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Agreement Between Pre- and Post-extraction Cone-Beam Computed Tomography Linear Measurements of Socket Walls for Immediate Implant Planning: An In Vitro Pilot Study

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Abstract

Introduction: In immediate implant placement, the thickness of the remaining socket wall after tooth extraction is strongly associated with the extent of subsequent bone resorption. This exploratory pilot study aimed to assess the agreement between cone-beam computed tomography (CBCT) measurements of buccal and lingual bone thickness and crestal bone level in dentate sites before extraction, and those obtained at the same sites after extraction.

Materials and methods: Thirty-one single-rooted teeth in six dentate dry human mandibles (convenience sample) were included. CBCT scans (PreXion3D Excelsior; PreXion Corp., San Mateo, CA, USA) were acquired with and without the tooth in place, at standard (0.1 mm slice thickness) and high (0.05 mm slice thickness) resolution. Scans with and without the tooth were superimposed, and two examiners performed linear measurements of crestal bone level and of bone thickness at 3, 6, and 9 mm apical to the cementoenamel junction. Measurements obtained before and after extraction were compared using two one-sided tests for equivalence with a prespecified, clinically derived margin of ±0.2 mm, stratified by resolution, surface, and measurement level, with a sensitivity analysis at alternative margins. Intra- and inter-examiner reliability was evaluated with the intraclass correlation coefficient (ICC).

Results: Intra- and inter-examiner reliability was excellent (ICC > 0.9). Measurements obtained before and after extraction were equivalent within ±0.2 mm in all strata ($p < 0.05$), except for bone thickness measured at 9 mm on high-resolution scans ($p = 0.349$; mean difference -0.172 mm, 90% confidence interval -0.293 to -0.050 mm). Bone thickness tended to be slightly underestimated, and crestal bone level slightly overestimated, in the presence of the tooth. All strata met equivalence at a margin of ±0.30 mm, whereas fewer strata met a margin of ±0.15 mm.

Conclusions: In this in vitro pilot study, pre-extraction CBCT measurements of socket-wall thickness and crestal bone level showed close agreement with post-extraction measurements of the same sites. Because the comparator was CBCT itself, absolute accuracy could not be established. These preliminary findings may support presurgical CBCT assessment for immediate implant planning but require confirmation in adequately powered studies with an independent reference standard and clinical validation.

Categories: Dentistry
Keywords: alveolar bone thickness, a pilot study, cone-beam computed tomography (cbct), dental implants, equivalence testing, immediate implant placement, measurement agreement, oral and maxillofacial radiology-related topics

Introduction

Immediate implant placement after tooth extraction has become a routine procedure that offers many advantages, including shorter treatment time, fewer surgical procedures, higher patient acceptance, less psychological stress, and improved esthetics [1]. Ericsson et al. reported that the reduced surgical trauma of immediate placement decreases the risk of bone necrosis and allows rapid bone remodeling and healing; extraction sockets are rich in periodontal cells and matrix, making healing faster and more predictable, and autogenous bone grafts can be used to fill the small osseous defects frequently found adjacent to implants placed at the time of extraction [2]. In addition, with careful site selection, immediate implants achieve success rates similar to those of implants inserted in healed sites [1,3].

It was previously suggested that immediate implant placement might limit post-extraction changes and resorption of the alveolar ridge [4], and some authors have recommended immediate placement to preserve bone at the extraction site [5,6]. However, multiple studies have shown that immediate implant placement

does not prevent alveolar ridge resorption [7-9]. Marked resorption of the buccal cortical plate relative to the lingual plate has been reported following immediate implant placement in fresh extraction sockets [10]. There is also a significant association between the thickness of the buccal wall and the extent of bone resorption, with a minimum thickness of 2 mm recommended to maintain the alveolar bone level [11,12]. The thicknesses of both the medullary bone and the cortical layer are decisive [13].

Most extraction sites in the anterior region present thin (<1 mm) buccal walls [14,15], which are more prone to resorption than those in posterior areas. In the anterior maxilla, close to half of the sites have a facial wall of 0.5 mm or less [14], so differences of a few tenths of a millimeter can determine whether a wall is classified as thin or thick. Therefore, in most clinical situations, augmentation procedures are needed to achieve adequate bony contours around the implant [12,16].

Three-dimensional (3D) imaging modalities such as cone-beam computed tomography (CBCT) allow 3D visualization and measurement of the patient's anatomy while avoiding the inherent limitations of two-dimensional imaging, such as distortion and superimposition. CBCT also allows measurements in planes that are not available or not accurately depicted on conventional radiographs [17].

For most clinical applications, CBCT images allow highly accurate and reliable linear measurements [18-21]. Nonetheless, the accuracy of reformatted CBCT images is affected by many factors, including the characteristics of the unit (e.g., spatial resolution and image quality), exposure parameters (tube current, tube voltage, and number of basis images), the reconstruction software, the measurement method, patient motion artifacts, and the clinician's interpretation [22,23]. For preoperative immediate implant planning, particularly when image-guided implant surgery is used, the fidelity of linear measurements and the accuracy with which anatomical structures are depicted are crucial [24,25].

Previous studies have validated CBCT measurements of alveolar bone around teeth against direct physical measurements [17,26-28]. However, to the best of the authors' knowledge, none has isolated the effect of the tooth itself by comparing measurements of the same socket walls obtained with the tooth in place and after its removal, which is the situation faced when planning immediate implant placement.

This in vitro study was designed as an exploratory pilot study. The primary aim was to assess the agreement between CBCT measurements of buccal and lingual bone thickness (at 3, 6, and 9 mm apical to the cementoenamel junction (CEJ)) and crestal bone level obtained before tooth extraction and those obtained at the same sites after extraction. The secondary aims were to determine whether this agreement differed between a standard-resolution (0.1 mm) and a high-resolution (0.05 mm) protocol, to estimate intra- and inter-examiner reliability, and to generate variance estimates to inform the sample size of a future confirmatory study. The null hypothesis (H0) was that the mean difference between pre- and post-extraction measurements lies outside the equivalence margin of ±0.2 mm (non-equivalence); the alternative hypothesis (H1) was that the mean difference lies within ±0.2 mm (equivalence).

Materials And Methods

Study design

This was an in vitro, exploratory pilot study of the agreement between two CBCT measurement conditions (tooth present and tooth absent) at the same anatomical sites. The study used anonymized dry human mandibles from the University of Texas Health Science Center at San Antonio. The study proceeded in the following sequence: (1) specimen selection and preparation, (2) CBCT acquisition with and without the tooth at two resolutions, (3) image orientation and superimposition, (4) definition of the reference level and linear measurements, (5) examiner calibration and reliability assessment, and (6) statistical analysis.

No a priori sample size calculation was performed. The sample comprised all single-rooted teeth in the available dentate dry mandibles that met the inclusion criteria (convenience sample). The study was therefore designed and is reported as exploratory, and its results are intended to provide variance estimates for the sample size calculation of a future confirmatory study.

Specimen selection and preparation

Six dentate dry human mandibles were collected, from which 31 single-rooted teeth (12 incisors, seven canines, and 12 premolars) were selected. Only single-rooted teeth that could be removed from their sockets and passively reseated in their original position without trauma to the surrounding osseous structures were included. Soft tissue was simulated by adding a 5 mm removable silicone layer over the buccal and lingual cortices, stabilized with pink wax. This uniform layer was intended to provide approximate soft-tissue attenuation and scatter; it does not reproduce the variable thickness and composition of the oral soft tissues (see Limitations).

CBCT scanning and parameters

CBCT scans with a 5 × 5 cm field of view were acquired with the PreXion3D Excelsior (PreXion Corp., San

Mateo, CA, USA) using two sets of parameters: standard resolution and high resolution. For each set of parameters, scans were acquired with and without the tooth in place. To allow accurate superimposition, movement of the mandible between scans had to be avoided; therefore, the scan without the tooth was acquired first, after which the tooth was reseated in its socket and the scan with the tooth was acquired. In addition, each mandible was positioned so that the desired field of view was included without readjusting the beam between scans, since any positioning discrepancy could render superimposition impossible.

Parameter 1: Standard quality, large adult setting: 110 kV, 3.2 mA, exposure time of 7.7 s, and slice thickness of 0.1 mm.

Parameter 2: Ultra-high-definition quality, large adult setting with the 1024 mode enabled: 110 kV, 3.2 mA, exposure time of 17.9 s, and slice thickness of 0.05 mm.

All scans were exported in Digital Imaging and Communications in Medicine (DICOM) format.

Image processing and superimposition

Superimposition and linear measurements were performed with 3D Slicer (version 4.11.20200930; open-source software, https://www.slicer.org) [29].

Image Orientation

For each extraction site, the images were reoriented according to three planes: (1) a horizontal plane parallel to the occlusal plane, (2) a vertical plane parallel to the long axis of the tooth, and (3) a mesiodistal plane passing through the center of the site and the adjacent teeth.

Superimposition

The Expert Automated Registration module of 3D Slicer was used to superimpose the scans of the same site acquired with the same parameters with and without the tooth [29]. For each pair, the scan with the tooth served as the fixed volume and the scan without the tooth as the moving volume, and a rigid (six-degree-of-freedom) registration was applied. Because the mandible was not moved between the two acquisitions, the expected transform was close to identity, and registration served only to correct residual sub-voxel displacement. Measurements on the scans with the tooth were made on the original, non-resampled volumes. Registration quality was verified visually in the axial, sagittal, and coronal planes by checking the alignment of the cortical outlines, adjacent teeth, and mandibular canal.

Reference level and linear measurements

Linear Measurements

A reference level was set at the level of the CEJ: on the oriented cross-sectional image of the scan with the tooth, the reference level was defined as the line perpendicular to the long axis of the tooth passing through the CEJ, a reproducible anatomical landmark that is clearly identifiable when the tooth is present. For each set of scan parameters, the same reference level was transferred unchanged to the second of the two superimposed scans (with and without the tooth), so both measurements of each pair shared an identical reference. Because the standard- and high-resolution scans were not superimposed on each other, the reference line was placed separately for each resolution, but always at the CEJ and using the same definition. As all comparisons were paired within a resolution, any sub-voxel difference in the placement of the reference line between resolutions does not affect the pre- and post-extraction differences analyzed in this study. The slice increment was set so that each scroll of the mouse moved the reference line by 3 mm. The thickness of the buccal and lingual bone was measured with the ruler tool at 3, 6, and 9 mm apical to the CEJ reference level, along lines parallel to the reference line. The vertical crestal bone level was measured from the reference level to the first bone point perpendicular to the reference line (Figure *1*).

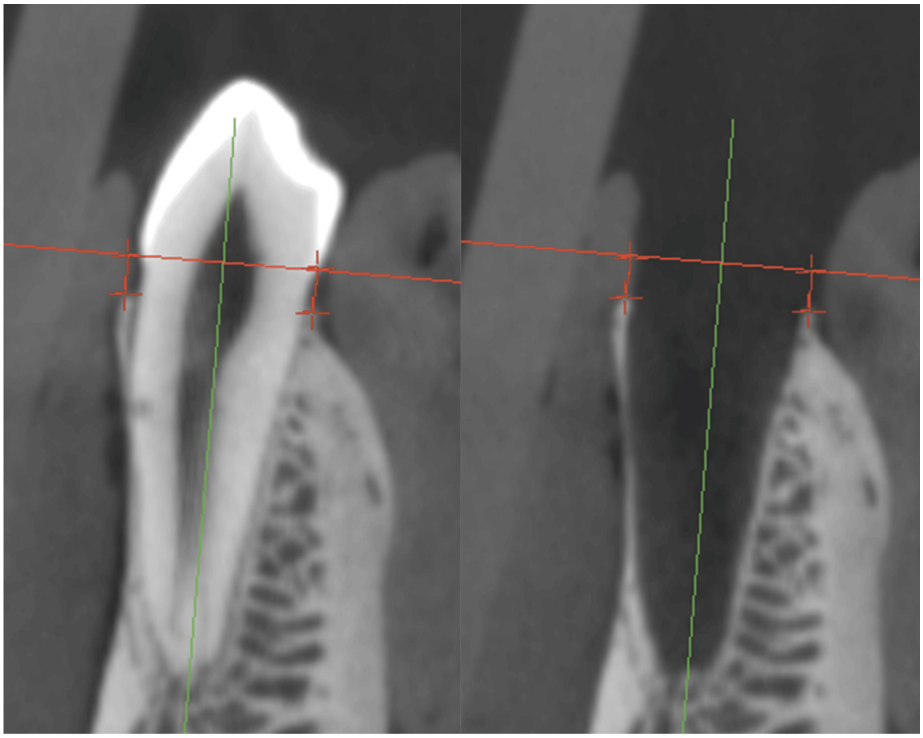


FIGURE 1: Measurement of the bone level on the buccal and lingual aspects with (left) and without (right) the tooth

Superimposed cross-sectional CBCT images of the same site. The red line indicates the reference level, and the green line indicates the long axis of the tooth.

CBCT: Cone-beam computed tomography

Measurement sequence

Measurements were first taken on the scans with the tooth, to limit bias from visualizing the bone without the tooth, and then on the scans without the tooth. Measurements obtained after tooth extraction served as the comparator for the agreement analysis; because they were obtained with the same imaging modality, they do not constitute an independent anatomical reference standard. The examiners could not be blinded to the scan condition, because the presence or absence of the tooth is evident on the images, and the measurement order was fixed rather than randomized (see Limitations).

Examiner training and calibration

Two oral and maxillofacial radiology residents (second and third year) performed the linear measurements independently. Images were viewed on a calibrated 24-inch in-plane switching monitor (Dell Technologies, Round Rock, TX, USA) at a resolution of 1920 × 1200 pixels, with 8-bit depth and standard dynamic range. Inter-examiner calibration was performed first: the examiners were trained to measure at the correct angulation and reference points on a sample of 10 study teeth until an ICC of 0.90 was reached. One week later, each examiner performed the study measurements independently. Two weeks after that, each examiner repeated 65 randomly selected measurements, distributed approximately equally (16 or 17 per stratum) among standard-resolution linear, high-resolution linear, standard-resolution vertical, and high-resolution vertical measurements, to assess intra-examiner reliability. The number of repeated measurements was chosen for the precision of the reliability estimate: assuming an ICC of 0.90 with two repeated ratings, 65 measurements yield an expected 95% confidence interval (CI) width of approximately 0.10 for each examiner's overall ICC, whereas approximately 16 measurements per stratum would yield a width of approximately 0.23 [30]. Stratum-specific reliability was therefore not estimated.

Statistical analysis

Data were analyzed using R (R Foundation for Statistical Computing, Vienna, Austria) [31]. Data were stratified by definition (high vs. standard resolution), locale (vertical crestal level and thickness at 3, 6, and 9 mm), and surface (buccal and lingual). The mean (standard deviation) and median (interquartile range) were calculated for each surface and locale for both definitions. The ICC was used to evaluate intra- and inter-examiner reliability. Measurements obtained before and after extraction were compared using two one-

sided tests (TOSTs) to assess equivalence [32,33], with a prespecified equivalence margin of ±0.2 mm. Equivalence was concluded when both one-sided tests were significant at α = 0.05, which corresponds to the 90% CI of the mean difference lying entirely within ±0.2 mm [33]. No adjustment for multiple comparisons was applied; given the exploratory design, p-values are reported unadjusted and interpreted descriptively.

Justification of the equivalence margin

The margin of ±0.2 mm was set before data analysis on clinical grounds. In the clinical experience of the investigators involved in implant planning and placement, 0.2 mm is the smallest difference in socket-wall thickness that is routinely taken into account when deciding on immediate placement and the need for simultaneous contour augmentation, and it is the tolerance most commonly applied in their practice. This choice is consistent with the literature. Most anterior tooth sites have a facial wall thinner than 1 mm, and close to half have a wall of 0.5 mm or less [14,15], while clinical decisions rely on thresholds of approximately 1 mm and 1.8 to 2 mm of buccal bone [11,12,34]; at such thicknesses, an error of 0.2 mm corresponds to 20% to 40% of the wall and may change the classification of a site. A margin of 0.2 mm is also of the same order as the error reported for CBCT measurements of buccal bone thickness against direct measurements (mean absolute difference 0.13 mm) [17], whereas the 0.5 to 1 mm thresholds used in many accuracy studies [35-38] would be too permissive for thin socket walls. Equivalence margins should reflect the smallest difference of clinical interest [32,33]; the chosen margin corresponds to two voxels at standard resolution and four voxels at high resolution.

Sensitivity analysis

Because the choice of any margin involves judgment, equivalence was also assessed at alternative margins of ±0.10, ±0.15, ±0.25, ±0.30, and ±0.50 mm. As TOST at α = 0.05 is equivalent to the 90% CI lying entirely within the margin [33], equivalence at each alternative margin was determined from the 90% CI of each stratum, and the smallest margin at which equivalence would be concluded (the largest absolute 90% CI bound) was reported.

Unit of analysis

The unit of analysis was the paired measurement (the same site, surface, and locale measured with and without the tooth). Because the 31 teeth were nested within six mandibles and each tooth contributed several measurements, these observations are not fully independent. A mixed-effects or generalized estimating equation model was not fitted, because six clusters are too few for reliable estimation of the between-mandible variance; consequently, the CIs and p-values may be too narrow, and the analysis is regarded as exploratory (see Limitations). The number of paired observations in each stratum is reported in the footnotes to Tables *2*-*4*. Measurements from both examiners were pooled, so each site contributed two paired observations; this further reduces the independence of observations and the effective sample size.

Results

For both examiners, the distributions of the CBCT measurements obtained before and after extraction were comparable. Intra- and inter-examiner reliability was excellent (ICC > 0.9) before extraction, after extraction, and overall (Table *1*).

Measure	ICC	Lower bound	Upper bound
Intra-examiner A, before extraction	0.994	0.987	0.997
Intra-examiner B, before extraction	0.968	0.937	0.984
Inter-examiner, before extraction	0.969	0.963	0.974
Intra-examiner A, after extraction	0.993	0.985	0.996
Intra-examiner B, after extraction	0.979	0.958	0.990
Inter-examiner, after extraction	0.975	0.971	0.979
Intra-examiner A, overall	0.993	0.989	0.996
Intra-examiner B, overall	0.973	0.956	0.983
Inter-examiner, overall	0.972	0.969	0.976

TABLE 1: Intraclass correlation coefficients for intra- and inter-examiner reliability

ICC: intraclass correlation coefficient. Lower and upper bounds are those of the 95% confidence interval.

With an equivalence margin of 0.2 mm, linear measurements obtained before and after extraction were equivalent when stratified by definition ($p < 0.001$) (Table 2, Figure 2). Equivalence was also demonstrated when measurements were stratified by both definition and surface ($p < 0.05$) (Table 3, Figure 3).

Definition	Null hypothesis	Mean difference (mm)	Lower CI (mm)	Upper CI (mm)	p-value
High resolution	Rejected	-0.068	-0.105	-0.032	<0.001
Standard resolution	Rejected	-0.079	-0.111	-0.048	<0.001

TABLE 2: Differences between measurements before and after extraction, stratified by definition

Two one-sided tests (TOSTs) for equivalence with a margin of ±0.2 mm; the null hypothesis is non-equivalence. CI: 90% confidence interval. n = 496 paired measurements per definition.

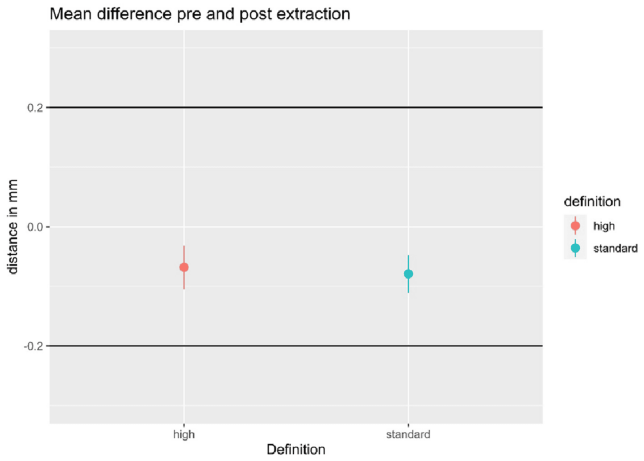


FIGURE 2: Mean difference before and after extraction stratified by definition

Definition	Surface	Null hypothesis	Mean difference (mm)	Lower CI (mm)	Upper CI (mm)	p-value
High resolution	Lingual	Rejected	-0.038	-0.081	0.005	<0.001
High resolution	Buccal	Rejected	-0.101	-0.162	-0.040	0.004
Standard resolution	Lingual	Rejected	-0.081	-0.114	-0.048	<0.001
Standard resolution	Buccal	Rejected	-0.077	-0.133	-0.022	<0.001

TABLE 3: Differences between measurements before and after extraction, stratified by definition and surface

Two one-sided tests (TOSTs) for equivalence with a margin of ±0.2 mm; the null hypothesis is non-equivalence. CI: 90% confidence interval. n = 248 paired measurements per stratum.

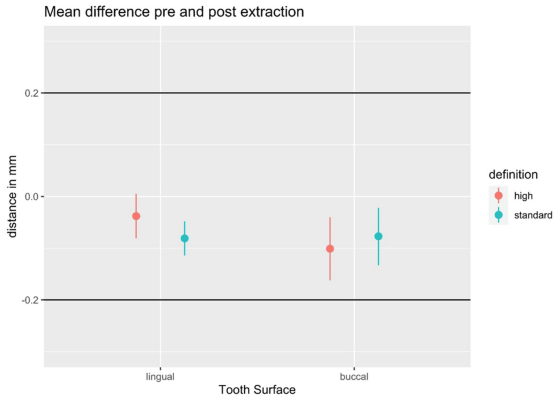


FIGURE 3: Mean difference before and after extraction stratified by definition and surface

When stratified by definition and locale, measurements were equivalent in all groups ($p < 0.05$), except for thickness measured at 9 mm on high-resolution scans ($p = 0.349$) (Table *4*, Figure *4*). Bone thickness was slightly underestimated before extraction, whereas the vertical crestal bone level was slightly overestimated (Figure *4*). In the non-equivalent stratum, the mean difference (-0.172 mm) lay within the margin, but the lower bound of the 90% CI (-0.293 mm) exceeded it. The underestimation of thickness increased with depth at both resolutions (high resolution: -0.029, -0.089, and -0.172 mm; standard resolution: -0.094, -0.141, and -0.148 mm at 3, 6, and 9 mm, respectively), and the 90% CI for high-resolution thickness at 9 mm (width 0.243 mm) was 3.7 times wider than those at 3 and 6 mm (0.065 mm) and 2.7 times wider than that for standard-resolution thickness at 9 mm (0.090 mm).

Definition	Locale	Null hypothesis	Mean difference (mm)	Lower CI (mm)	Upper CI (mm)	p-value
High resolution	Vertical	Rejected	0.017	-0.038	0.073	<0.001
High resolution	At 3 mm	Rejected	-0.029	-0.061	0.004	<0.001
High resolution	At 6 mm	Rejected	-0.089	-0.122	-0.057	<0.001
High resolution	At 9 mm	Not rejected	-0.172	-0.293	-0.050	0.349
Standard resolution	Vertical	Rejected	0.056	-0.042	0.154	0.008
Standard resolution	At 3 mm	Rejected	-0.094	-0.127	-0.062	<0.001
Standard resolution	At 6 mm	Rejected	-0.141	-0.177	-0.105	0.004
Standard resolution	At 9 mm	Rejected	-0.148	-0.193	-0.103	0.030

TABLE 4: Differences between measurements before and after extraction, stratified by definition and locale

Two one-sided tests (TOSTs) for equivalence with a margin of ±0.2 mm; the null hypothesis is non-equivalence. Vertical: crestal bone level; At 3, 6, and 9 mm: bone thickness at 3, 6, and 9 mm apical to the reference level. CI: 90% confidence interval. n = 124 paired measurements per stratum.

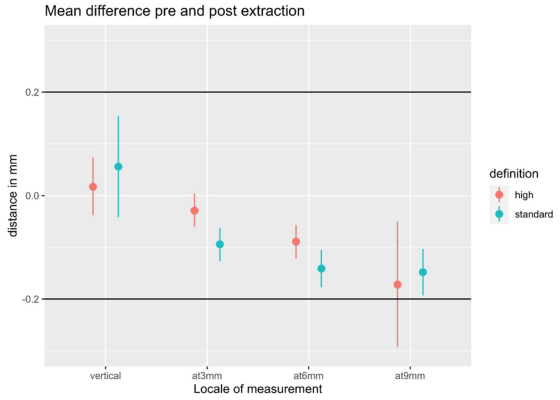


FIGURE 4: Mean difference before and after extraction stratified by definition and locale

In the sensitivity analysis (Table 5), all strata met equivalence at a margin of ±0.30 mm, and all except high-resolution thickness at 9 mm met it at ±0.25 mm. At ±0.15 mm, equivalence was retained for both definitions overall, for all surface strata except the high-resolution buccal surface, for high-resolution crestal level and thickness at 3 and 6 mm, and for standard-resolution thickness at 3 mm, but not for standard-resolution crestal level, standard-resolution thickness at 6 and 9 mm, or high-resolution thickness at 9 mm. At ±0.10 mm, only high-resolution crestal level, high-resolution thickness at 3 mm, and the high-resolution lingual surface met equivalence.

Stratum	90% CI (mm)	Smallest margin (mm)	±0.10	±0.15	±0.20	±0.25	±0.30	±0.50
High resolution, overall	-0.105 to -0.032	0.105	No	Yes	Yes	Yes	Yes	Yes
Standard resolution, overall	-0.111 to -0.048	0.111	No	Yes	Yes	Yes	Yes	Yes
High resolution, lingual	-0.081 to 0.005	0.081	Yes	Yes	Yes	Yes	Yes	Yes
High resolution, buccal	-0.162 to -0.040	0.162	No	No	Yes	Yes	Yes	Yes
Standard resolution, lingual	-0.114 to -0.048	0.114	No	Yes	Yes	Yes	Yes	Yes
Standard resolution, buccal	-0.133 to -0.022	0.133	No	Yes	Yes	Yes	Yes	Yes
High resolution, vertical	-0.038 to 0.073	0.073	Yes	Yes	Yes	Yes	Yes	Yes
High resolution, at 3 mm	-0.061 to 0.004	0.061	Yes	Yes	Yes	Yes	Yes	Yes
High resolution, at 6 mm	-0.122 to -0.057	0.122	No	Yes	Yes	Yes	Yes	Yes
High resolution, at 9 mm	-0.293 to -0.050	0.293	No	No	No	No	Yes	Yes
Standard resolution, vertical	-0.042 to 0.154	0.154	No	No	Yes	Yes	Yes	Yes
Standard resolution, at 3 mm	-0.127 to -0.062	0.127	No	Yes	Yes	Yes	Yes	Yes
Standard resolution, at 6 mm	-0.177 to -0.105	0.177	No	No	Yes	Yes	Yes	Yes
Standard resolution, at 9 mm	-0.193 to -0.103	0.193	No	No	Yes	Yes	Yes	Yes

TABLE 5: Sensitivity analysis of equivalence at alternative margins

Yes: the 90% confidence interval (CI) of the mean difference lies entirely within ± the margin, which corresponds to two one-sided tests at α = 0.05. Smallest margin: the largest absolute bound of the 90% CI, i.e., the narrowest margin at which equivalence would be concluded. Values derived from the 90% CIs in Tables 2-4. The primary prespecified margin was ±0.20 mm.

Discussion

This exploratory pilot study compared CBCT measurements of the socket walls of single-rooted mandibular teeth obtained with the tooth in place and after its removal. Pre-extraction measurements agreed with post-extraction measurements within ±0.2 mm in all strata except high-resolution bone thickness at 9 mm, with a small systematic underestimation of bone thickness and a small overestimation of the crestal bone level when the tooth was present. Because both measurements were obtained with the same imaging modality, these results describe the agreement between the two conditions rather than the absolute accuracy of CBCT.

Immediate implant placement is defined as the placement of a dental implant into a fresh extraction socket immediately after tooth extraction, and it is considered a predictable and acceptable procedure [39].

Successful dental implant treatment requires a thorough planning phase that includes an appropriate radiographic examination with images of diagnostic quality [40,41]. The American Academy of Oral and Maxillofacial Radiology (AAOMR) recommends cross-sectional imaging for preoperative implant site assessment, with CBCT as the current method of choice because it provides the greatest diagnostic yield at an acceptable radiation dose [21].

Compared with multidetector computed tomography, CBCT provides cross-sectional and 3D images at a lower radiation exposure [41,42] and a lower overall cost [20]. However, many clinicians rely on linear measurements performed on CBCT images when planning immediate implant placement without considering potential inaccuracies or inconsistencies. A systematic review concluded that cross-sectional CBCT images provide highly accurate and reliable linear measurements for implant planning in edentulous sites with a voxel size of 0.3 to 0.4 mm [43], which supports the use of post-extraction measurements as the comparator in the present study; nevertheless, this does not make post-extraction CBCT an independent gold standard, and systematic errors common to both conditions would not be detected by the present design.

Direct caliper measurements on the mandibles were not used as the gold standard because this would have required sectioning, and thus sacrificing, all of the dry mandibles, as well as placing physical radiographic markers to ensure that measurements were taken at the same sites, which could have induced beam-hardening artifacts and affected the measurements. Consequently, the present design quantifies the agreement between two CBCT conditions, and absolute accuracy could not be established (see Limitations).

In this study, all but one stratum showed equivalence of linear measurements ($p < 0.05$), leading to rejection of the null hypothesis of non-equivalence in those strata and indicating close agreement between pre- and post-extraction measurements, with an overall slight underestimation of bone thickness and slight overestimation of the vertical crestal level (Figure *4*). In the group measured at 9 mm on high-resolution scans, the p-value was 0.349, indicating that equivalence of the measurements before and after extraction could not be demonstrated at that level; the lower bound of the confidence interval for this group was -0.293 mm. The equivalence margin of 0.2 mm is stringent compared with that of many studies, in which bone measurements on CBCT images were considered precise when errors were less than 0.5 to 1 mm [35-38], and the sensitivity analysis showed that all strata would be equivalent at ±0.30 mm (Table *5*). However, the conclusions depend on the margin: at ±0.15 mm, several strata no longer met equivalence. In addition, given the small number of specimens, equivalence in the other strata should be interpreted together with the width of their CIs rather than as proof that no clinically relevant difference exists.

The direction of the differences is consistent with the physics of CBCT image formation. When the tooth is present, the root, the periodontal ligament space, and the lamina dura lie within a few voxels of each other, and partial-volume averaging and blooming at the boundary between dentin and bone can cause voxels of the inner cortical surface to be attributed to the root, resulting in a thinner apparent socket wall. Similarly, the thin bone at the alveolar crest may be partially averaged with the adjacent root surface and appear more apical, resulting in overestimation of the crestal bone level. Comparable mechanisms have been described in earlier studies: the alveolar crest appears more apical (bone height is underestimated) when the bone thickness approaches the voxel size [44], CBCT tends to overestimate dehiscences and fenestrations at sites with thin bone [26,27,45], and blooming from adjacent high-density structures compromises the estimation of buccal bone thickness [46].

The magnitude of the differences observed here is small compared with that reported in studies that validated CBCT against direct measurements of dentate specimens. Timock et al. reported mean absolute differences of 0.13 mm for buccal bone thickness and 0.30 mm for buccal bone height at a 0.3 mm voxel size [17], Leung et al. reported an absolute mean difference of approximately 0.6 mm for the alveolar bone margin at a 0.38 mm voxel size [27], and Patcas et al. found that bony measurements of the mandibular anterior teeth differed only slightly from physical findings, although thin bone coverage was not reliably depicted even at a 0.125 mm voxel size [26]. Menezes et al. likewise reported high accuracy for bone crest level measurements on dry mandibles, except at the mandibular incisors with a 0.4 mm voxel size [28]. In an in vitro study of thin cortical bone around experimental surgical defects in pig mandibles, measurements obtained with six exposure protocols differed significantly at some sites, but the differences were too small to be clinically important, and accuracy remained high even with lower-dose protocols [47]. The mean differences in the present study (-0.172 to 0.056 mm) are of a similar or smaller order. However, these comparisons should be made with caution, because the present study measured the agreement between two CBCT conditions rather than the error against a physical reference, and error shared by both conditions is not captured.

Voxel size determines CBCT image quality in terms of spatial resolution [20,48], with smaller voxel sizes providing a higher degree of detail. In some fields, such as endodontics, high resolution plays a significant role in the quality of diagnostic tasks [49,50]. However, for implant planning, a voxel size of 0.3 to 0.4 mm appears sufficient to provide accurate linear measurements [43]. In this study, the slice thickness was 0.05 mm at high resolution and 0.1 mm at standard resolution, and no relevant difference in agreement was observed between the two resolutions. These results agree with several studies reporting that smaller voxel sizes did not improve the accuracy of linear measurements at edentulous sites [36,51-53], as well as with other CBCT studies comparing voxel sizes ranging from 0.16 to 0.6 mm [26,54,55] and with the finding that lower-dose protocols preserved the accuracy of thin cortical bone measurements [47]. Because the high-resolution protocol required an exposure time of 17.9 s compared with 7.7 s for the standard protocol at the same tube voltage and current, it entailed approximately 2.3 times the tube current-exposure time product without improving agreement, which, in line with the as low as diagnostically acceptable (ALADA) principle, favors the standard protocol for this task. However, both resolutions used in this study were high, and the measured distances spanned only a few millimeters; measurements could therefore be affected by the presence of a tooth when lower resolutions or larger fields of view are used.

The failure to demonstrate equivalence for high-resolution thickness at 9 mm warrants specific consideration. The mean difference in this stratum (-0.172 mm) was close to that for standard-resolution thickness at 9 mm (-0.148 mm), which met equivalence; the two strata therefore differed mainly in precision, with a 90% CI that was 2.7 times wider at high resolution. This pattern suggests that the result reflects greater variability of individual measurements rather than a different systematic error. Two factors may explain this. First, the underestimation of thickness increased progressively with depth at both resolutions, suggesting that the inner boundary of the socket wall becomes more difficult to delineate toward the apical third, where the bone is thicker and the contrast between the root surface, the periodontal ligament space, and the surrounding bone is lower. Second, at the same tube voltage and current, smaller voxels receive fewer photons and therefore contain more image noise, despite the longer exposure time, which degrades the definition of low-contrast boundaries [19,20]. The combination of a less distinct boundary and higher noise at depth may have increased the scatter of the high-resolution measurements at 9 mm and widened the CI beyond the margin. Because the number of measurements per stratum was small, a

few discrepant sites may also have contributed disproportionately.

Intra- and inter-examiner reliability was excellent (ICC > 0.9), indicating high reliability of the measurement protocol and comparable to that reported for CBCT measurements of buccal bone thickness and height (0.90 to 0.97) [17]. However, these ICCs were estimated without accounting for the nesting of measurements within teeth and mandibles, and they reflect the reliability of trained examiners working on dry specimens under standardized conditions, which may be higher than that achievable in clinical images.

From a clinical perspective, the observed mean differences (0.172 mm or less) are small relative to the thresholds of 1 mm and 1.8 to 2 mm commonly used to decide on immediate placement and contour augmentation [14,15,34]. If confirmed in vivo, this would suggest that the presence of the tooth does not meaningfully bias the presurgical CBCT assessment of socket-wall thickness. The slight underestimation of thickness and overestimation of crestal bone loss would, if anything, make clinical decisions more conservative, whereas the wider variability observed apically indicates that measurements in the apical third should be interpreted with greater caution. These findings cannot be translated into clinical recommendations without validation in patients.

Limitations

This study has several limitations that should be considered when interpreting the results.

First, there was no independent anatomical gold standard. Post-extraction CBCT measurements served as the comparator, but they were obtained with the same imaging modality, device, and protocol as the pre-extraction measurements. Agreement between the two conditions therefore shows that the presence of the tooth had little effect on the measurements, but it cannot establish the absolute accuracy of CBCT, because errors common to both conditions (e.g., partial-volume averaging, device calibration, and examiner interpretation) would not be detected. Direct measurements on sectioned specimens or micro-computed tomography would be required to establish accuracy.

Second, this was an exploratory pilot study based on a convenience sample of 31 teeth from six mandibles, without an a priori sample size calculation. Equivalence tests with small numbers of observations per stratum have limited power, so the failure to demonstrate equivalence in one stratum may reflect imprecision rather than a true difference, and equivalence in the other strata should be interpreted together with the width of the CIs. The results should be regarded as hypothesis-generating and used to plan an adequately powered confirmatory study.

Third, measurements were nested within teeth and mandibles but were analyzed as independent observations, and the ICCs were not adjusted for clustering. With only six mandibles, mixed-effects or generalized estimating equation models could not be fitted reliably; ignoring the clustering may have produced CIs and p-values that are too narrow.

Fourth, the examiners could not be blinded to the scan condition, because the presence or absence of the tooth is evident on the images, and the measurement order was not randomized: the scans with the tooth were always measured before those without the tooth. Although this sequence was chosen to prevent knowledge of the post-extraction bone outline from influencing the pre-extraction measurements, recall of earlier measurements or anchoring on previously identified landmarks may have influenced the post-extraction measurements and could have inflated the agreement between the two conditions.

Fifth, the use of dry mandibles may limit generalizability. Dry bone lacks marrow, blood, the periodontal ligament, and the surrounding soft tissues; the marrow spaces and the periodontal ligament space are filled with air, which increases the contrast between bone, root, and the surrounding spaces compared with the in vivo situation. The teeth were reseated without a periodontal ligament, and patient motion was absent. These conditions are likely to favor the delineation of the socket walls, so the agreement observed here may overestimate that achievable in patients. CBCT reconstruction algorithms are optimized for in vivo scanning, which makes it challenging to apply findings from in vitro CBCT studies to clinical cases [26,51,56]. Although some studies have reported similar measurement accuracy with and without soft tissue or soft-tissue simulation [38,57], the adequacy of the dry-mandible model was not validated internally in the present study.

Sixth, soft tissue was simulated with a uniform 5 mm layer of silicone stabilized with wax over the buccal and lingual cortices. This layer does not reproduce the variable thickness, composition, and attenuation of the gingiva, mucosa, tongue, lips, and cheeks, or the scatter they generate, and it was not validated against specimens with intact soft tissues. Image noise and contrast in patients may therefore differ from those in the present model.

Seventh, although the mandibles were not moved between acquisitions and registration was verified visually, the registration error was not quantified, and a small residual misalignment between the paired scans may have contributed to the observed differences.

Finally, this study was limited to single-rooted teeth in the mandible, a single CBCT unit, and a small (5 × 5 cm) field of view, and did not include the maxilla or lower-resolution scan parameters. In addition, motion and beam-hardening artifacts, which may affect the resolution and accuracy of linear measurements, cannot be excluded [58]. No clinical validation was performed, and the findings have not been compared with in vivo measurements or clinical outcomes.

Further research is warranted to evaluate the effect of larger fields of view, lower scan resolutions, and maxillary dentate sites on the accuracy of bone measurements in dentate areas. Clinical measurements following minimally traumatic extraction could serve as a gold standard and would be valuable for validating the accuracy of linear measurements obtained before tooth extraction for immediate implant planning. Future studies should use an independent reference standard (e.g., histological sections or micro-computed tomography), include specimens with intact soft tissues, blind the examiners where possible and randomize the measurement order, apply statistical models that account for clustering, and base their sample size on the variance estimates obtained in this pilot study.

Conclusions

Within the limitations of this in vitro pilot study, CBCT measurements of buccal and lingual bone thickness and crestal bone level taken at dentate mandibular sites before tooth extraction agreed closely with those taken after extraction, at both slice thicknesses evaluated. Mean differences stayed within the predefined equivalence margin in all subgroups. Equivalence was shown in every subgroup except apical bone thickness on high-resolution scans. These findings suggest that adjacent teeth do not meaningfully affect the accuracy of CBCT-based alveolar bone assessment, although clinical studies are needed to confirm this. The presence of the tooth led to a slight underestimation of bone thickness and a slight overestimation of the crestal bone level, neither of which appeared clinically meaningful. Because the comparator was CBCT itself, absolute accuracy could not be established.

These preliminary findings may support the use of presurgical CBCT measurements of the socket walls when planning immediate implant placement in single-rooted mandibular teeth, provided that they are confirmed by adequately powered studies with an independent reference standard and validated clinically. Clinical studies including maxillary sites, lower-resolution protocols, and larger fields of view are needed to confirm these results under routine conditions.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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