Quality assessment of clinical computed tomography

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ABSTRACT

Three-dimensional images are vital for the diagnosis in dentistry and cranio-maxillofacial surgery. Artifacts caused by highly absorbing components such as metallic implants, however, limit the value of the tomograms. The dominant artifacts observed are blowout and streaks. Investigating the artifacts generated by metallic implants in a pig jaw, the data acquisition for the patients in dentistry should be optimized in a quantitative manner. A freshly explanted pig jaw including related soft-tissues served as a model system. Images were recorded varying the accelerating voltage and the beam current. The comparison with multi-slice and micro computed tomography (CT) helps to validate the approach with the dental CT system (3D-Accuitomo, Morita, Japan). The data are rigidly registered to comparatively quantify their quality. The micro CT data provide a reasonable standard for quantitative data assessment of clinical CT.

Keywords: Artifacts, implant, multi-slice CT, dentomaxillofacial CBCT, micro CT

1. INTRODUCTION

Clinical computed tomography has routinely been used to obtain three-dimensional (3D) images for dento-maxillofacial diagnosis. The use of these imaging techniques has not been restricted to oral- and dentomaxillofacial surgeons but has increasingly included dentists for the last decade. In dentistry, treatment with endosseous implants has revolutionized oral rehabilitation.[1] Here, appropriate imaging methods have become necessary to perform the complete implantation procedure. Dentists have used CT for planning purposes.[2, 3] Taking whole CT-scans results in high exposures/doses[4] and generates relatively high costs.[5] About a decade ago the modification of the CT, termed dentomaxillofacial cone beam computed tomography (CBCT), was introduced and has been characterized by significantly reduced exposures.[5-8] Notably, the artifacts owing to highly absorbing metallic implant materials are less dominant than using conventional CT.[9] For insertion of dental implants, the American Academy of Dentomaxillofacial Radiology[10] has recommended to evaluate the bone height and width for any potential implant site by means of cross-sectional images. Generally, these images have been the result of dentomaxillofacial CBCT that allows visualizing the bone anatomy in any desired cross-section. Consequently, the correct implant of appropriate length and diameter can be selected, even if bone defects are present. This means that dentomaxillofacial CBCT has become an exceptionally effective tool for pre-operative patient treatment. Post-operatively, however, the artifacts of the highly x-ray absorbing implants moderates the value of the imaging data. Hence, dentomaxillofacial CBCT is usually replaced by only two radiographs necessary to validate the surgery and for prospective follow-ups. The precise implant position and potential inflammation-based bony defects, however, remain covered by dark bands in the cross-sectional images. The artifacts by highly x-ray absorbing metals, such as dental restorative materials, have been described.[11, 12] Unfortunately, the well-established titanium- and zirconia-based compounds cause these persistent artifacts. Materials, which exhibit less or comparable x-ray absorption than teeth, namely ceramics such as alumina, silica or polymers are often no alternatives, since their mechanical properties are insufficient for many dental applications. Some studies demonstrated, however, that the partial replacement of metallic dental restorations by less absorbing materials such as composite resins led to significant artifact reduction.[13] Nevertheless, it is highly desirable to fully understand the nature of these artifacts and to find possibilities for their reduction. For the given implant material and surrounding tissue one can reduce the visibility of the artifacts increasing the accelerating voltage or the exposure time.[14-17] The success, however, is limited, since for the higher photon energies the tissue of interest becomes more and more transparent and longer exposure times increase the costs in exponential fashion. Other authors[11, 18-20] presented software solutions using iterative interpolation algorithms to partly correct the

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metal artifacts in the CT images. These approaches include the beam-hardening corrections.[14] The clinicians, who are faced to the patient-specific situation and restricted to the imaging systems available, have only limited possibilities to reduce the artifacts discussed above. Within very restricted ranges, they can vary accelerating voltages or beam currents. More effective might be to ask the patient to tilt the head that the maximal absorption along the source-detector line is minimal. In both cases the clinician needs a parameter to judge the image quality that allows for the effective optimization. An empirical approach to search for such a quality parameter cannot be performed with patients. The current study has been based on a post-mortem pig model - the lower jaw including the soft tissue parts and with two titanium implants - visualized by means of dental cone beam, spiral, and micro CT facilities.

2. MATERIALS AND METHODS

2.1 Pig model

The jaw was extracted from the meliorated country pig. It was five months old and held a weight of about 100 kg. At this stage, the pig was in the late phase of deciduous dentition and two tooth gaps in the anterior part of the jaw were present. These gaps provided space for two parallel implants (Straumann AG, Basel, Switzerland) each 4.1 mm in diameter and 10 mm in length. The rather bulky portions of muscles were reduced and partially substituted by soft-tissues to simulate the patient's situation. The tongue and parts of the vertebral column filled the cavities as shown in Fig. 1. For the experiments, the entire specimen was laminated in plastic foil. Between the experiments the specimen was frozen to -18 °C. For the micro CT measurements, a cylinder with a diameter of 30 mm that comprises the two implants was cut by means of a hole saw (cp. inset in Fig. 1).

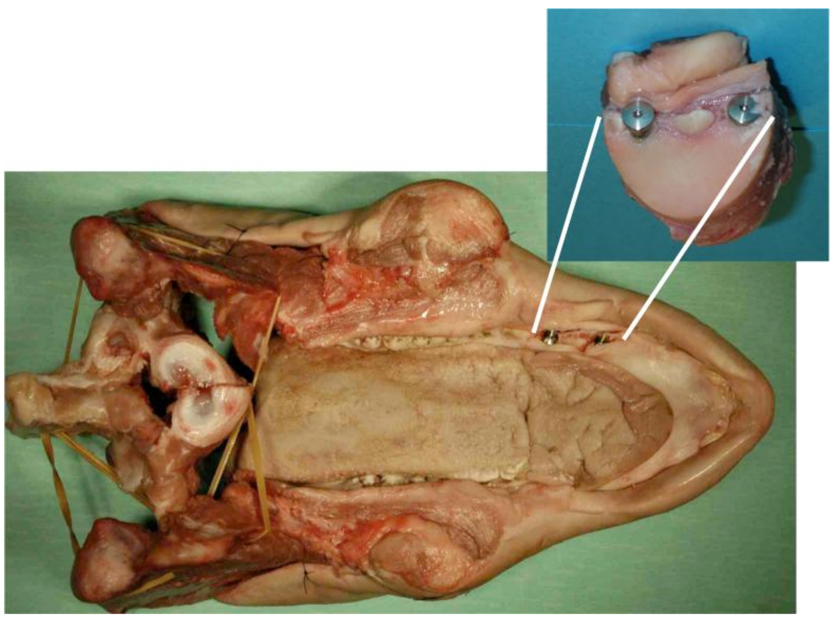

Fig. 1. The photograph shows the pig model consisting of the lower jaw with the tongue and the parts of the vertebral column. The two inserted implants are better seen in the inset that illustrates the specimen cut for the micro CT examination.

2.2 Dentomaxillofacial cone beam CT examination

The dentomaxillofacial CBCT 3D Accuitomo 60 (Morita, Kyoto, Japan) served to gain local tomographic data of the implants and the surrounding tissues comparable to the patient's situation in an radiological examination. Before the data recording, two projections termed scout images were taken to select the cylindrically shaped region of interest (60 mm high and 60 mm in diameter). These two images, perpendicular to one another, are represented in Fig. 2. They show that the two titanium implants are located within the volume dedicated for the local tomography. The data acquisition implies the 360° rotation of x-ray source and detector around the specimen within a period of 18 s. The CCD sensor recorded images with isotropic pixel sizes of 0.125 mm. Based on these projections, the Accuitomo software i-Dixel_image generates volumetric data that are exemplarily shown in Fig. 3 by three selected slices that are perpendicular to each another. The dentist or the oral surgeon can select any desired virtual cut to check the exact position and orientation of the implant or even to measure distances of clinical interest. The present study comprehends the variation of the accelerating voltage between 70 and 80 kV using the beam current of 2 mA. These data were compared with the clinical standard, namely 80 kV and 7 mA. Furthermore, at the accelerating voltage of 80 kV, the beam current was varied between 1 and 10 mA to uncover optimized conditions for the data acquisition.

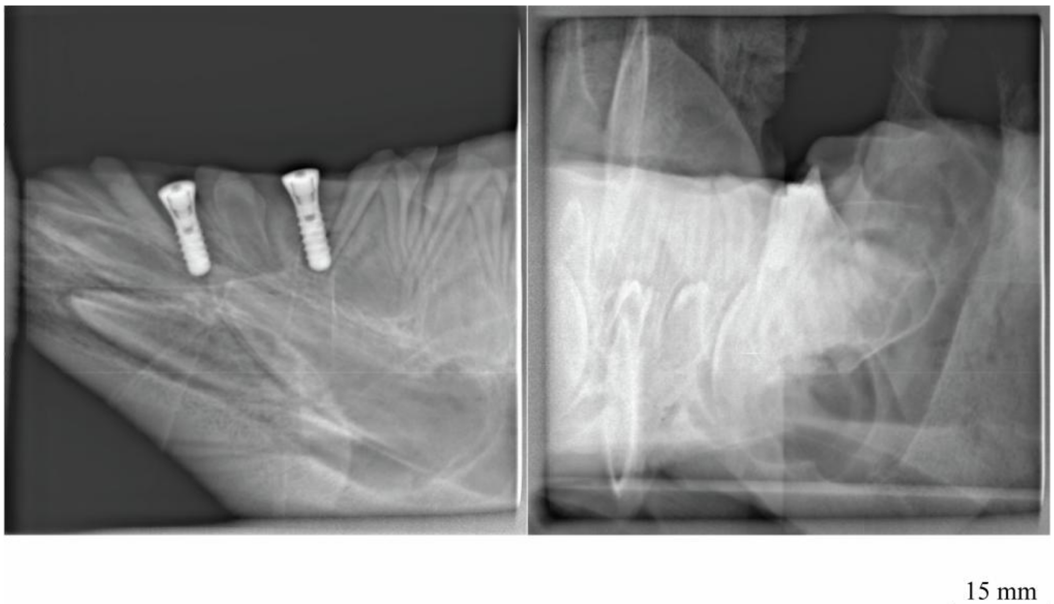

Fig. 2. In order to select the region for the local tomography, two radiographs have been recorded, termed scout images. These two projections, perpendicular to each other, enable the operator to shift the region of interest into the center. Note that on the right image the implants in the center of the image are hardly detectable.

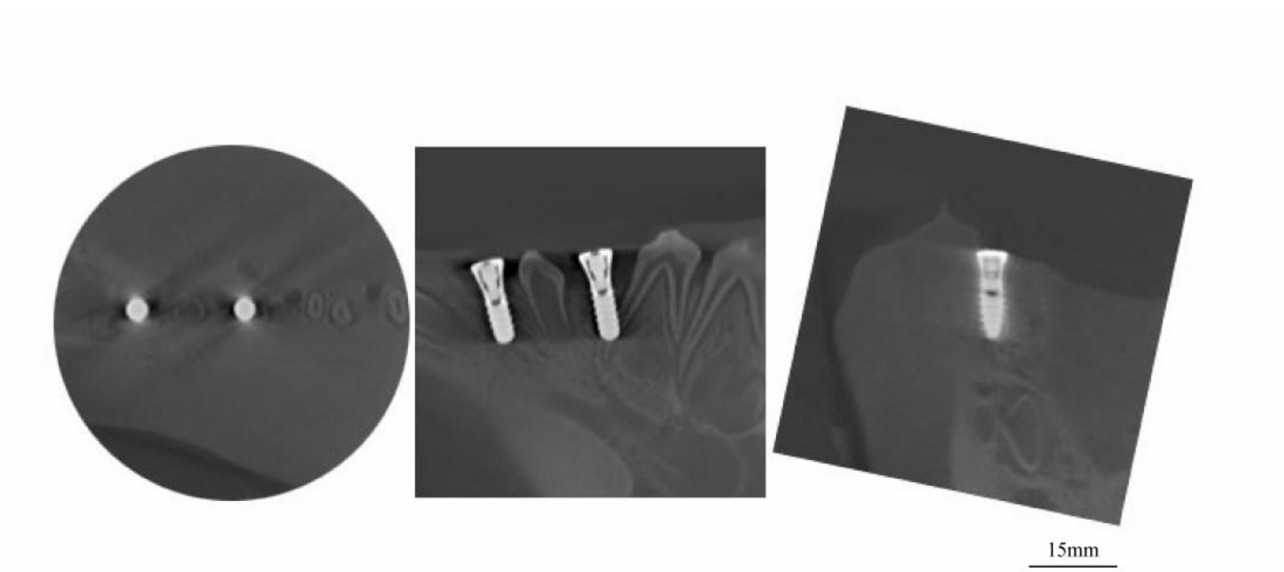

Fig. 3. The dentomaxillofacial CBCT provides virtual cuts of the cylindrically shaped region of interest as shown by the horizontal, frontal and transversal views. Rotating the data, the operator selects the views to precisely measure the implant's locations.

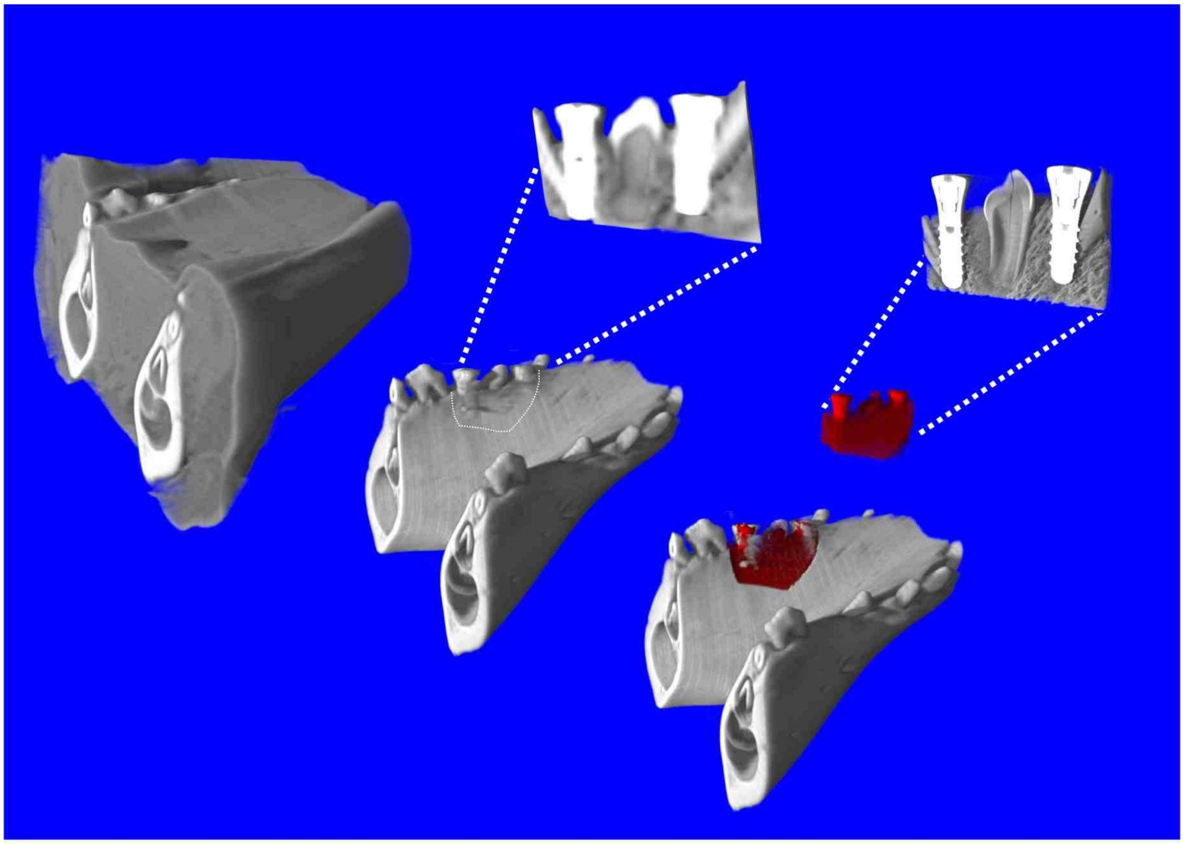

Fig. 4. The multi-slice CT allows visualizing the entire pig jaw consisting of soft and hard tissues including implants (3D representation on the left). Making the soft tissues transparent, the outer shape of the hard tissues become visible. The micro CT data are represented in red. The virtual cuts of the implants and the tooth in-between demonstrate the better resolution of micro CT with respect to the multi-slice CT. The images also show, which part of the pig's jaw has been studied by means of the different facilities.

2.3 Multi-slice CT

In order to visualize the entire specimen, the multi-slice CT Somatom Sensation 16 (Siemens Medical Solutions, Erlangen, Germany) was applied. The jaw orientation resembled to the patient’s one in vivo, i.e. occlusion plane perpendicular to the floor. The accelerating voltage corresponded to 120 kV and the beam current to 80 mA. The scan duration was set to 0.42 s per row. The data given in Fig. 4 show the pig’s jaw with the soft and hard tissue components as well as the two titanium implants. More detailed information can be extracted making the soft tissue components transparent or virtually cut the region of interest.

2.4 Micro CT

Micro CT systems are known to be effective for quantitative bone evaluation. Therefore, the mechanically extracted cylinder was scanned by means of the Skyscan 1172 (Skyscan, Kontich, Belgium). The specimen fixed on the precision rotation stage was made visible using the accelerating voltage of 100 kV, the beam current of 100 µA, the exposure time per projection of 2.655 s, and an image pixel size of 17.4 µm in rotation steps of 0.4°. The slices were reconstructed with the software of the machine (NRekon, Kontich, Belgium). In Fig. 4, the micro CT data are represented in red. The virtual cuts through the implants and the tooth in-between demonstrate the drastically improved spatial and density resolution of micro CT with respect to the multi-slice CT. The total exposure time of 80 min and the accelerating voltage of 100 kV permitted the almost artifact-free visualization of the two implants and the surrounding mineralized bony tissues as demonstrated by the horizontal, frontal and sagittal slices in Fig. 5.

Fig. 5. The extremely long exposure times and rather high accelerating voltage of the micro CT permit the almost artifact-free data acquisition as shown by the two implants and the surrounding mineralized bony tissues of the virtual slices in horizontal, frontal and sagittal views.

2.5 Pre-registration procedure

In order to directly compare the tomographic data of dentomaxillofacail CB-, multi-slice and micro CT-systems, the common volume of the registered datasets was determined. For this purpose the dental CBCT- and multi-slice CT-data were semi-automatically pre-registered with the micro CT-data via the manual selection of 3 non-collinear anatomical landmarks as described by Fig. 6. These three landmarks defined the data transformation (rotation, translation and scaling). First, the data were binned to get comparable voxel sizes for the different datasets. Second, the CT-data were interactively registered based on an IDL-tool to obtain a reasonable estimate for the automatic registration procedure.

2.6 Data visualization

The tomographic data were qualitatively evaluated and visualized by means of the commercially available software VG Studio Max 1.2.1 (Volume Graphics GmbH, Heidelberg, Germany). It allows generating any desired slice and the 3D representation of (sub-)volumes according to intensity-based segmentation procedures taking advantage of the gray value histogram.

2.7 Data treatment

Computer code developed on the basis of IDL 6.4 (ITT Visual Information Solutions, Boulder CO, USA) served for the quantitative data treatment. In order to calculate a parameter for the characterization of image differences, the squares of the differences of local x-ray absorption values (gray values) of registered slices were summed up. The lower this value, the more similar is the dataset of interest to the standard set.

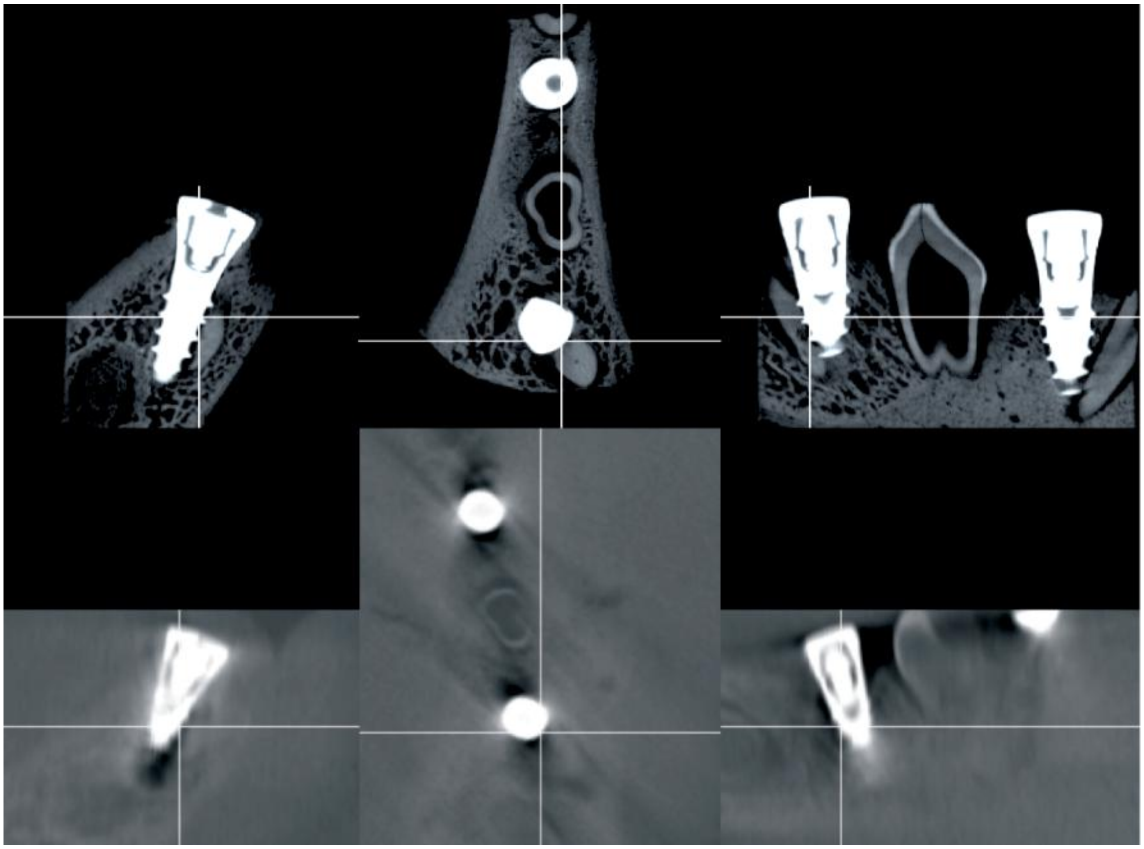

Fig.6. For the pre-registration of the dentomaxillofacial CBCT data with the micro CT ones, three non-collinear landmarks have been selected, which are identified by the bright crossing lines in both datasets. The three images in the top row are slices perpendicular to each other obtained from the micro CT, whereas the related slices below are dentomaxillofacial CBCT data. The subsequent loading of the transformed data helps to validate the procedure.

3. RESULTS

3.1 Definition of the standard dataset

From the clinical point of view, one should chose the dentomaxillofacial CBCT dataset with the default setting as recommended by the supplier. This choice, however, is somehow arbitrary. More important, this dataset contains the artifacts caused by the implants. Therefore, one should use the dataset with the best image quality and the obviously lowest amount of artifacts. As expected the micro CT data exhibit by far the best image quality. Both implants and bone are clearly identified and even the interface between bone and titanium implant appears artifact-free. Consequently, for the quantitative comparison of the tomographic data both standards are considered.

3.2 Registration of the data to extract the common volume

To quantitatively evaluate the tomograms of micro, dentomaxillofacial CB and multi-slice CT, they were registered by means of an affine transformation. The algorithm based on the rigid matching uses the classical maximization of the mutual information principle.[21, 22] Using the Powell multi-dimensional search algorithm[23] the nine registration parameters, i.e. three for each translation, rotation and scaling, were found for the considered registration. The pre-registration allowed for fast convergence and for the qualitative validation of the results obtained. Based on the registered tomograms, first the data were re-sampled to realize identical voxel sizes and orientations. Second, the volume that each dataset embodies has been extracted for further analysis. Hence, the data are available for the quantitative search of the best quality.

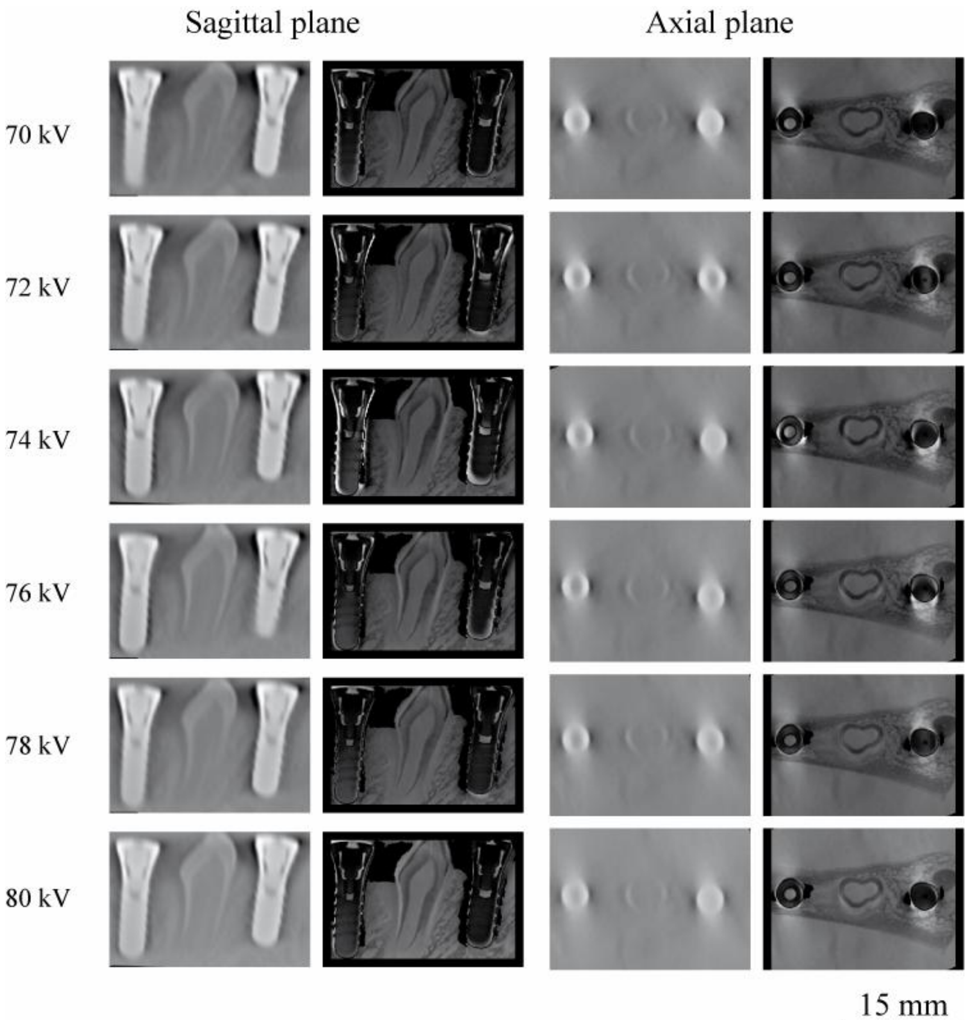

Fig. 7. The images, selected slices in sagittal and axial planes, illustrate the improvement of the image quality increasing the accelerating voltage from 70 to 80 kV in steps of 2 kV. This can even be better seen in the second and forth columns, where the differences of the images with the registered micro CT data are presented.

3.3 Selection of the quality factor

There are different approaches to define the quality of an image. Many of them rely on 2D images and cannot be used for tomograms. In general, the criteria are complex and lead to time-consuming data treatments. Therefore, the present study counts on a very simple definition of the quality factor. It is defined as the sum of the mean square of the gray value differences at each voxel. Thus, this quality factor characterizes the similarity between the dataset of interest and the selected standard.

3.4 Comparison of selected slices

Fig. 7 contains a series of virtual cuts in sagittal and axial planes (columns 1 and 3) obtained from the dentomaxillofacial CBCT varying the accelerating voltage from 70 to 80 kV in steps of 2 kV. In columns 2 and 4 the related difference images illustrate the improvement of the image quality increasing the voltage in the qualitative manner. The increase in the accelerating voltage from 70 to 80 kV improves the image quality. The contrast enhances. The blurring and the presence of dark bands at the bone-implant interfaces become weaker. Simultaneously, the white streaking artifacts in the axial planes of the specimen are significantly reduced.

3.5 Analyzing the quality factors of the 3D datasets

The quality factor of the common volume of each tomogram was determined for the two standards mentioned above. Fig. 8 represents the results for the variation of the accelerating voltages as bar plots. The filled bars of Fig. 8 show the relation to the micro CT standard, whereas the patterned bars relate to the clinical standard. Smaller quality factor means closer similarity to the standard. For both standards, the quality factors becomes smaller and smaller increasing the accelerating voltage. Therefore, the present setup should be operated at the highest possible voltage of 80 keV, if titanium implants are present. Analogue, one can vary the beam current at constant accelerating voltage to determine the optimized current for the given voltage. The results of the variation of the beam current between 1 and 10 mA in steps of 1 mA at the accelerating voltage of 80 kV are presented in Fig. 9 again as bar plot. The quality factor does not show any clear dependence on the beam current.

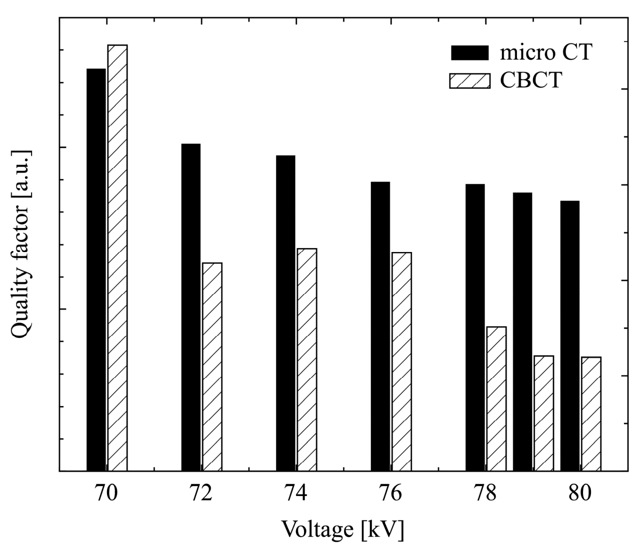

Fig. 8. The quality factor of a tomogram is defined as the sum of the mean square gray values at each voxel related to the registered standard tomogram. Here, the standard images correspond to the micro CT-data (filled bars) and to the parameter set recommended by the supplier of the dentomaxillofacial CBCT (patterned bars). Small quality factor, therefore, means close similarity to the standard.

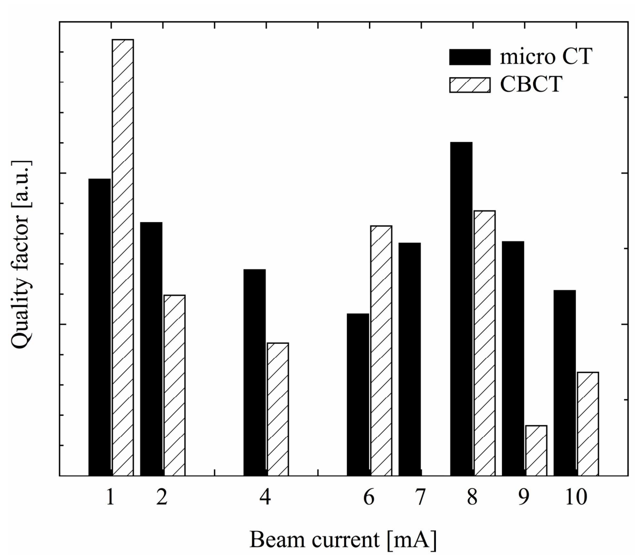

Fig. 9. The values of quality factor are showing similar tendencies regarding the standard (micro CT represented with filled bars.) and the clinical reference (dentomaxillofacial CBCT represented with patterned bars.).

4. DISCUSSION

An in-vitro model with a freshly extracted pig jaw was used to establish a quality assessment of dentomaxillofacial CBCT for patients with implants. This choice accounts for potential tissue damage by x-rays in patients. Nevertheless, this model provides comparable situations to the human visceral skull. The soft tissue influences the image quality.[24] Dentomaxillofacial CB and multi-slice CT are the x-ray tomography methods used in dental implantology. Both methods have pre-determined ranges of settings, which are limiting the quality. To assess bone morphology and the interface between bone and implants the micro CT is an efficient technique. It should be taken as the standard because of insignificant artifacts, adequate spatial resolution and reliable contrast of bony structures. The histological analysis is not necessary for the determination of the bone morphology.

The user of the dentomaxillofacial CBCT can generate images with a limited range of settings. The operator can vary, for example, the accelerating voltage. The implants that exhibit high x-ray absorption with respect to bone and soft tissues require higher photon energies. The dentomaxillofacial CBCT instrument is limited to the accelerating voltage of 80 keV that is not enough to get almost artifact-free images. Too high accelerating voltages, however, does not permit the visualization of the soft tissue components. Therefore, the operator has to determine an optimized value. The accelerating voltage of 80 keV is found to be the best choice for the present study. This corresponds to another study[25] that also shows less extensive artifacts for the higher photon energies. The use of filters can shift the average photon energy to higher values but reduces the number of photons implying larger scan times. This is often compensated increasing the beam current.[26]

The operator can also vary the beam current. Higher currents result in an increased number of photons and provide a better statistics or shorter exposure time. The disadvantage of high currents is the larger focal spot size, which usually leads to a reduced spatial resolution. These two dependencies let expect a continuous functional run. Unfortunately, the experimental data do not exhibit such a characteristic. The rather arbitrary dependence is expected to be the result of the gray value scaling incorporated into the reconstruction algorithm of the supplier, which needs a more detailed data analysis.

The quality parameter, defined as the sum of the mean square gray values at each voxel, always yields positive values. One cannot decide, which dataset is of better quality. In the present study one can easily see that micro CT gives rise to the best quality data and should be therefore be used as the standard. The choice of the quality parameter does not especially account for the artifacts. The incorporation of the square, however, somehow considers the artifact's presence. The quality parameter directly describes the similarities between 3D datasets. The images shown in the second and forth column of Fig. 7 impressively demonstrate that morphological features are even better seen in the differences, i.e. in the images describing the similarity.

In conclusion, the micro CT belongs to suitable standards to examine the quality and similarities within various tomograms, such as dentomaxillofacial CB and multi-slice CT. As expected the best images of the dentomaxillofacial CBCT have been obtained using highest possible voltage of 80 kV. The supplier should increase the value of the accelerating voltages to higher values as very recently realized for our system. Now, we can record images with voltages up to 90 keV and thereby reduce the artifacts considerably.

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