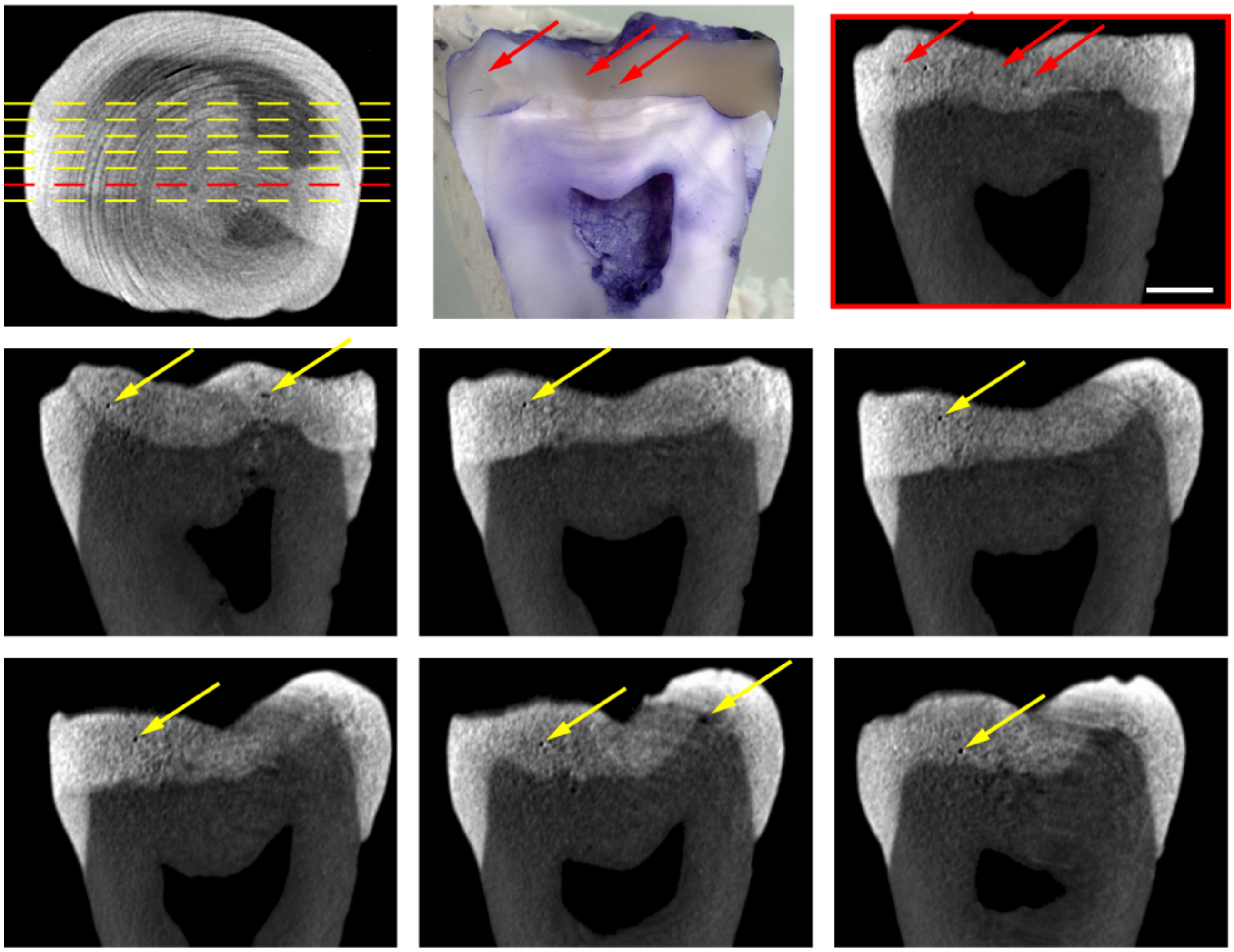

Figure 3. The image shows axial µCT slices through a selected tooth. The center and right image on the top row show the microscopy image and the corresponding slice through the µCT dataset. The images in the second and third row show parallel slices through the µCT data at different positions. The top left image, a transversal cut through the tooth crown, specifies the exact locations of the slices. In the microscopy image and the corresponding CT slice, imperfections in the composite material due to air enclosures during restoration are visible (red arrows). No imperfections can be found in the remaining slices. Dark spots (yellow arrows) are caused by ring artifacts and reconstruction imperfections near the rotation center. The length bar corresponds to 2 mm.

3.4 Two- versus three-dimensional analysis

In Table 1, the defect analyses for the 2D and 3D approaches are compared. The cross-entries give the number of specimens, in which defects of a given size were identified with microscopy and µCT. As expected, in none of the specimens microscopy revealed larger defects than the analysis of the µCT data. In 19 of the 33 restorations, µCT allowed finding more extended defects than seen on the micrographs (numbers in the cells below the table diagonal).

The defect distribution is inhomogeneous in the composite bulk material. Therefore, an arbitrarily chosen cutting plane does not guarantee a representative statement about the quality of the restoration. In Figure 3, an axial slice, the micrograph of the cut and seven slices parallel to the vertical cut through the tomographic dataset of one specimen are shown. The red and yellow lines in the axial cut give the position where the vertical slices were taken. On the micrograph, as well as on the corresponding tomographic slice, small air enclosures in the composite can be seen (red arrows). No additional defects could be detected in the µCT data. The dark spots, indicated by the yellow arrows, are attributed to ring artifacts and imperfect reconstruction near the rotation axis of the specimen.

Table 1. Largest detected defect extension on micrographs vs. largest detected defects with µCT.

max. defect size seen on µCT	max. Defect size seen on micrographs				
	< 200 µm	200-500 µm	500-1000 µm	> 1000 µm	total
< 200 µm	0				0
200-500 µm	1	4			5
500-1000 µm	4	5	5		14
> 1000 µm	0	3	7	4	14
total	5	12	12	4	

In this case, the information gained from the micrograph is misleading, as the overall quality of the restoration in terms of homogeneity seems to be better than expected. However, this situation was observed in only one specimen. It is unclear whether the lack of defect findings in the CT data is due to their real absence or a result of insufficient resolution in the virtual slices.

A defect with extension below 500 µm can be identified in the micrograph represented in Figure 4 (right part of restoration). While the diameter of the defect can be determined from the photograph, its extension perpendicular to the cutting plane is inaccessible. Again, the information obtained from the microscopy image is misleading, as revealed by the virtual cuts through the tomographic µCT dataset. The defect spreads across almost the whole width of the restoration.

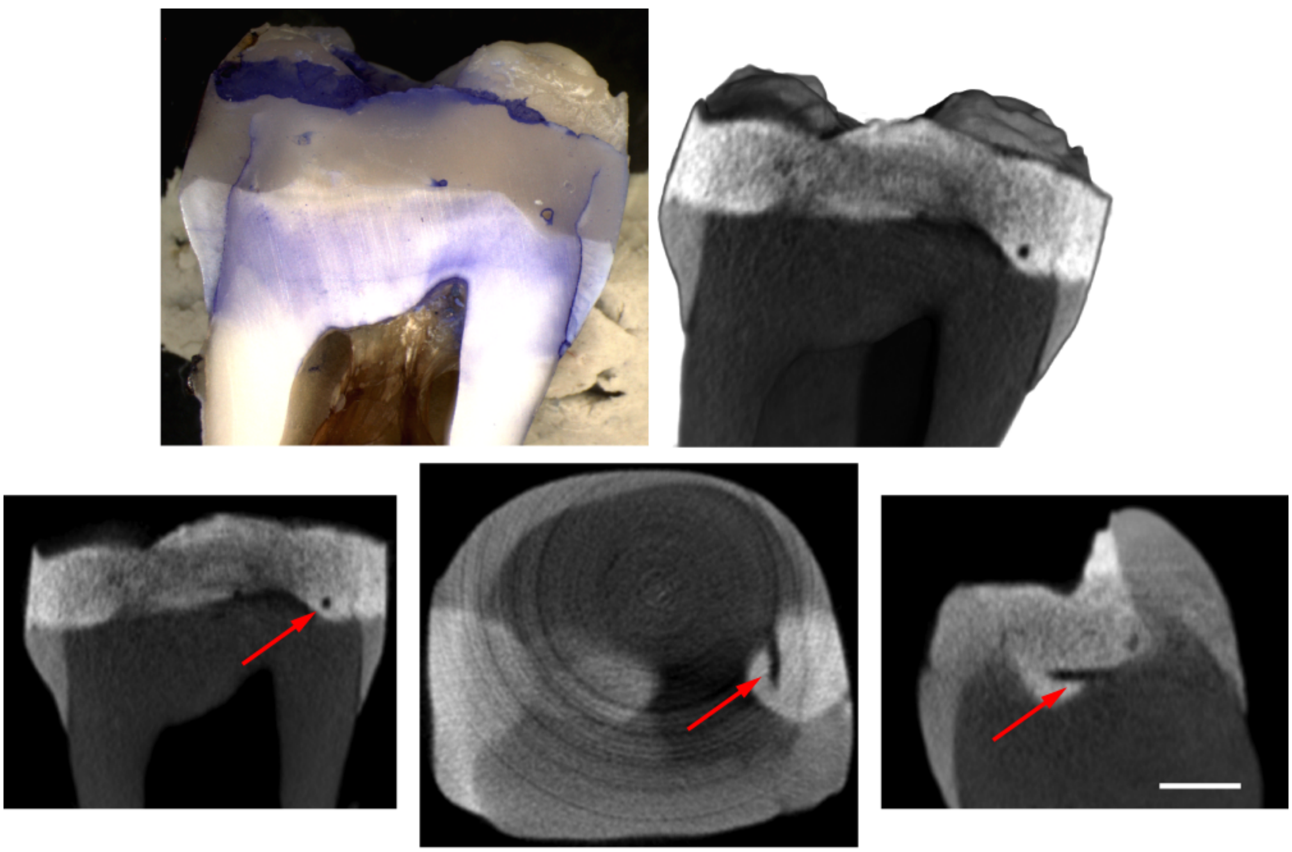

Figure 4. On the top, the micrograph and the corresponding 3D rendering of the cut are shown. In the bottom left corner of the restoration, a defect with a diameter below 500 µm is visible. The 3D µCT data reveal the maximal extension of the defect to be above 1000 µm. The length bar corresponds to 2 mm.

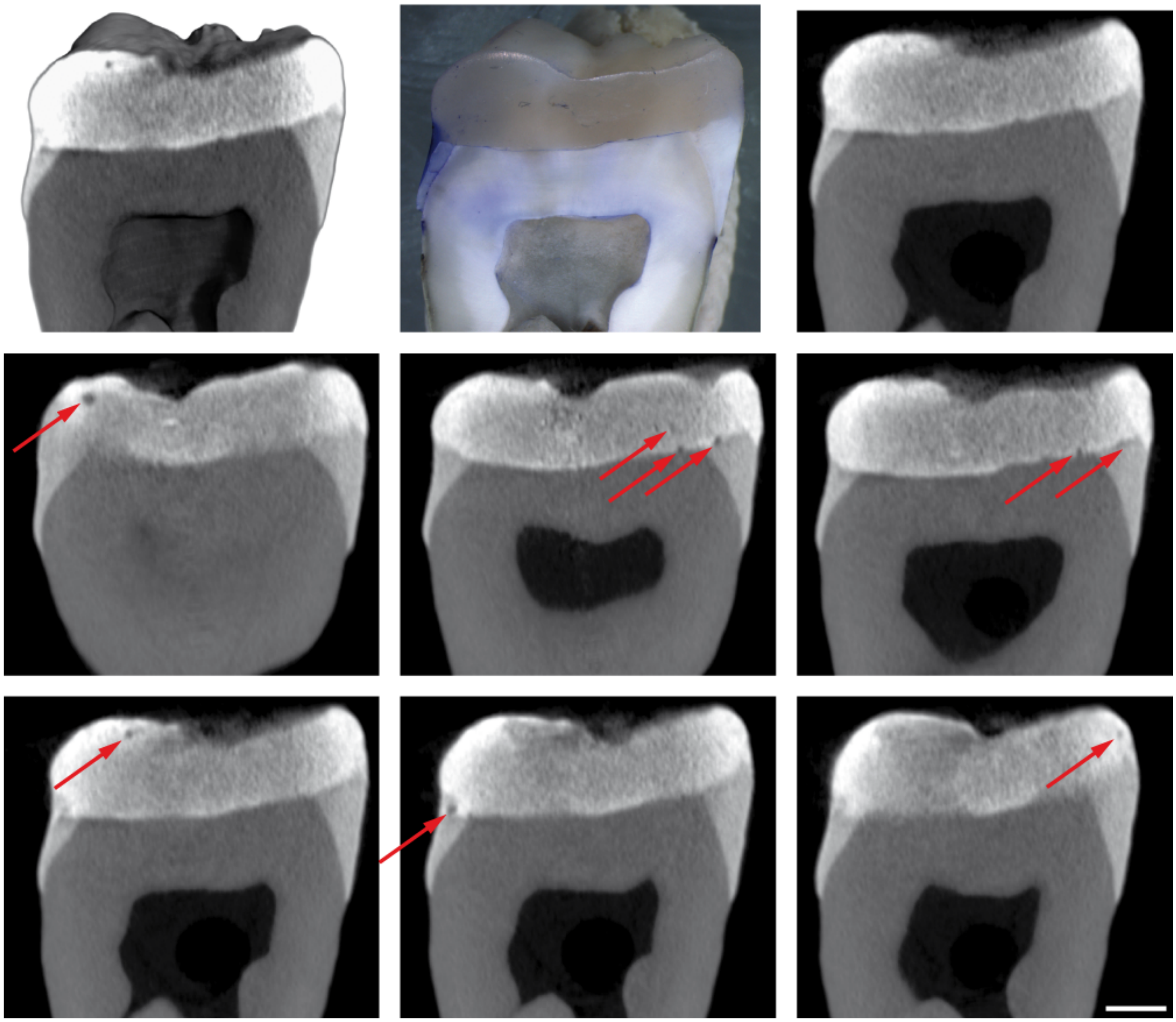

Figure 5. The central image in the top row shows a cut through one specimen where no major defects can be detected, left and right of it the corresponding µCT data. The images in the second and third row show parallel virtual cuts through the CT data of the same specimen at -1.72 mm, -1 mm, -0.4 mm, 0.16 mm, 0.360 mm and 0.64 mm from the cut in the top row. Red arrows indicate defects found in the composite material. The length bar corresponds to 2 mm.

In Figure 5 the inverse situation than in Figure 3 is demonstrated. No prominent air enclosures or gaps can be identified in the cutting plane micrograph. Inspecting the volumetric CT data brings to light different imperfections along the whole restoration, indicated by the red arrows. Again, the sole inspection of a 2D cut is misleading. Based solely on the information from the micrograph, the composite is expected to be defect free, while this is not the case.

4. CONCLUSIONS

The incorporation of state-of-the-art instrumentation into the teaching of students on university level is generally motivating and provides the students new insights into topics previously covered in lectures. X-ray based CT is integral part of the radiology lectures for students in medicine and dentistry. During the practical course, however, the authors realized that a significant number of students needed the practical experience to understand terms such as spatial resolution and contrast. For the better-educated students the direct contact with µCT was the initial point to start research in the field of 3D characterization of natural and man-made materials [8-14].

The main outcome of the present study, however, relates to the comparison between the 2D and 3D analyses. For years, many students have claimed that their restorations were better than others and the assistant had just chosen the wrong slice for microscopy. According the results of the present paper, some of them are right. Others, however, were even worse, as shown above. In most cases, however, the microscopy approach underestimates the defect sizes, so that the students obtained on average the 'better' results with microscopy compared to µCT. In conclusion, µCT contributes to the fairness between the students comparing their in-vitro composite restorations.

The integration of the µCT measurements into the training of students in dentistry allows them to get detailed feedback on their first restoration skills and to understand the importance of the different preparation steps. The presented approach allows drawing conclusions on the outcome omitting individual steps of the treatment. The students realize the significance to accurately follow the supplier's instructions. It should be noted, however, that the defects and voids found in this study may not be necessarily the result of improper handling of the composite during layering since voids are routinely found in bulks of composite materials [7]. Furthermore, besides a homogenous material the quality of a composite restoration depends on many factors and thus cannot be accurately assessed by detecting voids alone.

Nevertheless, already the simplest µCT-systems such as the low-cost SkyScan 1174^{TM} allow elucidating the advantages of the 3D approach. These systems should be used for educational purposes, since the students do not waste time for understanding detailed operation and can concentrate on the main issues. Furthermore, the costs stay reasonable as the investment is below 100,000 USD and the system is less susceptible to failure than more advanced instruments used for challenging research.

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