The Accuracy of Cone-Beam Computed Tomography for Evaluating Bone Density and Cortical Bone Thickness at the Implant Site: Micro-Computed Tomography and Histologic Analysis

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Abstract: The aim of this study was to evaluate the accuracy of cone-beam computed tomography (CBCT) for determining cortical thickness and the gray value, investigating its correlation with micro-computed tomography (CT) and histology analysis. Sixty-two bone samples from 4 anatomic regions of the jaw were analyzed. A radiographic surgical stent was used during CBCT and bone sample harvesting. The cortical thickness and gray value of the planned implant were evaluated by CBCT. Bone volumetric fractions, bone mineral density, and % porosity assessed by micro-CT and mineralized material by histology analysis from harvested bone samples were analyzed and assessed for the association with the CBCT using Pearson correlation. A correlation between cortical thickness measured from the CBCT and Micro-CT ($r=0.933$, $P<0.01$) was identified. There was no difference between gray values measured from the CBCT among regions, while bone density parameters from micro-CT and histologic analysis showed significant difference ($P<0.01$) among regions. Bone density parameters from micro-CT and histologic analysis showed correlation with cortical thickness but not with the gray value. In conclusion, CBCT is highly accurate in linear measurements and demonstrated correlation with genuine bone density. However, the gray value could not demonstrate the true bone density according to a low correlation to bone density variable measured from micro-CT and histologic analysis.

Key Words: Bone density, CBCT, cortical thickness, gray value, histology, micro-CT

The clinical examinations and preoperative radiographic information, in particular the bone quantity and quality, are very crucial for the success of dental implant placement. Low bone quality, being thin cortical bone and sparse trabecular bone, is one of the factors associated with dental implant failures from biological causes; for example, failure to establish osseointegration before implant loading, failure to maintain the osseointegration after implant loading. The implant surgical failure ranged from 3.2% to 5% in good-quality bone and 1.9% to 20% in poor bone quality, with most reports indicating a greater failure rate (up to 65%) in soft bone. The density of bone is known to impact upon implant success, with reduced bone density increasing the risk of failure. Poor bone quality and quantity have additionally been reported as the risk factors associated with the excessive bone resorption and impairment of the healing process after implant placement. Recent systematic review and meta-analysis also indicated that implants installed in poor bone quality and insufficient bone volume are statistically affect implant failure rates.

Cone-beam computed tomography (CBCT) offers comprehensive radiographic information for the structural and quantitative analysis of the bone. Histomorphometry is a destructive method and the analysis can only be performed on 3 to 4 histological sections per bone sample achieved from the dental implant site. Moreover, the measurements are made in two-dimensional (2D) images. Micro-CT, a nondestructive evaluation method of ex vivo small bone samples, was suggested for evaluating bone morphology and microarchitecture in 3D. It uses data from attenuated x-ray projections in multiple angles to reconstruct a 3D representation of the model that characterizes the spatial distribution of the material density. Micro-computed tomography can be used to demonstrate many bone microarchitectures, for instance, bone volume, total volume, bone volume fraction (BV/TV), trabecular thickness, trabecular numbers, and trabecular separation. However,
Micro-Computed Tomography Analysis

The samples were scanned with Scanco35 (Scanco Medical, Bruttisellen, Switzerland) using 70 kV and 114 μA. The 2D and 3D images from the scanning bone core were reconstructed by Scanco reconstruction software (Scanco Medical). The linear measurement was assessed by measuring the cortical bone thickness, which is the average cortical thickness from 3 regions of interest of the bone sample (most mesial point, midpoint, and most distal point). The parameters generated for the histomorphometric bone density analysis included the BV/TV, which is the total amount of bone present in relation to the analyzed bone volume, bone mineral density (BMD), which is the volumetric density of the average attenuation value of the analyzed bone volume, and the porosity, which is the percentage of the volume of pores in relation to the bone compartment.

Statistical Analysis

Statistical analysis was performed using software SPSS Statistics Bass 17.0 for Windows EDU (SPSS Inc, Chicago, IL) with the significance set at 5%. Data were presented as mean ± standard deviation. One way analysis of difference and multiple comparison by Tukey honest significant difference post hoc test were applied to reveal statistically significant difference between the 4 regions. Pearson coefficients and simple linear regression were used to evaluate the relationship between quantitative parameters. To determine the reliability of the measurement, all 6 measurements were repeated on 30 randomly selected CBCT, micro-CT, and histology slides 1 month after the initial measurement. The intraoperative reliability was reported by calculating the intraclass correlation coefficient between both measurements.

RESULTS

The intraoperative reliability was above 0.90 for all measurements, showing a high reliability. The CBCT image and corresponding micro-CT and histologic section of the maxilla (UA, UP) and the mandible (LA, LP) were shown in Figures 1 to 4, respectively.

Cortical Thickness

Mean cortical thicknesses from the CBCT and micro-CT were shown in Table 1. The cortical thickness in the mandible (LA and LP) was significantly greater than that in the UP region. The absolute mean difference of the CBCT to micro-CT was 0.08 ± 0.04 mm (range from −0.18 to 0.16 mm). No statistical significant difference between the CBCT and micro-CT was observed for the cortical thickness value. The cortical thickness from the CBCT showed high positive correlation with that from the micro-CT (r = 0.933, P = 0.000).
Density Value

Mean density values of the cortical-, trabecular-, and total gray values from the CBCT in UA, UP, LA, and LP were shown in Table 2 and Figure 5. There was no statistically significant difference among the groups for the cortical-, trabecular-, or total gray values from the CBCT as determined by one-way analysis of difference. Total gray values measured by the CBCT did not show any correlation neither with the bone density variables measured by the micro-CT nor with MM assessed by histomorphometry.

Histomorphometric bone density parameter variables expressed as BV/TV, BMD, and porosity assessed by micro-CT and MM by histology analysis were shown in Table 2. The density value from the micro-CT (BV/TV, BMD, porosity) and histolomorphometry (MM) of the LA group showed statistical significant difference from other groups.

Bone mineral density, porosity, and BT/TV assessed from the micro-CT showed moderate to high correlation to MM analyzed by histomorphometry (Table 3).

Correlation Between Cortical Thickness from the Cone Beam Computed Tomography and Bone Density

Correlations between cortical thickness from the CBCT and microstructure variables measured by the micro-CT and histomorphometry analyzed by Pearson correlation were demonstrated in Table 4. Positive correlations between BV/TV ($r = 0.634$, $P = 0.000$), BMD ($r = 0.818$, $P = 0.000$), and MM ($r = 0.738$, $P = 0.000$) with cortical thickness from the CBCT were identified. In addition, porosity ($r = -0.662$, $P = 0.000$) was negatively correlated with cortical thickness from the CBCT. However, gray values ($r = -0.047$, $P = 0.717$) did not show correlation with cortical thickness from the CBCT (Table 4).

![Image 1](https://example.com/image1.png)  
**FIGURE 1.** Bone biopsy from the upper anterior (UA) region. (A) Cone beam computed tomography image. (B) Three-dimensional sagittal view micro-computed tomography. (C) Two-dimensional sagittal view micro-computed tomography. (D) Histologic section.

![Image 2](https://example.com/image2.png)  
**FIGURE 2.** Bone biopsy from upper posterior (UP) region. (A) Cone beam computed tomography image. (B) Three-dimensional sagittal view micro-computed tomography. (C) Two-dimensional sagittal view micro-computed tomography. (D) Histologic section.

![Image 3](https://example.com/image3.png)  
**FIGURE 3.** Bone biopsy from lower anterior (LA) region. (A) Cone beam computed tomography image. (B) Three-dimensional sagittal view micro-computed tomography. (C) Two-dimensional sagittal view micro-computed tomography. (D) Histologic section.

![Image 4](https://example.com/image4.png)  
**FIGURE 4.** Bone biopsy from lower posterior (LP) region. (A) Cone beam computed tomography image. (B) Three-dimensional sagittal view micro-computed tomography. (C) Two-dimensional sagittal view micro-computed tomography. (D) Histologic section.

<table>
<thead>
<tr>
<th>Variable</th>
<th>UA (n = 12)</th>
<th>UP (n = 19)</th>
<th>LA (n = 10)</th>
<th>LP (n = 21)</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortical thickness (mm)</td>
<td>1.01 ± 0.23</td>
<td>0.87 ± 0.18*</td>
<td>1.19 ± 0.24*</td>
<td>1.16 ± 0.25*</td>
<td>'0.003, *0.001</td>
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<tr>
<td>Micro-CT</td>
<td>1.00 ± 0.25</td>
<td>0.90 ± 0.18*</td>
<td>1.20 ± 0.22*</td>
<td>1.17 ± 0.25*</td>
<td>'0.007, *0.003</td>
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<tr>
<td>$P$</td>
<td>0.811</td>
<td>0.186</td>
<td>0.783</td>
<td>0.797</td>
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</table>

CBCT, cone beam computed tomography; CT, computed tomography; UA, upper anterior; UP, upper posterior; LA, lower anterior; LP, lower posterior.  
*Statistically significant as indicated in $P$ values.
DISCUSSION

Due to the dose-sparing technique and affordability of CBCT equipment in comparison with alternative medical CTs, the CBCT is commonly used in dental practice.\textsuperscript{30,31} The 2D and 3D images generated from the CBCT are informative and have been used as a prerequisite tool for preoperative quantitative and qualitative analysis of dental implant sites. However, the accuracy of the CBCT for linear measurement and bone density evaluation has been published and debated by many studies.

In this study, the CBCT was used as the preoperative dental implant planning for evaluating the cortical bone thickness and bone density of dental implant sites. The corresponding areas from maxilla and mandible bone specimens were harvested and analyzed for their correlation of the variables with micro-CT and histology analysis. The result indicated that CBCT demonstrated high accuracy in linear measurement for cortical thickness evaluation. While bone density from CBCT could not demonstrate any correlation with the micro-CT and histologic section which indicated that CBCT is not reliable to reveal the actual bone density.

The linear measurement of the distance is commonly performed in presurgical implant planning to determine the dimension of the alveolar bone and the nearby vital structures. Many studies

<table>
<thead>
<tr>
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<th>UA (n = 12)</th>
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<th>LA (n = 10)</th>
<th>LP (n = 21)</th>
<th>P</th>
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<tr>
<td>CBCT</td>
<td></td>
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<tr>
<td>Cortical gray value</td>
<td>714.2 ± 35.40</td>
<td>710.6 ± 116.30</td>
<td>749.4 ± 68.59</td>
<td>732.6 ± 109.60</td>
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<td>Trabecular gray value</td>
<td>418.7 ± 28.91</td>
<td>433.3 ± 119.53</td>
<td>475.6 ± 69.96</td>
<td>446.7 ± 97.92</td>
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<tr>
<td>Total gray value</td>
<td>567.2 ± 33.00</td>
<td>571.16 ± 116.72</td>
<td>610.92 ± 67.11</td>
<td>587.12 ± 103.38</td>
<td>0.648</td>
</tr>
<tr>
<td>Micro-CT</td>
<td></td>
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</tr>
<tr>
<td>BV/TV</td>
<td>35.23 ± 10.68*</td>
<td>36.11 ± 9.15*</td>
<td>63.25 ± 19.85*</td>
<td>46.74 ± 13.14*</td>
<td>-0.01</td>
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<tr>
<td>BMD (mg/ccm)</td>
<td>356.72 ± 157.07</td>
<td>341.46 ± 140.50*</td>
<td>521.18 ± 210.70*</td>
<td>480.76 ± 186.21</td>
<td>0.047</td>
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<tr>
<td>Poorest (%)</td>
<td>64.76 ± 10.68*</td>
<td>63.89 ± 9.15*</td>
<td>45.83 ± 13.59*</td>
<td>53.26 ± 13.14</td>
<td>-0.001</td>
</tr>
<tr>
<td>Histology</td>
<td>44.55 ± 9.98</td>
<td>40.51 ± 11.54*</td>
<td>55.62 ± 9.97*</td>
<td>51.61 ± 13.87*</td>
<td>0.01, 0.025</td>
</tr>
</tbody>
</table>

BV/TV, bone volumetric fractions; BMD, bone mineral density; CBCT, cone beam computed tomography; CT, computed tomography; MM, mineralized material; UA, upper anterior; UP, upper posterior; LA, lower anterior; LP, lower posterior.

*Statistically significant as indicated in P values.

FIGURE 5. The gray values (cortical, trabecular, and total) from different locations of the jaw bone.
confirmed the accuracy of the CBCT for linear measurement compared with a 2D lateral cephalometry,\(^2\) medical CT,\(^{33,35}\) micro-CT,\(^{36,37}\) and actual specimen.\(^{38,39}\) The mean difference of the CBCT to the actual specimen varied from \(-0.01\) to 0.27 mm.\(^{37,39,40}\) In this study, the micro-CT was used as a standard reference to assess the accuracy of the linear measurement on the cortical thickness of alveolar bone specimens, and the mean difference was 0.08 ± 0.04 mm which was comparable to previous studies. The data also supports a high positive correlation between the linear measurement of the distance assessed by the CBCT and by the Micro-CT (\(r = 0.933\)). The factors that may affect the accuracy include the gray value range,\(^{41}\) low contrast resolution,\(^{42}\) and error in the algorithm or change in the wobble pattern over time.\(^{43}\) Regarding the present study and previous reports, there was a high accuracy in the CBCT image for linear distance measurement and therefore it could be used for preoperative implant planning.

Concerning the bone density information, while previous studies have confirmed the reliability of the gray values from CBCT data for evaluating bone density,\(^{44}\) the validity of gray values from the CBCT for bone density determination is still controversial. Parsa et al\(^{45}\) analyzed accuracy of CBCT in evaluating trabecular bone density in human cadavers jaw compared with the microstructure analysis using micro-CT and MSCT. They reported the strong correlation between CBCT, MSCT, and micro-CT for bone density evaluation at implant sites. Gonzalez-Garcia and Monje\(^{46}\) studied the reliability of CBCT to determine bone density of the dental implant site in the maxillary bone and presented the strong positive correlation of bone density assessed by CBCT and micro-CT. On the contrary, Corpas Ldos et al\(^{47}\) assessed the correlation of peri-implant bone tissue density utilizing CBCT and histologic images in 80 peri-implant sites in a minipig model. The results of their study showed that the CBCT was not found to be reliable for bone density measurement compared with histologic analysis (\(r = 0.28\)). Livada\(^{48}\) assessed bone density at the implant sites by 4 types of measurements (clinical, CBCT, histological, and tomographical) from 23 implant sites. The results indicated that there was no association between clinical, radiological histological, and micro-CT data of bone density. In agreement with the present study, gray values measured by the CBCT has low validity and did not show any correlation with the histomorphometric bone parameters measured by micro-CT and histology analysis. It should be taken into consideration that the CBCT machines do not utilize a standardized system to scale the gray values which representing density values. Consequently, it is difficult to interpret the gray values or to compare the values resulting from different CBCT machines.\(^{49}\) So the CBCT should not be used for determining bone quality.\(^{48}\) According to this finding, utilizing data from a CBCT as the tool for evaluation of bone density should be done with caution.

The inaccuracy of gray values from a CBCT may be due to various factors. The location of the tissue being scanned affected in different gray level values despite having same density due to the effect of an image value of a voxel of a tissue depends on the position in the image volume.\(^{50}\) The CBCT’s gray values also were influenced by the machine and scanning setting,\(^{51}\) and are very sensitive to movement due to its high spatial resolution. In addition, the CBCT image quality may be affected by artifacts from nearby high-density structures such as metal pontoon, crown or implants.\(^{51}\)

A recent study has been reported concerning the correlation between the cortical bone thickness and bone density. Thiele et al\(^{52}\) evaluated the factors affecting the stability of screws in osteoporotic bone using 18 femora from cadavers. Their results indicated a minor but significant correlation between cortical thickness and trabecular BMD (\(r = 0.537, P < 0.005\)). The present study demonstrated a strong correlation between the cortical bone thickness and bone density variables represented either by micro-CT or by histologic analysis. To our knowledge, no previous study regarding the relationship between cortical thickness and bone density at the dental implant site has been performed. These high correlations between the cortical thickness and bone density variable may afford the clinician to estimate the intraoperative bone density during the implant placement from the preoperative CBCT information.

The design of this present study inherently increased the possibility of identifying the actual human bone density by collecting adequate bone samples from every region of maxilla and mandible which including all bone quality types. In addition, the surgical guide with the radiopaque marker was applied and check for the fitting in both the CBCT and during the surgical bone harvesting procedures and single examiner performed the measurement of all parameters to minimize the error associated with sample identification.

In conclusion, a CBCT is highly accurate in linear measurement of distance. However, the gray values from a CBCT could not demonstrate the actual bone density at dental implant sites according to low correlation to bone density variables measured from micro-CT and histologic analysis.

Cortical bone thickness demonstrates a strong correlation to BV/TV, porosity, and BMD measured by a micro-CT and MM assessed by histologic analysis at the dental implant site. This parameter could be utilized as the preoperative prediction for bone quality at the implant installation site. Further study should be performed to evaluate the correlation of the cortical thickness at dental implant site as the indicator for bone quality and the long-term success of dental implant.

### REFERENCES
