Comparison of Geometric Accuracy of Low-Dose and Standard-Dose Dental CBCT Imaging Protocols in CAD/CAM-Guided Dental Implant Surgery

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Purpose: This preclinical comparison study assessed the diagnostic accuracy of low-dose CBCT protocols compared with standard-dose protocols in digital implant treatment planning and template-guided implant surgery. Materials and Methods: Thirty mandibles of pig cadavers underwent both CBCT protocols on an Orthophos SL Unit (Dentsply-Sirona). Surface scans of the regions of interest were performed to create a digital diagnostic wax-up followed by 120 subsequent implant plannings (one implant per quadrant). Simple randomization (1:1) was assessed to assign each quadrant into one of the imaging protocols. Sixty implant surgical guides were manufactured using CAD/CAM technology, followed by the fully guided placement of 60 implants following the surgical protocol in randomized order. Geometric accuracy between the planned and definitive implant position was determined regarding apical distances between the central axes and angle deviation. Descriptive statistics and linear regressions were used for the statistical analysis of the data. Results: Regarding implant apex deviation using low-dose CBCT, the following differences were observed: apical deviation of 0.75 ± 0.63 mm and angular deviation of 2.5 ± 2.12 degrees, while the standard-dose CBCT showed the following results: apical deviation of 0.92 ± 0.55 mm and angular deviation of 3.06 ± 2.12 degrees. The regression analyses could not show evidence for a significant difference between the two CBCT protocols, neither with regard to the apical distance nor in view of the angular deviation. Conclusion: Low-dose CBCT imaging protocols providing accurate 3D anatomical information with an improved benefit-risk ratio according to the as low as diagnostically acceptable (ALADA) principle could become a promising option as a primary diagnostic modality as well as for radiologic follow-up. Int J Oral Maxillofac Implants 2022 December 14. doi: 10.11607/jomi.9851. Online ahead of print.

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image distortion, magnification, and nonsharp overlapping structures restricting their use in more complex oral and maxillofacial surgical procedures. To overcome these limitations, 3D imaging modalities such as computed tomography (CT) or CBCT were successfully introduced in implant dentistry, leading to a growing trend in the use of 3D information. They provide highly accurate cross-sectional anatomical images of the region of interest (ROI) and minimize perioperative risks and complications by offering valuable additional radiographic data, such as volumetric reconstructions of craniofacial structures to the performing surgeon.

Although CBCT offers inadequate soft tissue contrast and standardized grayscale values compared with CT, it is considered the gold standard for computer-assisted navigation systems in oral and maxillofacial surgery due to its greater accessibility, lower radiation exposure, and lower cost. Based on multi-directional reconstructions from CBCT data, digital implant treatment planning and the use of CAD/CAM technology in guided implant surgery have opened up the possibility of using safer and more efficient surgical approaches such as flapless surgery, resulting in less swelling and bleeding while reducing postoperative pain and recovery time, thus increasing patient satisfaction. Nevertheless, computer-guided template-based surgical implant placement is still associated with various risks, such as inaccuracies and application errors.

However, radiation exposure during CBCT examinations is up to 10 times lower than during medical CT scans, with patients exposed to a dose of approximately 18 to 200 μS per scan. This is particularly relevant for repeated radiation exposure to the thyroid gland in radiation-sensitive, genetically susceptible young patients, as recent reports suggest a relationship between dental radiology and increased lifetime risk of radiation-induced cancer. Considering the controversy over the need for continued optimization of radiation doses according to the “as low as reasonably achievable” (ALARA) principle and the recently proposed shift to the “as low as diagnostically acceptable” (ALADA) principle, it is critical to understand the unique indications and limitations of radiographic CBCT examinations. Despite a large number of CBCT scanner manufacturers and the associated heterogeneity of scan-specific parameters, a significant reduction in radiation dose can be achieved by reducing the field of view (FOV) or ROI, or by adjusting the tube voltage and determining the minimally acceptable tube current. Despite the altered image resolution and image noise due to these modifications in tube voltage and current, previous studies have shown that low-dose CBCT imaging protocols present a promising diagnostic modality in many clinical settings, with El Sahili et al emphasizing that the use of low-dose CBCT imaging protocols provides sufficient image quality for implant planning and placement.

Nonetheless, prior to the clinical application of low-dose CBCT imaging protocols in dental implant surgery, further studies are required to investigate its accuracy. This pre-clinical comparison study aimed to assess the diagnostic accuracy of low-dose CBCT protocols compared with standard-dose CBCT protocols in digital implant treatment planning and template-guided implant surgery.

MATERIALS AND METHODS

Study Design and Ethics

In this ex vivo comparative study setting, 30 mandibles of pig cadavers obtained from the local slaughterhouse in Zurich, Switzerland, were subjected to radiographic examination using a predetermined, manufacturer-specific low-dose and standard-dose CBCT imaging protocol. After performing 60 CBCT scans (30 pig mandibles underwent both imaging protocols each), surface scans of the ROIs (.ssi files) were performed to create a 3D digital diagnostic wax-up followed by 120 subsequent implant plannings (one implant planning per quadrant based on low-dose CBCT and a planning of the same implant based on standard-dose CBCT). Simple randomization was used to assign each quadrant into two groups (implant planning based on [a] standard- or [b] low-dose imaging protocols). Hence, using CAD/CAM technology, 60 implant surgical guides were manufactured and used to place 60 implants fully guided following the surgical protocol in randomized order. Finally, the .ssi files of the preoperative virtual implant planning and the postoperative implant position were superimposed for each implant and checked for the differences in the apical distances between the central axes (mm) determined as a vector between the apical endpoints of the implants and the angle of deviation (degree; Fig 1).

For ethical and safety reasons, this radiologic study could not be performed in vivo. However, pig mandibles are considered a suitable and common animal model in orofacial research because of their close anatomical resemblance to the human oral and maxillofacial system. Considering scientific, economic, and ethical factors, this common animal model in dental research was selected for this study. A declaration of non-responsibility was obtained from the Office of Animal Welfare and 3R of the University of Zurich. Consequently, all experiments comply with the guidelines of the University of Zurich, Switzerland, for animal experimental research. Reporting complies with the ARRIVE (Animal Research: Reporting of In Vivo Experiments) guidelines.
CBCT Data Acquisition and Surface Scanning
All pig mandibles underwent low-dose and standard-dose CBCT imaging protocols on an Orthophos SL 3D scanner (Dentsply Sirona) with an FOV of 112 × 112 mm and an isotropic voxel size of 0.22 mm. The following specifications defined the applied standard CBCT imaging protocol: 85 kV, 10 mA, 360-degree rotation with a radiation time of 4.4 seconds, dose area product of 781 mGy cm², and effective radiation dose of 145 µSv, while the applied low-dose CBCT imaging protocol was characterized by the following specifications: 85 kV, 10 mA, 360-degree rotation with a radiation time of 2.2 seconds, dose area product of 109 mGy cm², and effective radiation dose of 20 µSv. To mimic in vivo conditions as closely as possible, soft tissue was simulated using a cold pack (12 × 29 cm, GELLO Geltechnik) in the center of the mandible. Consequently, a total of 60 CBCT scans (30 low-dose imaging protocol and 30 standard-dose imaging protocol) were performed.

Digital impressions of the 60 implant regions of the pig mandibles were taken using an intraoral scanner (CEREC Primescan 2, Dentsply Sirona). Special software was used to create a 3D digital diagnostic wax-up (InLab CAD software 20.0.3, Dentsply Sirona) and exported as an .ssi file.

The CBCT DICOM data and .ssi files of the digital wax-up were imported into the GALILEOS implant planning software (Sirona Dental Systems). Both DICOM imaging datasets were manually aligned with the .ssi surface scan files by pair-point registration using anatomical landmarks, especially the teeth, as reference points. Subsequently, superposition was performed using a manufacturer-specific algorithm mechanism.

Virtual Implant Planning and Guided Implant Surgery
Virtual implant planning was performed 120 times (30 pig mandibles, 60 quadrants with one implant per quadrant, and two imaging protocols), determining the implant insertion position between the canine and the first premolar. Simple randomization with a 1:1 allocation ratio was performed to assign each quadrant into one of the two groups, group A (standard-dose CBCT imaging protocol) and group B (low-dose CBCT imaging protocol), in an Excel spreadsheet (Microsoft Excel 2020, Microsoft; Fig 2). Therefore, using CAD/CAM technology, 60 surgical drilling templates (Cerec Guide 2 blocks, InLab MC X5, Dentsply Sirona; 30 for each imaging protocol) were fabricated and used to place 60 implants fully guided. Subsequent surgical implant placement was performed by an oral surgeon (S.U.) with more than 5 years of experience in dental radiology and implant surgery in all pig mandibles in randomized order. After guided soft tissue removal, 60 implants were placed at bone level (3.6 × 8 mm, Astra Tech Implant System Osseospeed EV, Dentsply Implants, Dentsply Sirona) fully guided following the surgical protocol. After immediately positioning a sandblasted Astra Tech titanium base abutment (Dentsply Sirona), a postoperative surface scan of the implant position, surrounding soft tissue, and adjacent teeth was performed with CEREC Primescan 2, providing a second .ssi dataset for the digital wax-up of the final position (Fig 3).

Data Evaluation
The .ssi files of the preoperative virtual implant planning and the postoperative implant position were superimposed for each implant using the titanium base abutment as reference structure in the GALILEOS implant planning software (Sirona Dental Systems). According to the previously performed study protocols, the following parameters were evaluated: the differences in apical distances between the central axes (mm) determined as a vector and the angle of deviation (degree) between the virtual and definitive implant axes. To perform reproducible measurements, auxiliary geometries were created that could be aligned with the surfaces of the implants to accurately determine the targeted endpoints.
Statistical Analysis

Descriptive statistics were calculated such as means, standard deviations (SD), medians, interquartile ranges, minimums, and maximums regarding the apical distances between the center axes (mm) and the angle of deviation (degree) between the virtual and definitive implant axes. Two linear models, one for each endpoint, were fitted to the data to evaluate the differences between the low-dose and standard-dose CBCT imaging protocols. Thereby, the apical deviation and angle deviation of the endpoints were analyzed as a function of the explanatory variables, CBCT imaging protocol, and mandibular quadrant. The possibility of an interaction term between the independent variables was investigated but was not deemed necessary in either of the models. Model assumptions (normality and homoscedasticity of residuals) and fits were thoroughly checked. Marginal means were estimated and statistically compared for the CBCT protocol factor in the models. All statistical analyses were conducted on a significance level of $\alpha = .05$ and performed using the statistical software R 4.0.5 (R Foundation for Statistical Computing), including the packages tidyverse and emmeans.

RESULTS

Considering the 42 evaluated implants (18 evaluations had to be excluded after fabrication of the respective surgical guide due to the intraoperative relatively unstable position of the templates on the residual dentition of the porcine jaw) using low- and standard-dose CBCT imaging protocols, the mean differences of the apical distances between the center axes of the implant planning were 0.83 mm (SD, 0.57 mm; median, 0.66 mm; interquartile range [IQR], 0.964; minimum, 0 mm; maximum, 1.87 mm), whereby the mean angle of deviation between the virtual and definitive implant axes was 2.79 degrees (SD, 2.06 degrees; median, 2.35 degrees; IQR, 2.95; minimum, 0 degrees; maximum, 7.7 degrees).

Focusing only on implant planning performed with low-dose CBCT imaging protocols ($n = 21$), the following differences were observed: apical deviation of 0.75 mm (SD, 0.63 mm; median, 0.58 mm; IQR, 0.798; minimum, 0 mm; maximum, 1.87 mm), and angular deviation of 2.5 degrees (SD, 2.12 degrees; median, 2.1 degrees; IQR, 2.23; minimum, 0 degrees; maximum, 7.7 degrees), whereas the standard-dose CBCT imaging...
protocols (n = 21) presented the following results: apical deviation of 0.92 mm (SD, 0.55 mm; median, 0.93 mm; IQR, 0.79 mm; minimum, 0.1 mm; maximum, 1.85 mm), and angular deviation of 3.06 degrees (SD, 2.12 degrees; median, 2.7 degrees; IQR, 3.27; minimum, 0 degrees; maximum, 7.4 degrees; Table 1; Fig 4).

In the regression analysis, the CBCT protocols did not display a significant difference with regard to apical deviation (estimated difference of 0.17 mm; P = .36). In terms of angular deviation, the linear model also did not show a significant difference between the low-dose and standard-dose CBCT imaging protocols (estimated difference of 0.57 degrees; P = .40; Fig 5).

**DISCUSSION**

This preclinical study aimed to evaluate low-dose CBCT protocols compared with standard CBCT protocols regarding geometric reliability in digital implant treatment planning and fully guided implant surgery. The low-dose CBCT imaging protocol applied in this experimental setup, which was developed in accordance with the current literature, demonstrated no substantial disadvantages in terms of diagnostic accuracy and geometric parameters in digital implant treatment planning and CAD/CAM–guided dental implant surgery compared with standard-dose CBCT, although the applied radiation dose is approximately 7% of the high-dose and 14% of the standard-dose CBCT imaging protocols. Furthermore, comparable accuracy and quantitative deviation in terms of the geometric parameters vector for apical distances (LD = 0.75 ± 0.63 mm, SD = 0.92 ± 0.55 mm) and angular deviation (LD = 2.5 ± 2.12 degrees, SD = 3.06 ± 2.12 degrees) between the virtual implant planning and the final implant planning could be achieved by using low-dose CBCT in this fully guided approach. In general, previous reports in the literature emphasized that the use of low-dose CBCT imaging protocols provides sufficient image quality for implant planning and placement, whereas recently, Horsch et al presented low-dose CBCT in an in vitro comparative study with high-dose CBCT as a possible alternative in computer-assisted implant dentistry, with the latter appearing to be superior. Thereby, the geometric accuracy of partially guided dental implant placement showed lower accuracy for the low-dose CBCT protocol, resulting in greater deviation in terms of implant apex (0.7 ± 1.1 mm) and angular deviation (4 ± 5.6 degrees), with the osseous entry-point showing no significant difference compared with the high-dose CBCT. Compared with the present results, these deviations cannot be confirmed, as the present study found a 2 mm and 10 degree lower deviation for apical and angular deviation, respectively, compared with the experimental setting of Horsch et al despite using the same low-dose CBCT protocol. This could be explained by various factors, such as the placement of the implants linearly in a sagittal direction beside the actual tooth rows (in an anterior, middle, and posterior position) in only eight pig mandibles. In contrast, in the present experimental setup, one implant per quadrant in 30 pigs was placed in the tooth row determined at the position between the canine and first premolar.

| Table 1 | Mean Differences, SD, Median, IQR, Minimum, and Maximum of Apical Deviations of Distances Between Center Axes of Implant Planning and Angular Deviation Displayed Considering Low- and Standard-Dose CBCT Imaging Protocols and the Two Quadrants Separately, with Left Representing the Third and Right the Fourth Quadrant in the Mandible |
|----------|------------------|------------------|------------------|------------------|------------------|------------------|
| **CBCT** | **Apical deviation (mm)** | **Angular deviation (°)** |
| LD-CBCT left | 0.868 | 0.731 | 0.580 | 1.40 | 0.10 | 1.87 |
| LD-CBCT right | 0.604 | 0.481 | 0.580 | 0.36 | 0.00 | 1.65 |
| SD-CBCT left | 0.841 | 0.622 | 0.815 | 1.09 | 0.07 | 1.60 |
| SD-CBCT right | 0.976 | 0.493 | 0.925 | 0.69 | 0.26 | 1.85 |

IQR = interquartile range; min = minimum; max = maximum; LD-CBCT = low-dose CBCT; SD-CBCT = standard-dose CBCT.

**Fig 4** Graphical visualization of descriptive statistics. In these box plots, the apical deviation and the angle deviation in both CBCT imaging protocols, considering the two quadrants separately, with left representing the third and right the fourth quadrant in the mandible, is displayed.
Previous reports suggest that the bone quality of pig mandibles is not identical to that of humans and varies depending on the position of the implant. Therefore, the anatomy of the pig jaw might have influenced the results, as it has more morphologic lacunae in the trabecular bone and variable apical anatomy compared with the human mandible.\(^3^3,^3^4\) In addition, different software, different implants, and the difference between partially and fully guided procedures could have influenced the results. Chen et al indicated discrepancies of 1.5 mm at the apex and 1 mm at the osseous entry-point,\(^3^1\) whereas Kühl et al reported a mean deviation of 1.8 mm at the apex and 4.3 degrees for the angle in an in vitro experimental setup.\(^3^2\) To the authors’ knowledge, the present study is the only study protocol that investigated fully guided implant surgery by comparing a standard CBCT protocol with a low-dose CBCT protocol, effectively reducing the radiation dose by 85% (LD = 20 mSv; SD = 145 mSv). Regarding angular deviation, the present data from both imaging protocols seem to be in accordance with the data available in the literature. Furthermore, the results confirm the statement that fully guided implant surgery is superior to partially guided or hand surgical procedures in terms of accuracy.\(^3^1\) However, the accuracy of these preclinical data supporting fully guided surgical implant placement with low-dose CBCT is within the clinically acceptable range.\(^3^5\)

The undeniable advantage of multidirectional reconstructions by CBCT has revolutionized preoperative diagnostics in implant dentistry and led to indication-specific and patient-specific treatment options. The ability to depict structures from multiple angles allows visualization of the architecture and dimension of the anatomical and especially bony structures.\(^3^6\) Given the increasing use of CBCT in dental radiology, the primary goal of this experimental setting was to optimize radiation dose without losing the diagnostic value according to the ALADA principle, since accurate volumetric assessment of the ROI and adjacent critical anatomical landmarks is critical in dental implantology.\(^1^9,^3^6\) The low-dose CBCT imaging protocol applied in the present experimental setup, halving the radiation time (LD = 2.2 seconds; SD = 4.4 seconds) and applying a bigger copper diaphragm (LD = 1 mm copper diaphragm; SD = 0.3 mm copper diaphragm), resulted in an effective radiation exposure reduction of 85% (LD = 20 mSv; SD = 145 mSv). Hence, these low-dose imaging protocols open the possibility of generating 3D data, both in preoperative diagnostics and postoperative follow-up, with a radiation
dose comparable to that of conventional 2D imaging modalities such as PAN. In this context, these advantages can be used for follow-up care in complex cases or intraoperative imaging in the future.

CBCT scanners vary in their capabilities and device-specific imaging protocols; therefore, further research is required to facilitate the development of standardized protocols that can be applied regardless of manufacturer-specific settings. From a clinical perspective, it is essential to understand that obtaining a high standard of diagnostic information depends on the individual patient-specific case and the performing surgeon. From a radiologic perspective, optimizing radiation exposure can be accomplished through several modifications, such as reducing tube current (mA), resolution, scan time, use of partial rotations, and number of projections. In this context, choosing a small FOV (4 × 4 cm) compared with the largest FOV (17 × 12 cm) or adjusting the tube voltage (kV) and setting the minimum acceptable tube current (mA) can significantly contribute to effective radiation dose reduction by 40% and 80%, respectively.

In this study, there are several limitations that may have affected the accuracy of computer-assisted implant surgery in this experimental setup. First, only one CBCT scanner and one intraoral scanner were used by the same oral surgeon who had performed the surgical implant placement. Therefore, the equipment and the experience of the physician could have affected the results. However, because both CBCT protocols used the same approach with the same performing oral surgeon, the key comparison should be valid. Conclusions between the results obtained with other intraoral scanners and CBCT scanners must be taken with caution due to predetermined, manufacturer-specific settings. Therefore, further studies comparing different scanners, devices, and software are needed to assess the reliability of the results. Second, the image quality of low-dose CBCT was not affected by motion artifacts because the study protocol was performed in accordance with existing protocols in the literature. Additionally, the CBCT images were affected by rare hardening artifacts, resulting in decreased performance when aligned with the intraoral scans. Third, the anatomy of the pig mandibles might have affected the stability of the surgical guide positioning, resulting in a slight movement during the surgical procedure. This resulted in the exclusion of 30% of planned implant placements because the guides were intraoperatively unstable when positioned on the residual dentition of the pig mandible. This aspect should be taken into account in future research projects and should be considered with caution when transferred to the human mandible, as this would be inappropriate from a scientific and economical point of view. Nevertheless, the literature supports the statement that fewer problems should occur when performed in the human jaw. However, in this study, except for the use of different CBCT protocols, identical approaches were applied to the study and control groups. Therefore, the key comparison should be considered valid.

From a clinical perspective, dose-reduced CBCT imaging protocols are necessary and promising imaging modality in various dental specialties and subspecialties such as pediatric dentistry, endodontics, orthodontics, and oral and maxillofacial surgery due to the growing use of 3D radiographic data. In the absence of guidelines for using low-dose protocols, and with scanner and scan parameters varying upon implementation, continuous modernization and standardization of low-dose CBCT protocols are desired to ensure consistency and discriminability, while addressing relevant scientific, economic, and ethical factors. Therefore, this promising imaging technique has the potential to be used in future clinical routines for personalized therapies, as it offers advantages over 3D imaging with a significant dose reduction while still providing a high standard of diagnostic accuracy.

CONCLUSIONS

The use of low-dose CBCT imaging protocols in digital implant treatment planning and CAD/CAM-guided dental implant surgery provided confidential diagnostic predictability in terms of anatomical and morphologic characteristics, without substantial disadvantages compared with standard-dose CBCT imaging protocols. After further validation of these preclinical data in human studies, the targeted use of low-dose CBCT protocols could be implemented in clinical practice in the future, both as initial diagnosis and for postoperative follow-up, with an improved benefit-risk ratio due to significantly lower radiation exposure while maintaining the same clinical outcome.

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