Clin Oral Invest (2013) 17:1601–1609
DOI 10.1007/s00784-012-0841-y

ORIGINAL ARTICLE

Accuracy of peri-implant bone thickness and validity of assessing bone augmentation material using cone beam computed tomography

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Received: 22 June 2011 / Accepted: 4 September 2012 / Published online: 12 October 2012
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Abstract
Objectives The aim of this study was to evaluate the accuracy of measuring bone thickness surrounding dental implants and the reliability of assessing existence and completion of osseous integration of augmentation material using a cone beam computed tomography (CBCT) system.
Materials and methods In jaws of foxhounds, artificial defects were regenerated by guided bone regeneration and then dental implants were placed. After putting down the dogs, the jaws were separated from the bodies and exposed in a CBCT system. The bone thickness was measured on both buccal and oral sides of the implants at different levels. Every examiner evaluated existence and integration of bone augmentation materials (BAM) and the completeness of marginal implant covering. The same measurements and evaluations were performed at digital images of the corresponding histological sections.
Results The mean and the standard deviation of the differences between radiological and histological measurements of peri-implant bone thickness were −0.22 mm and 0.77 mm, respectively. Sensitivity and specificity were 0.77 and 0.60 for existence of BAM, 0.59 and 0.74 for completed integration, and 0.39 and 0.71 for full covering of the implant surface.
Conclusions The present study indicates that the PaX Duo3D® CBCT system allows measurements of peri-implant bone thickness at an accuracy of half a millimeter, and—within limits—assessing the existence and integration of BAM. It is not possible to evaluate whether the implant is covered completely by hard tissue.
Clinical relevance Peri-implant bone thickness is a key factor for obtaining initial implant stability. The accuracy of its measurement has clinical impact. Radiological assessment of existence and integration of BAM would be of great benefit to the evaluation of augmentation procedures.

Keywords Radiological study · In vivo experiment · Linear measurement · 3D Imaging · Histological study · CBCT

Electronic supplementary material The online version of this article (doi:10.1007/s00784-012-0841-y) contains supplementary material, which is available to authorized users.

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Introduction

The development of oral implantology partially depends on the improvement of oral radiological techniques. Regardless of the pre-operative assessment of bone quantity and quality in the region of interest, or post-operative evaluation of integration of bone augmentation material (BAM), good validity and reliability of radiological evaluation are essential. Cone beam computed tomography (CBCT) has been widely used in clinical practice of oral and maxillofacial surgery, demonstrating the advantages of high resolution, easy handling, easy accessibility, reduced costs, lower radiation dose, and possibly less disturbance from metal artifacts [1] compared to CT imaging. Research has concentrated around the accuracy of measurements in CBCT images, but only a few studies focus on the accuracy of measurements of the peri-implant bone thickness next to implants [2–5]. This topic is, however, of great clinical importance since obtaining initial stability is the key to the overall success of dental implant surgery. Besides implant design and placement technique, sufficient bone thickness is also an essential factor for assurance of initial stability. Braut et al. investigated the radiological evaluation of the facial bone wall prior to extraction [6]. In a finite element study of orthodontic mini-implants, Dalstra et al. demonstrated that increasing cortical bone thickness drastically reduced the peak strain development in the peri-implant bone tissue [7]. An inverse relationship between cortical bone thickness and peak strain development suggests that cortical bone thickness is one of the key determinants of initial stability, although two cortical bones could have the same thickness but completely different bone mineral densities and different initial stability. Razavi et al. [2] placed dental implants in bovine ribs and exposed these specimens in two different CBCT scanners (i-CAT NG, Accuitomo 3D60 FPD). They found the accuracy of measuring bone thickness near implants was different depending on the CBCT scanner used and concluded the different scanner resolutions being the reason. Fienitz et al. [3] used another CBCT (Galileos) to scan the jaws of dogs being treated with dental implants and bone augmentation procedures. Fienitz concluded that the evaluation of peri-implant bone defect regeneration by means of CBCT is not accurate for sites providing a bone width below 0.5 mm and that a safe assessment of the success of the guided bone regeneration technique is not possible after the application of a radiopaque bone substitute material. Corpas et al. used the Accuitomo 3D (Morita, Kyoto, Japan) to investigate implants in minipigs. They found the CBCT deviating 1.20 mm from the histology regarding bone defects [5]. The present study was designed to reevaluate the accuracy of linear measurements of the peri-implant bone thickness and the radiological evaluation of bone-augmentation procedures using a different CBCT scanner.

In addition, assessment of BAM integration might be also a point of interest of CBCT application in oral implantology. In cases of bone augmentation before implant placement, integration of BAM is a prerequisite to implant surgery. Similarly, in cases of endosseous implants with simultaneous bone augmentation, radiological assessment of BAM integration would be helpful for the evaluation of therapeutical outcome. An animal experiment is supposed to be a very accurate method to investigate the accuracy of such a radiological diagnostic procedure, although few directly related papers have been published [3]. Hence, this study aims to assess the reliability of estimation of BAM existence and integration using a CBCT system.

Materials and methods

Animal study

In 2009, Schwarz et al. and Mihatovic et al. made a foxhound experiment to investigate bone augmentation procedures prior to implant surgery [8, 9]. The experiment was approved by the Animal Care and Use Committee of the Heinrich Heine University and the local government of Düsseldorf. The biopsies obtained at the end of the experimental phases were used for a supplementary radiological assessment and therefore served as a basis for the present study.

The animal study included a total of six foxhound dogs (age 18–22 months, weight 32–42 kg). It was performed in three surgical phases. In the first phase, the mandibular and maxillary first, second, third, and fourth premolars as well as the first and second molars (P1–M2) were extracted. After a healing period of 10 weeks, a total of 48 standardized saddle-type defects (mesio-distal width = 10 mm; height = 8 mm) were randomly prepared in both the upper and the lower jaw of each dog. The defects were filled using natural bone mineral or biphasic calcium phosphate, halfway with added autogenous bone and with random assignment of these treatment procedures to anterior and posterior sites, respectively. Subsequently, the treated defects were randomly allocated in a split-mouth design to the use of either a polyethylene glycol membrane or a collagen membrane. At 8 weeks, modSLA titanium implants were inserted at the respective treated defect sites and left to heal in a submerged position for 2 weeks before the dogs were put down. All surgical autopsy procedures were performed by two experienced operators (F.S. and I.M.). For details, see Mihatovic et al. and Schwarz et al. [8, 9].

CBCT radiography

The complete oral tissues of the put down dogs were perfused with formalin; both maxilla and the mandible including soft tissues were dissected from the bodies and packed tightly in airtight bags. All of the jaws were scanned using a CBCT system (PaX Duo3D®; Vatech, Seoul, Korea) within a few hours after dissection. A wooden scaffold served to place the jaws in a reproducible position for scanning in the CBCT machine. The laser orientation beam was used to adjust the jaws accurately to the scanning volume. The exposure settings were adjusted to 85 kV and 4.9 mA. The scanning parameters were set to a field of view of 50-mm diameter and 50-mm height at a voxel size and a slice thickness of 0.08 mm both. Following the exposures, the image data was saved to DICOM files by the Byzz program version 5.7.2 (copyright 2009; Orangedental GmbH & Co. KG, Biberach, Germany).

Image processing

The viewing software utilized to analyze the CBCT images was Ez3D 2009 Professional (version 1.2.1.0; Vatech). For every single implant, the image display was standardized to adjust the implant vertically and transversal to the alveolar bone in the multiplanar reconstruction (MPR) view at a slice thickness of 80 μm and at an image zoom of 250 %. Following, these standardized views were saved as “projects” separately for every implant.

Two examiners with different levels of experience in 3D imaging and CBCT usage participated in the first part of the study. One examiner was an oral surgeon (A.K.) having many years’ experience in CBCT imaging. The other examiner was a dentist (D.W.). Both of them were trained thoroughly on operating the CBCT machine used.

The examiners were instructed by a detailed step-by-step image processing protocol. Both were given two individually randomized viewing lists to reload the saved projects and carry out the measurements on identical slices twice in differently randomized orders to produce the data for inter- and intra-examiner reproducibility. The interval between first and second reading was 6 weeks at minimum.

In order to facilitate the measurement and save examiner time, a transparent plastic sheet was printed which showed five black horizontal lines and one vertical line, following a suggested method of Razavi et al. [2]. The distance between the first and last line was exactly the whole length of the implants on the computer display from interface edge to apex. These lines represent 0 %, 25 %, 50 %, 75 %, and 100 % of the implant length, respectively. The sheet was fixed by adhesive tape on the display directly over the

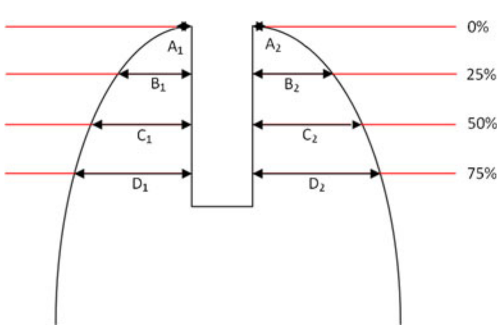

Fig. 1 Schematic diagram: Measurement of the bone thickness at four levels

radiographic images to indicate the levels where measurements were required from the examiners and was readjusted for every image. The peri-implant bone thickness on both the buccal and oral side of the implant was measured at the levels 0 %, 25 %, 50 %, and 75 % (Fig. 1).

Three more observers joined to the second part of the study to provide a total of five examiners. One of them was an examined oral surgeon and two of them dentists advanced in postgraduate education of oral surgery, all of them trained and licensed for the use of cone beam tomography. The assessment of integration of BAM was accomplished by the examiners answering the three following questions:

- Is there any augmentation material?
- If yes, is the augmentation material completely integrated into the bone?
- Is the implant completely covered with bone and/or augmentation material?

The five observers repeated their readings after at least 4 weeks. In the end, there were 10 evaluations per implant of existence, completed BAM integration and completed bone covering.

Histological reference

After exposure of CBCT, the specimens were processed in hard-tissue histology according to Donath [10] with some modifications. The jaws were cut at every implant site in the bucco-oral direction resulting in sections of approximately 40-μm thickness, as close as possible to the implant axis. All sections were stained with toluidine blue. For details, see Schwarz et al. [8, 9].

The histomorphometrical analysis was performed twice by both of the investigators (D.W. and A.K.) in randomized order. For image acquisition, a color CCD camera (Color View III; Olympus, Hamburg, Germany) was mounted on a binocular stereomicroscope (SZ61; Olympus, Tokyo, Japan). The optical zoom was calibrated to a magnification factor of ×1.0. The histological slices were repositioned for every microscopic photo.

The histological images were checked for conformity with the corresponding radiological images. Seven out of the 48 implants were eliminated from the study due to non-conformity of histological and radiological image planes leaving 41 implants for this investigation.

The histological section measurements, corresponding to the levels examined on the CBCT images, were then carried out using a microscopic imaging program (Cell D® v3.1; Olympus Soft Imaging Solutions GmbH, Münster, Germany). The evaluators answered the same questions regarding the augmentation materials as before in the radiological evaluation. Complete integration of BAM was defined as completed osseous inclusion of BAM granules with direct contact to living bone. To ensure a reliable reference, a number of borderline cases were excluded from the second part of the study if the amount of BAM was very small (e.g., only a few granules) or if the integration of the BAM was nearly but not fully completed. Complete covering of the implant was rated if the top level of bone or BAM being in contact to the implant was at or above the marginal edge of the interface at both sides of the implant. Concluding 30 specimens with identical results in all repetitions of the histological evaluations were selected for the evaluation of recognition and integration of BAM and complete covering of the implants.

Statistical analysis

Statistical analysis was performed using a commercially available software program (SPSS Statistics 20.0; SPSS Inc., Chicago, IL, USA). To provide a reliable reference, at first the differences between the repeated histological readings were calculated. Wherever the difference between two histological readings at the same site was above 0.5 mm—usually because the bone surface was uneven or oblique to the measurement line—this measurement point was eliminated from the investigation. Finally, the statistics were based on 279 points measured eight times (twice radiology and twice histology by two observers each) making a total of 1,116 radiological and of 1,116 histological measurements both. The histological measurements were averaged for every site. The differences between every radiographic measurement and the mean of the histological measurements at the corresponding point were calculated. The correlation between radiology and histology was calculated by using the Pearson correlation coefficient (PCC). Then both intra-observer reliability and inter-observer reliability of the radiological measurements were examined by PCC.

Results

The PCC for intra-observer correlation of the radiological readings was 0.937 (observer D.W.) and 0.972 (observer A.K.), respectively. Figure 2 visualizes the correlation between the first and second measurements of observer A.K. The PCC for the inter-observer correlation was 0.936 (Fig. 3). Both demonstrated good reproducibility within and between examiners. The Pearson correlation between radiological and histological readings was 0.912 (see Fig. 4).

The mean value and the standard deviation of the differences between radiological and histological measurements at all measurement points were −0.22 mm and 0.77 mm, respectively (complete table of measurements in Online Resource 1). The largest underestimation of bone thickness was −3.31 mm for observer D.W. and −3.11 mm for observer A.K; the largest overestimations were 3.47 mm and 2.47 mm, respectively.

According to the histological sections, BAM existed in 23 of 30 cases (76.7 %) at the time of CBCT exposure (Table 1). Six out of the 23 cases with existing BAM (26.1 %) were considered as completely integrated BAM. In 18 of the 30 specimens (60.0 %), the top level of bone or BAM was at or above the marginal edge of the interface at both sides of the implant, thus classifying these cases as full coverings of the implant surface.

In the CBCT images, the existence of BAM was diagnosed in 205 of 300 readings (68.3 %). In 177 cases in which the existence of BAM was diagnosed correctly in radiology, the observers rated 60 times (33.9 %) for completed integration. In 106 of 300 readings (35.3 %), the viewers rated the implant being fully covered by bone or BAM (complete table of measurements in Online Resources 2).

Sensitivity and specificity were 0.77 and 0.60 for evaluating the existence of BAM, 0.59 and 0.74 for evaluating its completed integration, and 0.39 and 0.71 for evaluating full covering of the implant surface. Checking the differences with chi-square test did not show statistical significance for any of the diagnostic questions (α=0.05).

Examples of partially integrated BAM on the oral side (left side of the figure) and non-integrated bone on the buccal side in a CBCT image and in a histological section are shown in Fig. 5. The BAM which is almost completely integrated shows homogeneity in the CBCT image whereas loose BAM material looks granular. In CBCT, new bone (dark blue in histology) looks fainter compared to elder bone. The implants appear thickened with an increased diameter.

Figure 6 shows CBCT and histological images without BAM. One should note that it is possible to distinguish the band of new woven bone from the compact bone at the lingual side (right side of the figure) and to identify some but not all of the gaps between implant and bone in CBCT, which show in histology. However, it is difficult to identify correctly in CBCT the contour of the bone at the buccal side of the implant.

Discussion

Many papers related to the accuracy of linear measurements have been published [2, 11–24]. Usually dry skulls [2, 11, 12, 14–16, 18–20, 22, 23, 25] were used as study model, sometimes artificial specimens [17, 21]. Often measurement data obtained from these dry skulls or mandibles by using a caliper were considered as objective standard. This is sufficient to examine superficial anatomical sites and distances; however, measurements in the sagittal plane are difficult and

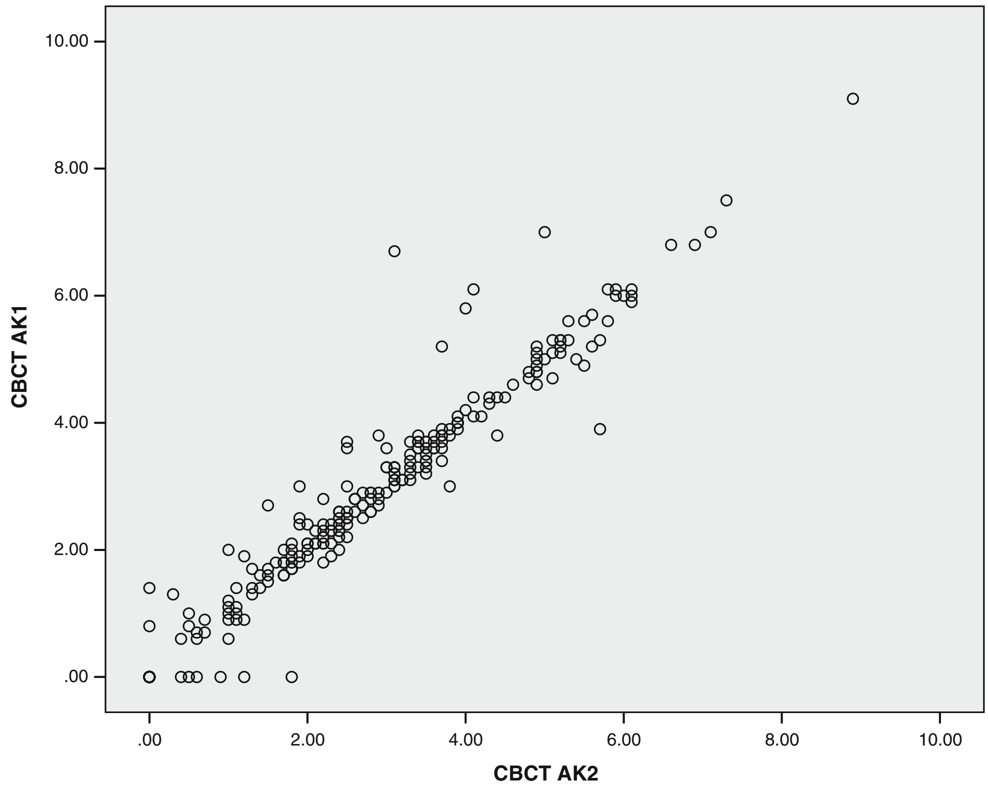

Fig. 2 Intra-observer correlation for CBCT measurement (first and second measurement of observer A.K.)

prone to bias in this way. Moreover, due to the lack of soft tissue, dry skulls and mandibles show less blurring, compared to typical imaging results in clinical cases, and therefore might show different results.

To overcome the limitations mentioned above, Suomalainen et al. exposed the mandible immersed in sucrose solution isointense with soft tissue [20]. Razavi et al. used bovine ribs embedded in a poly-ethylene mold with laboratory putty with

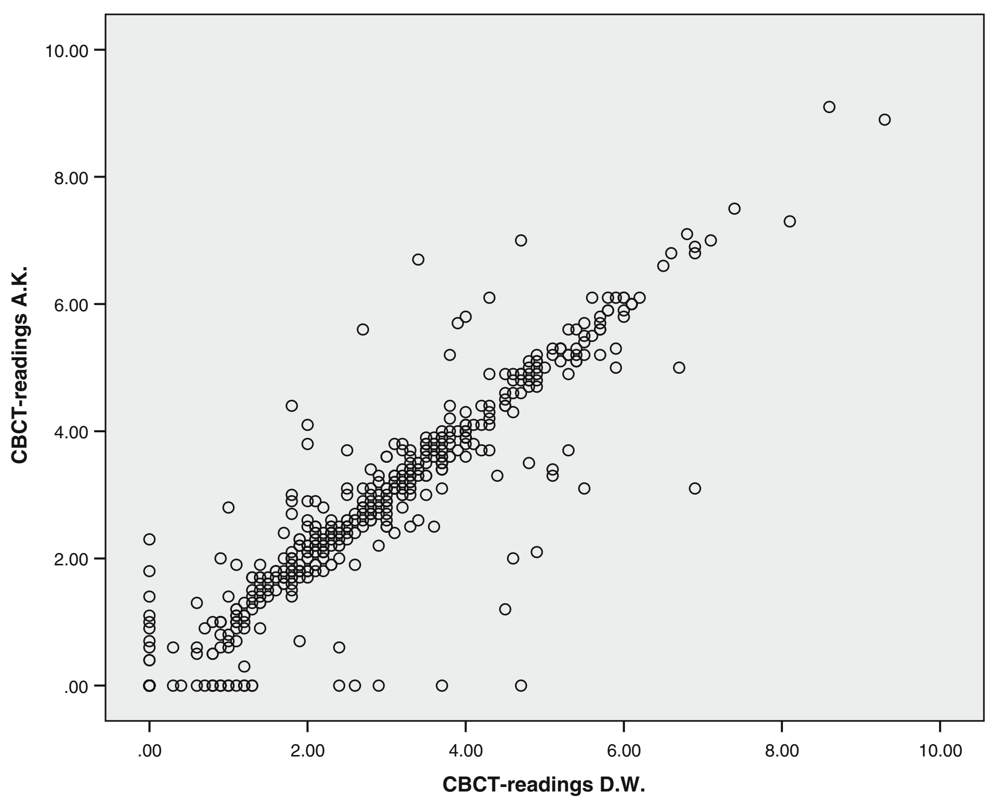

Fig. 3 Inter-observer correlation for CBCT measurement of observer A.K. to observer D.W.

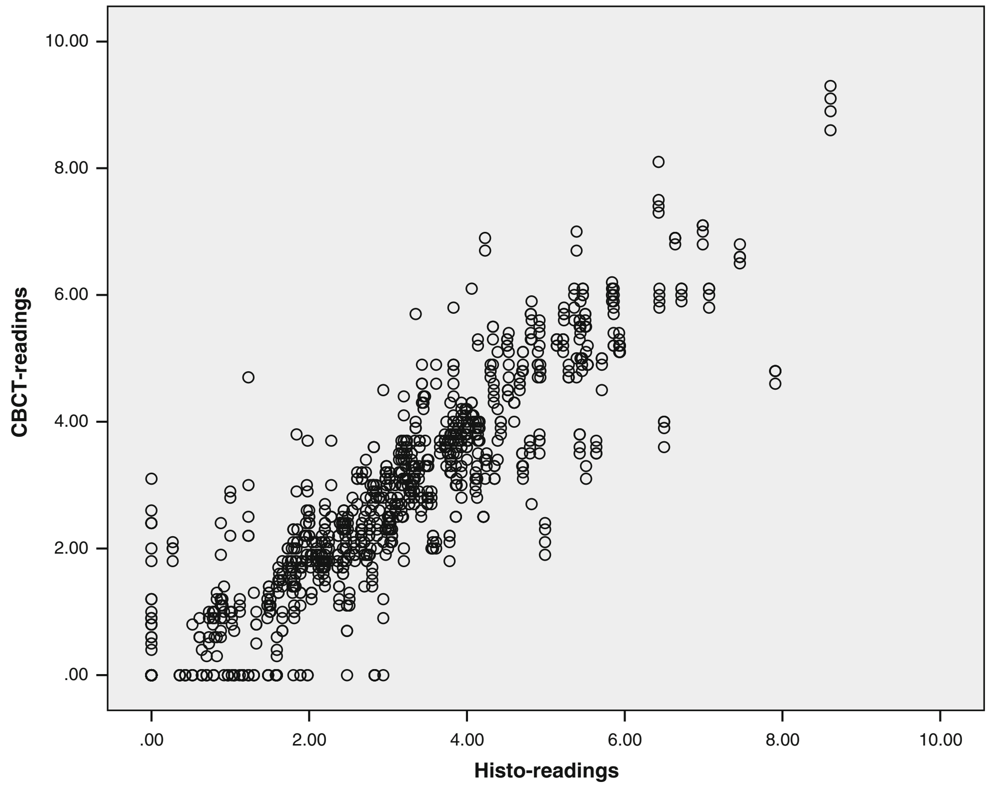

Fig. 4 Correlation of radiological and histological measurements

implants planted in each rib to measure the cortical bone thickness surrounding implants using CBCT [2]. Subsequently, histological sections were prepared in buccal–oral direction along the long axis of the implants, allowing an evaluation of the accuracy of measuring the cortical bone thickness adjacent to the implants. Even though in vitro bovine rib is feasible to assess the accuracy of linear measurements, this study does not give information to measurements of bone with BAM. Fienitz [3] and Corpas [5] used animal experiments to evaluate the accuracy of CBCT measurements at the peri-implant tissues with bone defects, and Fienitz included BAM.

An ongoing beagle study designed for the investigation of peri-implant bone augmentation procedures gave chance to add a radiological investigation allowing to evaluate the diagnostic accuracy of peri-implant bone and implant measurements and of the evaluation of peri-implant bone regeneration in CBCT.

Table 1 Qualitative assessment of peri-implant bone and BAM in CBCT and in histology

	BAM existence	BAM integration	Implant covered
Histology	23/30 (76.7 %)	6/23 (26.1 %)	18/30 (60.0 %)
CBCT	205/300 (68.3 %)	60/177 (33.9 %)	106/300 (35.3 %)
CBCT sensitivity	0.77	0.59	0.39
CBCT specificity	0.60	0.74	0.71

Compared to the golden standard of histological measurements, the linear measurement of bone using CBCT provides values at an accuracy in a sub-millimeter range [16]. The differences between CBCT and histology measured in this study seem similar to the results of Fienitz and below the results of Corpas.

Even though the results demonstrate sufficient accuracy of linear measurements using this CBCT system, it has to be kept in mind that the accuracy of metric measurements might be limited by several factors. First of all, in a preliminary test some distortion was found in the images obtained from the PaXDuo3D® CBCT system, which may result in different magnifications at different positions in the volume. This might be a reason for the limitations of the diagnostic accuracy found in this investigation. Furthermore, in this investigation the voxel size setting of the CBCT machine was set to 80 μm. Any distance measurement might contain an unavoidable error of at least this voxel size. In addition, usually low contrast range and low resolution of radiological images are charged as potential sources for error, limiting the precision of measurements by blurring the boundaries between bone and soft tissue and bone-to-implant interface [16]. It should be noticed that high resolution images of perfect technical quality might be related to similar measurement inaccuracies if the measured objects have irregular borderlines. The placing of measurement lines on such borderlines gets a stochastic component giving it the property of a more or less statistical sample. This might be a reason for the limits of intra- and

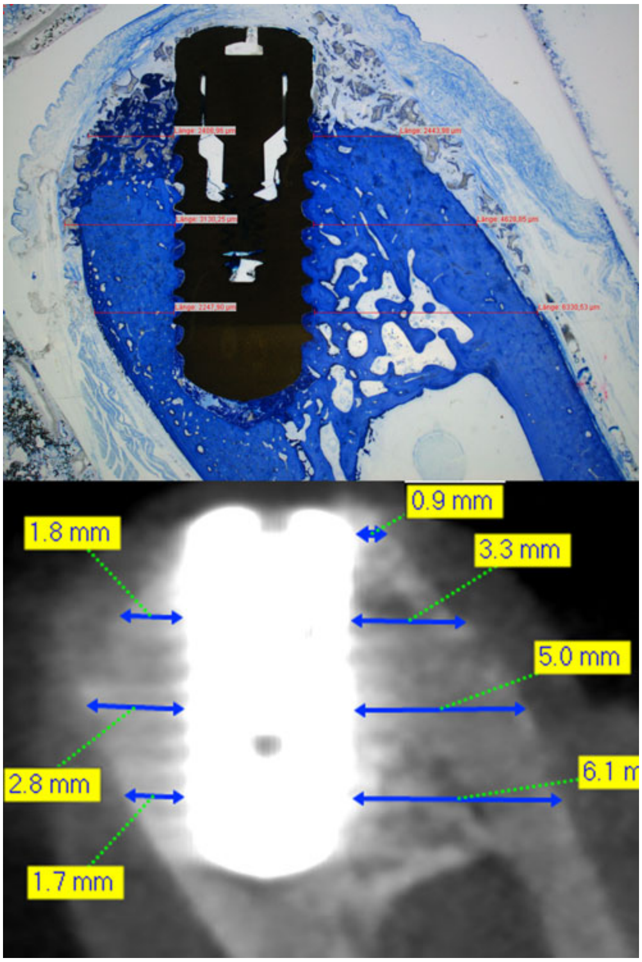

Fig. 5 Histological and corresponding CBCT image: measurement of the bone thickness at four levels. The radiopacity at the buccal side of the implant is granular and proves as non-ossified augmentation material in histology

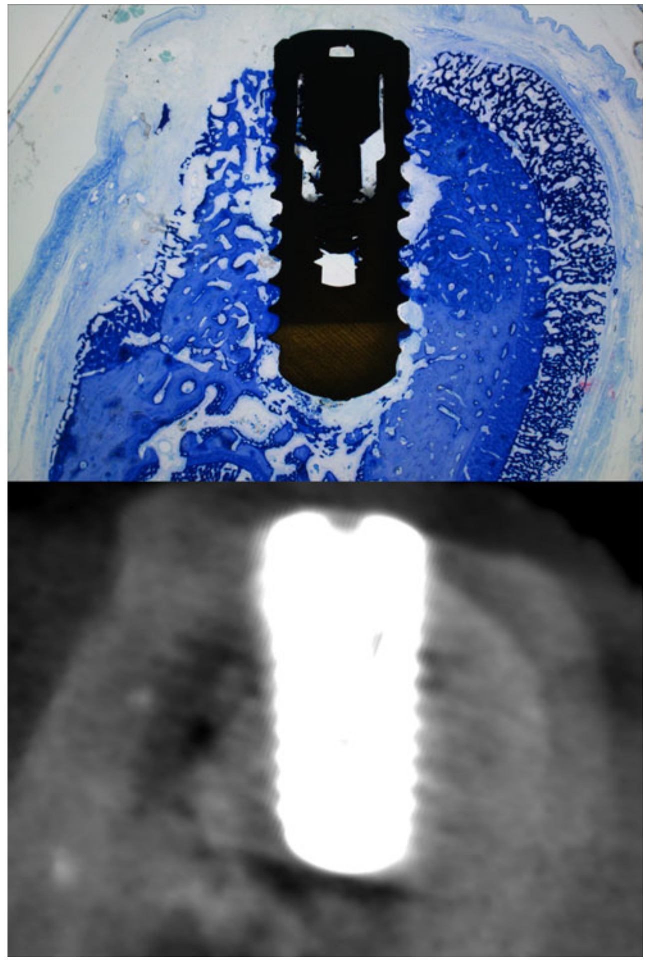

Fig. 6 Histological and corresponding CBCT image: a double contour line, a lingual band of new, not yet fully mineralized bone (dark blue in histology) shows at the lingual side both in histology and CBCT. The bone-to-implant contact is less than expected in the CBCT image. The implant contour is thickened in CBCT

inter-observer reliability seen in the histological measurements. The blurring in radiological images compared to histological images seems to have a smoothing effect on the surfaces under inspection, thus smoothing the stochastic variations in placing the measurement lines.

The existence of radiodense objects like implants causes beam hardening artifacts [26] and might complicate the visualization of the bone–implant interface [2]. Although larger flat panel detectors used in current CBCT scanners possibly lead to less beam hardening artifacts [1], they might be affected by more scattered radiation because of an enlarged field of view [27].

It might be of interest whether BAM could cause beam hardening artifacts. Our preliminary tests showed the radiopacities of the BAM used in this investigation being only slightly or not above the radiopacities of human bone or dog bone. This is no surprise as the BAM used is of bone origin or is composed of the same chemical elements as bone. Therefore, significant beam hardening artifacts by the BAM used in this investigation are unlikely.

The integration state of BAM on histological sections served as an objective standard in the present study. Compared to it, the existence of BAM was seen less often in CBCT than in histology. Vice versa, the observers more often stated a completed integration of existing BAM in CBCT than in histology. However, rating existence and completed integration of BAM in radiological images did not show a significant difference to the histology. Sensitivity and specificity to evaluate the existence and integration of BAM with the CBCT system at the experimental settings used are below expectations for a diagnostic procedure. In clinical practice, the PaX Duo3D® CBCT system seems to provide some clue, at least, whether BAM is completely integrated or not.

It would be of clinical impact to answer the diagnostic question whether the implant is completely covered by bone or BAM. BAM shows as high-density radiopaque granule structures. If these were in a homogenous contact to the adjacent bone, they were supposed to represent BAM completely integrated into living bone in the present study. Often there is some doubt or error because it is difficult to distinguish newly formed bone and bone substitute granules in CBCT images. One should keep in mind that the implants were placed 8 weeks after guided bone regeneration procedure. Unfortunately, the sensitivity of the CBCT system to answer such a question is poor and the specificity moderate, at least at the exposure settings used.

For successful implantology, both bone quantity and bone quality are essential. This study focused on the accuracy of assessment bone quantity by measuring peri-implant bone thickness in CBCT. This study did not assess bone quality, which is mainly manifested as bone density. However, a systematic review of the literature [1] demonstrated that present CBCT machines can hardly be used for the estimation of bone density because of inconstant gray levels not representing the Hounsfield units (HU). HU are CT values in the measurement of CT images used to quantitatively describe tissue density. In other words, it meant that scanned regions of the same density in the skull can have different grayscale values in the reconstructed CBCT dataset. However, to the authors' knowledge, no paper has focused on the feasibility and validity of bone density measurements using the PaX Duo3D® CBCT system, which might be a future study.

Conclusion

The present study indicates that the PaX Duo3D® CBCT system allows measurements of peri-implant bone thickness at an accuracy of half a millimeter, and—within some limits—assessing the existence of BAM and its integration into the bone, but not the evaluation of complete hard-tissue covering of the implant surface.

Acknowledgments The authors appreciate the contribution of Orange Dental, Biberach, Germany, for providing the PaX Duo3D® CBCT system for the present study. Dongyun Wang was kindly supported by grant number CF 51001 of the Camlog Foundation, Basel, Switzerland for her research fellowship at the Department of Oral Surgery at the Heinrich Heine University Düsseldorf.

Conflict of interest The authors declare that they have no conflicts of interest.

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