A novel approach for crown manufacturing based on digital volume tomography and CAD

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***Abstract*—In the production of dental prostheses, it is currently only possible to provide the dental technician with the necessary information about the prepared tooth in a complex way. The purpose of this thesis is to develop a concept for the fabrication of a dental crown on the basis of CBCT data and finally to produce a prototype. For this purpose, a conventional tooth impression, a modern intraoral scan, and a CBCT x-ray image were taken from a real patient case for data comparison. Subsequently, a conventional dental crown was produced based on the intraoral scan data using a conventional CAD/CAM procedure. The DICOM data of the CBCT X-ray was again adapted to the required processing properties and then converted into the STL grid structure. Based on this data, a dental crown could be fabricated using the CAD/CAM process, which was finally compared with the conventionally fabricated denture. The study showed that fabrication of the CBCT-based data is possible and has some advantages. Problems such as the generation of the bite state were identified, which still need to be overcome before denture fabrication on CBCT data is possible in clinical practice. For this purpose, a thin wax plate could allow an occlusal state, which would simplify the matching of contact points. Similarly, better image quality of CBCT images should be achieved with different record settings.**

***Index Terms*—cone-beam computed tomography, computer-aided design, crown, DICOM, dentistry.**

I. INTRODUCTION

IN case of an accident, carious defect, or age-related wear, it may be necessary to fabricate a dental prosthesis. To restore the full static and aesthetic functionality of a defective dental crown, the corresponding tooth must be reproduced with an exact fit. This is necessary to maintain the regular bite pattern and masticatory muscle stress, which could otherwise lead to considerable impairment of the patient and displacement of the remaining teeth. The dentist tries to create an even and smooth surface of the tooth stump with a clearly visible preparation border to the untreated part of the tooth. To provide the dental technician with the necessary information to achieve the best possible fit, an impression of the prepared dentition is made in a painful and cumbersome manner. The gum of the subgingivally prepared tooth is surgically retracted by iron sulphate treated retraction sutures to illustrate and stop the flow of saliva and blood as seen in Figure 1.

According to the dentists interviewed, this procedure can irrevocably sever the Sharpey fibres between the treated tooth and the jawbone [2]. This can lead to a pathological enlargement of the tooth pocket at the sulcus, which in turn can result in paradonthosis. According to the dentists interviewed, the undamped transmission of masticatory forces to the periodontium can lead to jaw atrophy and loss of the tooth stump [2].

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Fig. 1. Six prepared ones of the upper jaw are visible. The anterior tooth, as well as the molars, were treated with retraction sutures. The gums were retracted by the black threads treated with Orbat. This allows a low-liquid impression without disturbing gingiva. [1]

The resulting benefits of the saved tooth should outweigh the risk of tooth loss from the treatment. Although the prepared area is locally anesthetized during the procedure, there may be pain, swelling, and bleeding in the area of the prepared tooth after treatment. The tooth impression can be distorted by air and liquid inclusions in the impression material, deformation when removing the tray, and undesired imaging of the retraction threads. Shrinkage of the model in the course of curing is also to be expected, which represents a falsification of the real tooth situation. The deformable impression material can cause it to flow under older dentures and considerable forces are needed to pull it out. According to three dental technicians interviewed, only 30% of the impressions provided in the practice are in an easily recognizable condition and can be worked with without any problems [3]. In some cases, it may be necessary to take another impression in an additional treatment of the patient.

In Figure 2 shows a tooth crown with a gap that is too large. Deposits have formed due to the inappropriate transition to the existing tooth stump. In case of a carious defect, further death of the tooth sump and loss of the tooth crown may occur. The gums have started to recede in the treated area. This cannot be replaced by any procedure, which is why it is important

Fig. 2. On the left side, you can see an inserted crown on a front tooth of an upper jaw, which has an insufficient accuracy of fit. A gap to the existing tooth stump can be seen. the dark deposits (yellow arrow) may be caries. The right picture also shows the anterior teeth of an upper jaw, where a dental crown was also inserted. The insufficient accuracy of fit causes inflammation of the gums on the front teeth, as can be seen in the yellow circle. [4]

to avoid it. The picture on the right shows a crown that is too tight. T he contact and pressure causes inflammation of the gingiva. T his strain can lead to paradonthosis, which can result in the loss of the tooth. As shown in the yellow circle, the improper fit can also result in inflammation of the adjacent teeth.

This study aims to develop a process that provides the dentist and dental technician with more accurate information about the tooth situation and the preparation margin with less effort. The described distortions can also occur with a purely optical impression with an intraoral scanner. In this case, the patient's open and closed oral cavity is filmed without contact for several minutes using a video camera and then a three-dimensional grid model is generated in STL format. The dental technician then uses this surface data to produce the denture using the CAD/CAM (Computer-Aided Design/ Computer-Aided Manufacturing) method. With both methods described, an X-ray must still be taken as there is an indication to check the worthiness of preserving the tooth to be crowned, as no subgingival information is known in the treatment so far. It has to be weighed up whether the health advantage for the patient by preserving the remaining tooth justifies an increased cancer risk because of the ionised radiation exposure [5].

This is how the idea came about to use the patient's legally required X-rays because the hard tissue is visible without soft tissue in the CBCT data. According to Michael Hülsmann, the radiation exposure of an OPG (orthopantomogram) is approximately 19 μSv [6]. The radiation exposure of a three-dimensional CBCT (Cone Beam Computer Tomography) image depends on the imaging mode, the resolution, and the size of the viewed volume. According to Dr. Gerd Frahsek, the radiation exposure is only 8 to 64 μ Sv [8]. Compared to this, according to Detlef Gumprecht et al., 2006, the radiation exposure of a CT scan is about 2.3 mSv [7] [8]. With CBCT images, an x-ray sensor travels around the patient's head in a few seconds and creates around 500 slice images, which are merged into a three-dimensional model on the computer. According to the German Federal Office for Radiation Protection, around 40 million X-ray images are taken every year in the field of dentistry, whereby only a fraction are CBCT images, as these are not usually covered by statutory health insurance [9] [10]. For the dentist himself, the running costs are the same, only the acquisition costs for a CBCT device are significantly higher compared with conventional OPG devices [2][10].

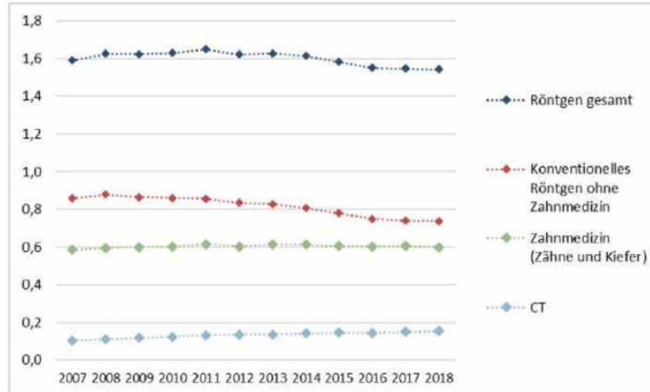

Fig. 3. The graph shows the proportion of X-ray admissions per inhabitant per year from 2007 to 2018. The X-axis describes the temporal course over the twelve years. The y-axis shows the sum of annual X-ray exposures from 0 to 1.6. The blue values describe the number of CT exposures, whereby a growth from 0.1 to almost 0.2 can be seen. The number of X-ray exposures in dentistry is shown in green, whereby these remain constant at a value of 0.6. In red, the values of all conventional X-ray exposures can be seen, whereby these have decreased over the years from approx. 0.9 to 0.7. The blue curve describes the sum of all X-ray exposures. It can be seen that approx. 1.6 x-rays are taken per person per year. [11]

Teeth have the advantage that they can be clinically examined. Thus, various systems have been established in dentistry to show visually recognizable tooth and gingiva surfaces. However, in this case, no information is known about the health condition beneath the surface of the mouth, or why it is recommended that an X-ray is taken in addition [2]. Gums also need to be treated surgically if the preparation margin below the gingiva is to be visualized. After insertion of the denture, this border should no longer be visible to ensure successful treatment. The resulting idea is to take a three-dimensional X-ray of the patient, which can be used for the fabrication of the denture. Modern dentistry requires effective treatment that is fast, painless, and free of complications for the patient [2]. Due to the easily representable anatomical structures in the oral cavity, imaging techniques, and especially X-ray technology, have enriched dentistry. It is recommended to make as many documentations of the oral cavity as possible to have an overview of the temporal changes of the tooth positions and the disease progression. Looking at the distribution of X-rays per inhabitant and year from Figure 3, a slight in- crease in CT (computed tomography) images can be seen in Germany. This is due to the development of technology in recent years, with experts talking about an increasing trend. The benefits of CBCT in dentistry, a rising tendency can be observed, too. The share of CT examinations in inpatient medicine has increased by about 80 percent between 2007 and 2018 [11].

II. METHODS

IN the patient case under consideration, a dental prosthesis was fabricated for molar tooth 3-6. First, an intraoral scan of the oral cavity and the occlusal condition was performed, and a dental crown was fabricated on this data using the CAD/CAM procedure. In addition, a CBCT image had to be taken for medical reasons. As can be seen in the illustration of the CBCT device used in Figure 4, the patient bites with the front teeth on a bite block for fixation (yellow circle) while the sensor moves around the head. The temple and forehead are as well fixed during the X-ray exposure.

Fig. 4. The cone beam computer tomograph Orthophos xg 3d from the company dentsply sirona can be seen. The yellow circle contains the bite block for fixing the patient. Next to it are the sensor and detector, which move in a circle around the patient during the exposure. [12]

As the tooth had to be extracted due to an unforeseen diagnosis, it was a phantom case in the further course, as no final check of the accuracy of fit could be carried out on the patient, but only on models. The CBCT data are stored in DICOM (Digital Imaging and Communication in Medicine) data format and contain all information about the patient. Therefore, they were anonymized and made unrecognizable using the SyngoShare Webview software. The anonymized DICOM data are now further processed in the open-source software Invesalius 3 by selecting the corresponding Hounsfield Unit area of the radiograph in, which the teeth are visible without gums and soft tissues. For the patient case, a Hounsfield Unit range of 622 to 1988 was selected, as shown in Figure 5, as it represented the best image data range.

The data is then exported into the STL (Standard Triangle Language) data format and opened with Meshmixer from Autodesk for further processing of the triangle grid. Now all superfluous image sections and artifacts are removed for process optimization. Afterward, the upper and lower jaws are extracted in full, holes are closed, and the surfaces are smoothed. The upper jaw is now manually positioned in such a way that possible contact points to the lower jaw are

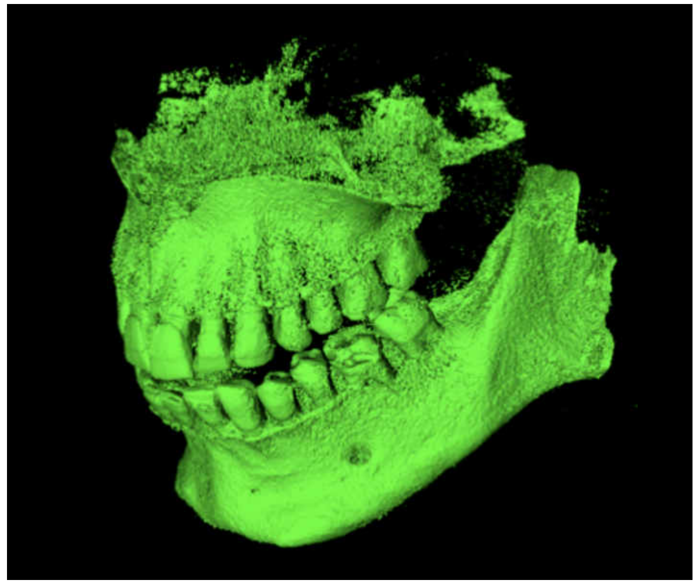

Fig. 5. The reddened head area of the patient with upper jaw and lower jaw can be seen. The selected Hounsfield Unit area was set to 622 to 1988. With a larger range, other areas of the head would also be displayed, which would interfere with the diagnosis and contain no relevant information. If a smaller range is selected, parts of the bone structure are no longer displayed, as can be seen in Figure 11. The opening of the jaw due to the bite splint of the CBCT device is clearly visible. You can also see the prepared tooth 3-6 on the lower jaw.

present. The data is then saved again in STL data format and imported into the CAD/CAM software dds Dental of the dental laboratory. There, the denture is designed by conventional methods, as can be seen in Figure 6.

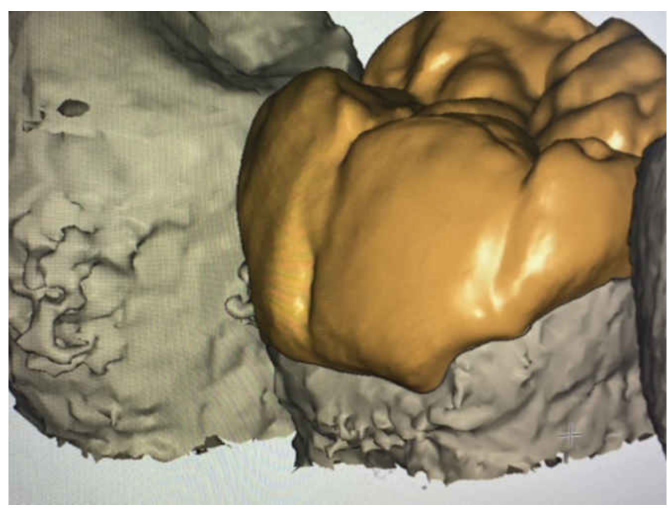

Fig. 6. The prepared tooth stump with its suture teeth can be seen. Due to the number of artifacts, it is difficult to position the preparation margin evenly on the tooth surface. Therefore, there are small protrusions on the edges of the orange crown. This was selected using the CAD programme's sample palette. The exact adaptation of the crown shape, cusps and fissures is based on the shapes of the natural teeth and the experience of the dental technician.

Figure 7 shows the crown as it was designed in the CAD programme. On the cusp, an attempt was made to show the influences of the antagonist using a digital articulator. Due to the opening of the jaw during the exposure and the associated displacement, no usable occlusion was created. Nevertheless, some contact points are shown in colour on the occlusal surface.

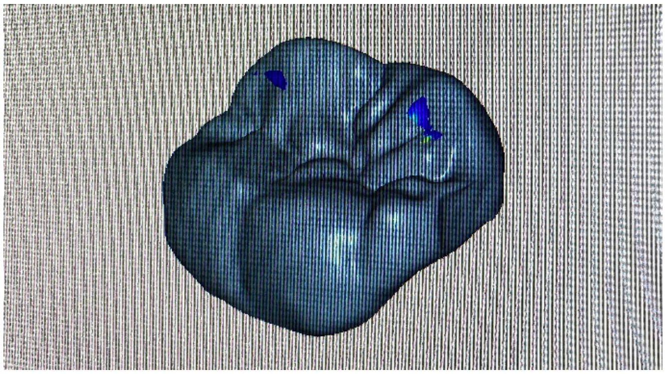

Fig. 7. The second designed dental crown can be seen in the CAD programme. The contact points of the crown with the antagonist have been partially achieved and are shown by the coloured areas on the occlusal surfaces. In the digital articulator, the match is shown increasing from blue to red.

Figure 8 shows the crown milled from ceramic and reworked using the CAM method based on the CBCT data. The subsequent articulation of the model and occlusion is the same for both methods.

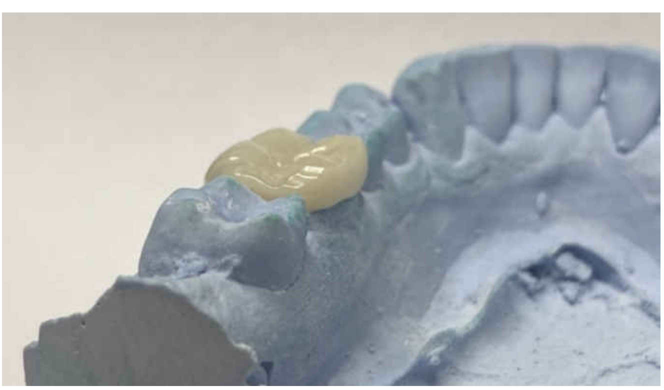

Fig. 8. The plaster model of the lower jaw impression from an oral perspective is shown. On tooth 3-6 there is the dental crown made purely on CBCT data. For the six experts interviewed, there was no qualitative difference in the accuracy of fit between the two crowns.

To be able to compare the different fabricated dentures with each other, a plaster model of the lower jaw was made again. As can be seen in Figure 9, on the anterior teeth, there were unwanted inclusions in the area between the teeth. The air and plaster deposits dis- tort the original image.

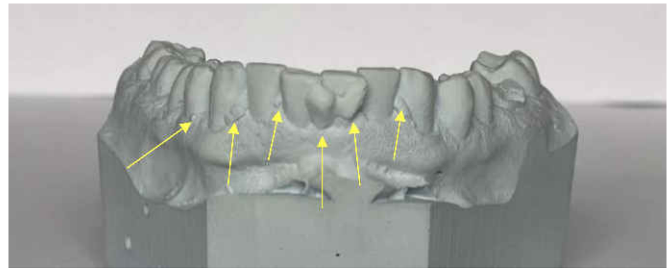

Fig. 9. Frontal view of the Second Cast Mandible. Deposits (yellow arrows) can be seen in the interdental spaces of the anterior teeth. These are distortions of the real mouth area and can hinder the fabrication of the denture.

III. Results

ALL dentists and dental technicians interviewed confirmed that the prosthesis made from CBCT data is of sufficient quality for a time-limited dental work and offers advantages [2] [13]. The creation of CBCT data requires only a few seconds and hardly any preparation, whereas conventional impressions can take several minutes to several sessions due to the surgical exposure of the preparation margin and must always be performed by the dentist himself.

Comparing the data quality of the CBCT image with the conventional scan data, the CBCT images have a higher image resolution in detail. As can be seen in Figure 567, the intraoral scan of the patient has inaccuracies in detail. However, the course of the preparation margin is recognisable. It is therefore possible to design and fabricate the dental crown in the CAD programme Dental CAD V3 from DDS.

The image data from the intraoral scanner has a smoother surface with more regularities, but there is more blurring in the image detail, as can be seen in Figure 10. The production of dental restorations based purely on intraoral scan data is only possible inaccurately due to the lack of image information. Pathological diagnoses are only possible with X-ray data.

By fixing the patient with the bite block, the jaw is opened at a minimal angle and no occlusal condition is possible during the radiograph. A manual shifting of the grid with a CAD program does not lead to a representative result of an occlusion according to the dental technical view, because an individual position and rotation is depending on the patient and the temporomandibular joint [13]. If the upper jaw is only moved in a vertical direction, a suitable occlusal condition is still not achieved, because in reality the jaws slide into each other when biting together. The tightening of the jaw muscles also has an influence on the occlusion. [14]. There should be an occlusal condition during the image acquisition, as the teeth may be displaced due to tightening of the jaw muscles in the real bite situation. Nevertheless, there must be a certain distance between the jaws during the radiograph

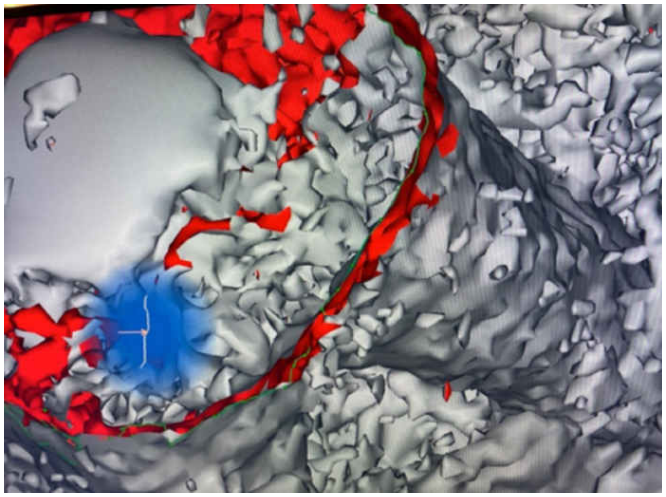

Fig. 10. It can be seen a detailed view of the X-ray data after conversion to STL format. In the CAD programme, this should be placed as evenly as possible on a smooth tooth surface. The prepared area is defined on it, after which the CAD programme defines the edge of the tooth crown. Due to the selected Hounsfield unit area, many artefacts occur. Defining the preparation margin (green line) is made difficult by the coral-like irregularities. The red area marks all surface areas that lie at the preparation margin.

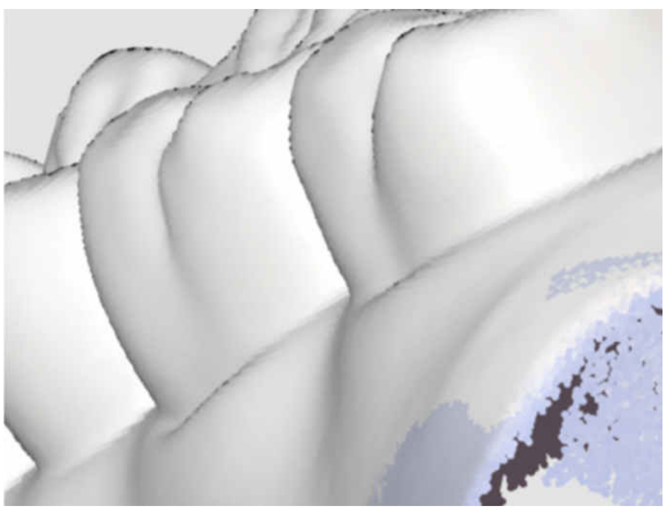

Fig. 11. The right side shows a detailed view of the intraoral scan of the untreated posterior molars. On close inspection, inaccuracies can be seen on the tooth surface.

to be able to distinguish between the teeth on the computer model. Importing the CBCT data into the CAD program of the MeditLink intraoral scanner has led to initial success in matching the maxilla with the mandibula, as can be seen in Figure 12.

Due to the different jaw openings during the scan and the gradual shifting, only an inaccurate result can be achieved. The four teeth of the upper jaw of the CBCT data partially penetrate the surface of the scan data. Since the scanner data set (dark grey) is not extracted, the underside is shown hatched in red. Figure 13 shows the STL dataset of the intraoral scanner in dark grey. The light grey CBCT dataset of the maxilla was inserted manually. The overlap of the two datasets is not representative in Meshmixer due to rotation, but it can be seen

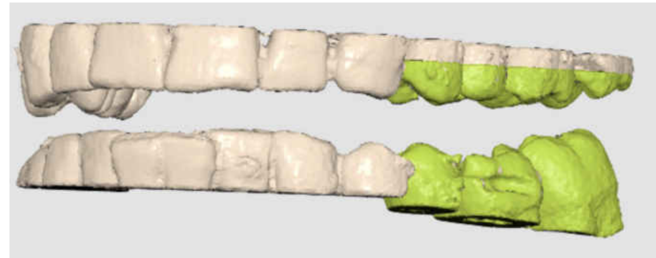

Fig. 12. Matching the two data sets is only possible once the complete maxilla and mandible are imported based on the intraoral scan data. In the green CBCT data, a difference can be seen on the buccal exterior compared to the scan data. This is marked with the yellow arrow.

that the scaling of the two datasets matches.

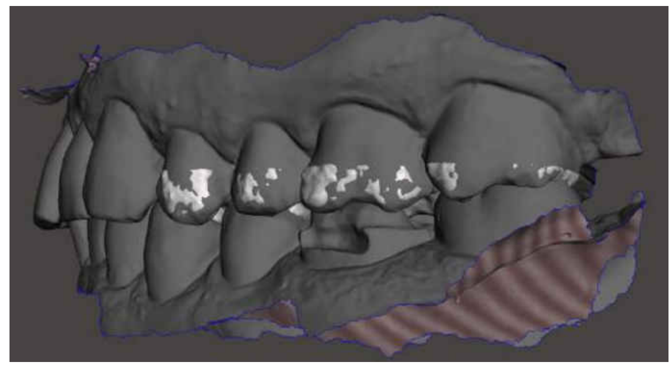

Fig. 13. Overlay of the two data sets in Meshmixer. The scan data is shown in dark grey, the X-ray data in light grey.

As can be seen in the yellow circles in Figure 14, there are unwanted contact points with the neighbouring teeth, both in the CBCT image (top) and the scan (bottom). This leads to a distortion of the real intraoral space as well.

A search for an existing patent revealed that a German dentist had already patented this procedure in 2013 [15]. But, at that time he had enormous problems because of interference from artifacts, so he stopped trying to establish the procedure in modern dentistry. As there were still few CBCT devices available on the market at that time, he used a conventional CT (computer tomography) with higher radiation exposure for the patient [15].

To obtain a meaningful comparison of both fabricated crowns, an artificial laboratory case would have to be created and dentures fabricated for the identical tooth stump using conventional impression procedures and CBCT-based impression procedures. For clinical reasons, only one CBCT image was taken in the low-dose mode in this patient's case. A comparison with the conventional procedures would have to be made with the maximum possible image quality of the high-definition mode. The coral-like artifact formation of the CBCT data is based on the patient's movements during the acquisition and possible scattered radiation from metallic objects. Thus, better blocking of the patient's movements during the acquisition must be taken into account [2]. The process of CBCT- based tooth replacement is therefore only possible for patients who do not have any other metallic

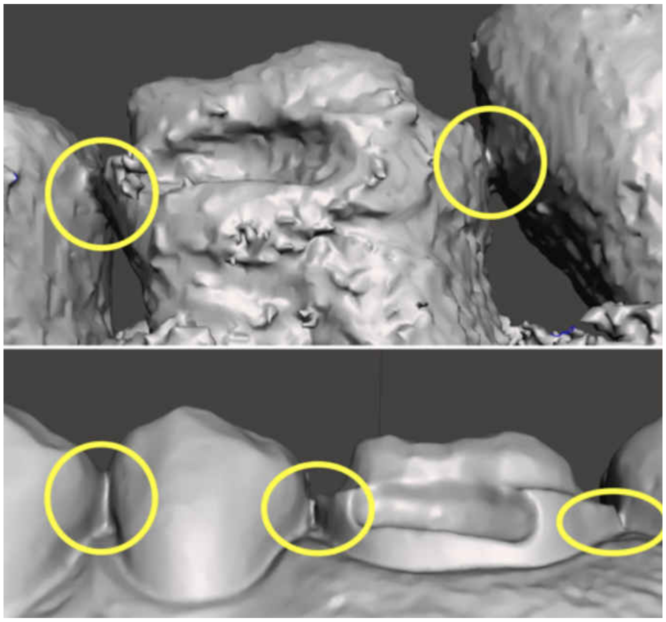

Fig. 14. The buccal view of the prepared tooth stump can be seen in MeditLink. Unwanted contacts to the neighbouring teeth can be seen in the upper CBCT data and the lower scan data (yellow circles). In the comparison of the data, the gingiva is visible in the scan data, which is hidden in the X-ray.

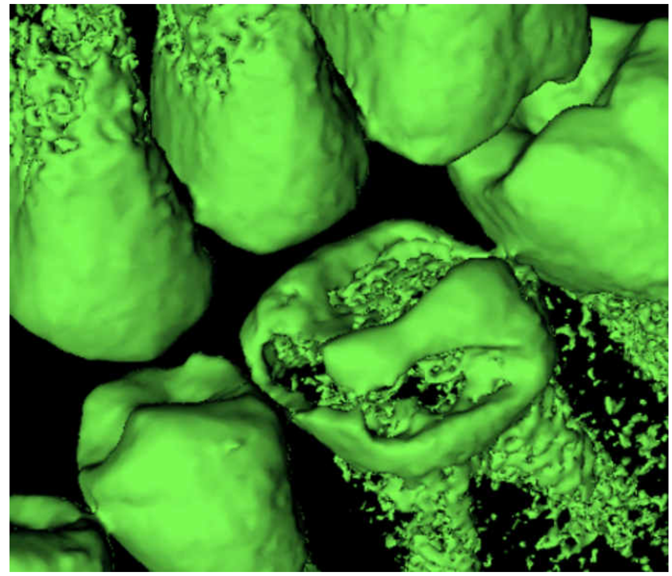

Fig. 15. A detailed view of the jaws with the HU range from 1199 to 1299. This representation cannot be used because very many holes in the prepared tooth led to inaccuracies during processing.

objects like jewellery, implants or dentures on or in their bodies. Scattering of dental restorations is caused by amalgam fillings, implants, dental crowns, dental bridges, re- tainers, and dental posts. Ceramic or zirconium dental restorations, on the other hand, do not produce scattered radiation. To reduce artefact formation due to blurring, the patient's movements would have to be additionally blocked. As an additional option, the recording time can be reduced. With modern devices, software is used to try to filter out artefacts mathematically with algorithms [16].
The preparation margin is always recognizable in the CBCT images by the adjustable Hounsfield area, regardless of its gingival position. One problem with the CBCT data is the coralline artifacts. These vary according to the selected Hounsfield parameters, but all necessary areas of the teeth can remain visible. Care must be taken to optimize the Hounsfield Unit parameters, as this can lead to the formation of holes in the enamel area, as can be seen in Figure 15.

In the case of a matching Hounsfield Unit area, the image artifacts must nevertheless be subsequently worked out with the CAD program Meshmixer. After the conversion processes, the CBCT impression has provided the dental technician with the same information as the conventional impressions, whereby a view of the tooth root below the gingiva is possible [2]. Thus, a faster tooth restoration fabrication process based on CBCT data is possible, even though time is needed to process the artifacts in the conversion process. If no conventional manual or intraoral scan impressions have to be made, conventional preparation of the tooth and gum is no longer necessary. This has the hygienic advantage that fewer bacteria and pathogens can be transferred through blood and saliva.
Since the dentist must work closely with the dental technician, outsourcing the production process is a conceivable option, but it has the local disadvantage that the dental technician would still have to come to the dental practice for any necessary reworking.

An occlusal imaged condition gives the dental technician the necessary information about the contact points of the future denture. Nevertheless, there must be a certain distance during the radiograph to be able to differentiate between the various teeth on the radiograph. This could be realized by a deformable wax plate, as its layer thickness of 0.5 mm allows occlusion, is radiopaque, and still provides a distance on the CBCT image [17]. Even a deformation in the μ-range can later lead to grinding and tension in the whole body. These described wax plates could also be used to create a minimal distance to the adjacent teeth so that at least on the CBCT images no proximal contacts are visible anymore [17]. Although today a more modern technology would allow tooth replacement production based on CBCT data, the patent for the process remains unused. With the modern equipment used in today's dentistry, it should be possible to take images without interference by fixing the patient. In 2013, the dentist Volker Knorr also had the problem of matching the jaws, but this became unproblematic thanks to modern CAD programs such as MeditLink [7]. The modern CBCT devices have many advantages in terms of acquisition costs, radiation exposure, and image quality compared to the CT devices of ten years ago, why a focus should be placed on CBCT dentistry [18].

IV. Conclusion

THE aim of the study was to mould the subgingival preparation margin without surgical treatment and to fabricate a prosthesis based on CBCT data. This procedure was tested on real patient data with a supragingival preparation margin. However, this had no influence on the fabrication process. The gingiva can be masked out in the CBCT procedure due to the different Hounsfield area to bone. According to the dentists and technicians interviewed, the accuracy of fit of the prosthesis produced was sufficient on the phantom model, even though the fit of the prosthesis could not be checked on the patient due to extraction. To be established in practice, the fabrication of dentures on CBCT data would have to be defined by official regulations Thus, the problems described in the Introduction can be circumvented with the newly developed process.

To be able to make a statement about the worthiness of preservation of a tooth, an X-ray must be taken in every case. The OPG and CBCT procedures have a comparable radiation exposure for the patient. Since the preparation margin can be visualized with the CBCT procedure without surgical intervention, the patient's risk of paradonthosis is reduced, because the Sharpey fibres cannot be injured as with conventional procedures. Likewise, the procedure offers the advantage that the prepared tooth area can be imaged subgingivally without saliva, blood, or remnants of the retraction threads. Nevertheless, because of movement artifacts and scattered radiation, the CBCT image quality is still not one hundred percent sufficient to produce a perfectly fitting dental crown without any problems. A problem to be considered for the future is the fixation of the head and the visualization of the occlusion. Here it should be possible to represent an occlusal condition on the X-ray with a deformable, thin medium without having to make an additional conventional impression. Nevertheless, each patient and disease case is individual, which makes the fabrication of an optimally fitting dental prosthesis a complex process in the micrometer range. The introduction of the new process and more image information has nevertheless brought us closer to the goal of ensuring that the denture has an optimal fit and finish on the tooth stump.

At the current state of dentistry, conventionally made dental impressions do not represent the one hundred percent real image of the oral cavity. Techniques such as intraoral scanning can prevent more and more inaccuracies in the impression. Nevertheless, the existing possibilities of the three-dimensional X-ray technique should be included. This is helpful to obtain further views of the jaw and to be able to mask out areas of soft tissue. All dentists and dental technicians interviewed agreed that due to the progressive development of algorithms for back projection, the future of modern dentistry will see three-dimensional X-ray technology prevail [19]. Due to the lower radiation exposure of the patient with modern CBCT devices, as well as the high investment costs of intraoral scanners, X-ray technology will remain competitive in imaging procedures in the future.

The patent to produce dentures based on X-ray data already exists, but there are still enough parameters that could be examined and improved. The radiation exposure of the devices alone has been reduced in recent years. The algorithms for removing image artefacts have also become more successful [20]. Based on the facts presented, it makes sense to further investigate and optimise the process of CBCT manufacturing. The surface quality of the CBCT images would have to be examined in detail to further test the practicality of the process. The aim will be to provide the dental technician with an image of the jaw in STL data format that is as unaltered and smooth as possible. For this purpose, a single prepared tooth should first be imaged in the conventional procedure and the radiographic procedure. If the detailed image quality of both data sets is available in comparable resolution, a phantom model of a complete jaw can be used. It should now be investigated to what extent the occlusion can be imaged on the radiographs. As soon as these data sets match, the experiment must be oriented towards a real patient case. For this purpose, other tooth sets should also be included to investigate the development of image artefacts through interaction. If the CBCT data sets match the data sets of the conventional fabrication, a denture should be fabricated on a living patient. For this purpose, interfering factors such as the patient's movement, saliva and blood flow and soft tissue must be considered during the impression process. Finally, the detailed accuracy of fit of both manufacturing processes of the denture must be compared on the patient's tooth stump. The treated area can be scanned or x-rayed again for verification.

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