The reliability of cone-beam computed tomography to assess bone density at dental implant recipient sites: a histomorphometric analysis by micro-CT

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Key words: bone volumetric fraction, CBCT, cone-beam CT, density values, dental implants, histomorphometry, micro-CT, radiographic bone density

Abstract

Objectives: The aim of this study was to objectively assess the reliability of the cone-beam computed tomography (CBCT) as a tool to pre-operatively determine radiographic bone density (RBD) by the density values provided by the system, analyzing its relationship with histomorphometric bone density expressed as bone volumetric fraction (BV/TV) assessed by micro-CT of bone biopsies at the site of insertion of dental implants in the maxillary bones.

Material and methods: Thirty-nine bone biopsies of the maxillary bones at the sites of 39 dental implants from 31 edentulous healthy patients were analyzed. The NobelGuide™ software was used for implant planning, which also allowed fabrication of individual stereolithographic surgical guides. The analysis of CBCT images allowed pre-operative determination of mean density values of implant recipient sites along the major axis of the planned implants (axial RBD). Stereolithographic surgical guides were used to guide implant insertion and also to extract cylindrical bone biopsies from the core of the exact implant site. Further analysis of several osseous micro-structural variables including BV/TV was performed by micro-CT of the extracted bone biopsies.

Results: Mean axial RBD was 478 ± 212 (range: 144–953). A statistically significant difference (P = 0.02) was observed among density values of the cortical bone of the upper maxilla and mandible. A high positive Pearson’s correlation coefficient (r = 0.858, P < 0.001) was observed between RBD and BV/TV, with the regression equations: (1) Axial RBD = 19.974 + 10.238 · BV/TV; (2) BV/TV = 14.258 + 0.72 · Axial RBD. RBD was also positively correlated with the trabecular thickness (Tb.Th) and trabecular number (Tb.N), but negatively correlated with trabecular separation (Tb.Sp), structural model index, and inverse connectivity (Tb.Pf). Density values upper than 450 were associated with BV/TV upper than 50%, mean Tb.Th upper than 0.2 mm, mean Tb.Sp lower than 0.3 mm, and mean Tb.N upper than 2.

Conclusion: RBD assessed by CBCT has a strong positive correlation with BV/TV assessed by micro-CT at the site of dental implants in the maxillary bones. Pre-operative estimation of density values by CBCT is a reliable tool to objectively determine bone density.

Several authors have studied the relationship between bone density and dental implants survival rate. Misch [1988] observed that those areas of the maxillary bones with similar bone density showed almost equal implant survival rates, and suggested that bone density was more related with the implant survival than the site occupied by implants in the maxillary bones. Based on the subjective classification of bone density by Lekholm & Zarb [1985], Engquist et al. [1988] observed that 78% of all dental implant failures occurred within soft bone, similar to Friberg et al. [1991] who observed 66% failure rate in soft maxillary bones with severe atrophy. Also, Jaffin & Berman [1991] demonstrated a 35% failure rate for dental implants placed in any region of the maxillary bones with poor bone density.

The advent of new radio-diagnostic technologies in the maxillofacial area allows the clinician to objectively quantify the density...
of the bone in which dental implants are inserted and also provides a progressive implementation of the available information concerning the placement of dental implants. Computerized tomography (CT) scan is mandatory in many situations for the adequate insertion of dental implants (Yahima et al. 2006). Together with this desirable diagnostic accuracy, transfer of the information obtained by pre-operative planning of dental implants to the patient by computed-aided manufacturing (CAM) of anatomic models, and also by the use of surgical guides based on computer-aided design (CAD) have allowed more accurate treatments (Klein & Abrams 2001; Choi et al. 2002; Almog et al. 2006).

The usefulness of medical CT-scan to objectively evaluate radiographic bone density (RBD) has been previously reported. However, both high radiation administered to the patient and expensiveness may limit its use in selected patients in dental implantology. Cone-beam CT (CBCT) scan offers some interesting advantages over medical CT-scan, such as lower radiation and cost (De Vos et al. 2009, Scarfe et al. 2010, Behneke et al. 2011), although its reliability to objectively assess the density of maxillary bones has not been properly studied in human clinics. Micro-CT has become the “gold-standard” for evaluation of bone morphology and micro-structure in the murine model ex vivo. It uses data from attenuated X-ray projections in multiple angles to reconstruct a 3D representation of the model which characterizes the spatial distribution of the material density. It allows the study of structures of a few micrometers such as bone trabecules (Martin-Badosa et al. 2003). Architectural metric parameters such as bone volume (BV), tisular or total volume (TV), and bone surface can be directly determined from the 3D images without assuming the geometric model, in contrast to classic histomorphometry (Sukovic 2003).

The purpose of the present study was to analyze the relationship between RBD assessed by the density values obtained by CBCT and the histomorphometric micro-structure of the maxillary bones at the site of dental implants assessed by micro-CT. This relationship may determine the accuracy of CBCT as a reliable tool to pre-operatively assess bone density and also to determine the best sites for dental implant insertion.

Material and methods

The present research has been conducted in full accordance with ethical principles, including the World Medical Association Declaration of Helsinki. The study was independently reviewed and approved by the local ethical committee of the University Hospital Infanta Cristina (Badajoz, Spain). Written consent of each subject was also obtained. Inclusion criteria were: (1) patients older than 18 years without personal history of serious diseases and non-smoking habit, presenting an edentulous upper maxilla and/or mandible subsidiary to implant rehabilitation; (2) presence of bone adequate in width and height for the primary insertion of 4 × 13 mm dental implants at the analyzed implant site, without needing pre-implant bone grafting; (3) written consent by the patient to be included in a clinical and photographic study protocol. Exclusion criteria were: (1) presence of local or systemic infectious diseases at the moment of implant insertion; (2) osseous systemic pathology such as osteoporosis or osteopenia; (3) renal disease, oncologic disease or disturbance of the calcium metabolism; (4) local benign or malignant disease of the maxillary bones; (5) traumatisms or surgical procedures on the maxillary bones; (6) previous pre-implant or pre-prosthetic surgery; (7) previous or active intake of bisphosphonates; (8) previous administration of radiotherapy in the head and neck.

Thirty-one patients were included in the study. Thirty-nine of 52 bone biopsies from the sites of implant placement were finally analyzed. Mean age was 51.56 ± 13.78 years old (range: 20–79) for the whole series, with a 4:5 male : female distribution. Distribution according to age range was (1) 18–25 years old: 8.82%; (2) 26–50 years old: 35.29%; (3) 51–75 years old: 50%; and (4) >75 years old: 5.88%. Most patients were included in the group between 26 and 75 years (85.29%). Twenty-six of 39 [66%] implants were placed in the upper maxilla, whereas 13 [33%] were inserted in the mandible.

Images from the maxillary bones of the patients were acquired by the CBCT i-CAT® Model 17–19 (Imaging Sciences International LLC, Hatfield, PA, USA). Images were obtained in DICOM format and exported to the software for pre-operative implant planning NobelGuide™ (Nobel Biocare AB®, Goteborg, Sweden) (Fig. 1). To study the relationship between the axial RBD and the micro-structural properties of the in vivo maxillary bones at the recipient site of insertion of dental implants, it was necessary that the analyzed volume of interest (VOI) in CBCT corresponded exactly to the extracted bone biopsies in diameter and length. At each analyzed implant recipient site, mean axial RBD was calculated from the measurement of five equidistant 2-mm diameter spheres along the main axis of the planned implant by the use of a specific tool for measurement of density values supported by the software. This “core” for measurement was equal in length and width than the cylinder of bone obtained by the 2.0 trephine at the surgical field. Also, mean density values from the cortical and medullar bone (paraxial cortical RBD and paraxial medullar RBD) were calculated at the planned implant recipient sites.

From the CBCT images with the planned implants, a CAD/CAM stereolithic surgical guide was specifically fabricated for each patient. This mucosal-supported guide was anchored to the upper maxilla or the mandible with three 1.5-mm diameter anchor pins. Once anchored, for each of the analyzed implants, a 2-mm diameter trephine was first introduced through the specific hole of the stereolithographic surgical guide to obtain a bone biopsy cylinder. Later, a guided 3.2-mm diameter spiral drill (Guided Twist Drill 3.2; Nobel Biocare AB, Goteborg, Sweden) was introduced 13-mm deep at 3.784 g. After all, regular platform self-screw Nobel Speedy™ Groovy (Nobel Biocare AB®, Goteborg, Sweden) 4 × 13 mm implants were inserted and the surgical guide removed.

Selected bone biopsies were preserved at −20°C and scanned with the high resolution Micro-CT SkyScan1172® (SkyScan NV®, Aartselaar, Belgium) in a 100 KeV voltage and 100 µA. Time exposition was 450 ms. Images from the scanning of biopsies were reconstructed by the software Nrecon® (Sky-Scan NV®) to obtain 2D and 3D images [Fig. 2]. The analyzed histomorphometric variables have been previously described in the literature [Hildebrand & Rüegsegger 1997; Odgaard 1997]: (1) BV, (2) TV, (3) bone volumetric fraction [BV/TV], which is the result of dividing BV and TV; BV/TV was in our study the main variable to compare with RBD; (4) trabecular thickness [Tb.Th], mean thickness of the trabecules in the VOI [in mm]; [5] trabecular separation [Tb.Sp], mean separation of the trabecules in the VOI [in mm]; [6] trabecular number [Tb.N], number of trabecules that crosses a particular one per unit of length across the VOI; (7) trabecular pattern factor [Tb.Pf], which is an inverse connectivity index: the higher the it is trabecules are less connected; (8) structural model index [SMI], which gives information about preponderance of trabecular morphology [0 is an ideal plate, whereas 3 is an ideal cylinder] [Hildebrand & Rüegsegger 1997]; (9) degree of anisotropy (DA), which is the presence or
absence of aligned trabecules in a particular
direction (1 is considered isotropic, >1 is con-
sidered anisotropic), and (10) fractal dimen-
sion (FD), which indicates the complexity of
the specimen surface.

**Statistical analysis**

Statistical analysis was performed by the soft-
ware SPSS 15.0 [SPSS Inc., Chicago, IL, USA].
Chi-square test was used for the analysis of
qualitative variables. Relation between
qualitative and quantitative variables was
studied by the Student’s t-test. To study the
relationship between quantitative variables,
the Pearson’s correlation was used. When
available the pertinent regression equations
were obtained for these quantitative variables.

**Results**

Mean axial RBD was 478 ± 213 (range: 144–
953). Mean cortical paraxial RBD was
609 ± 218 (range: 300–1071). Mean medular
paraxial RBD was 411 ± 211 (range: 13–958).
A positive correlation was observed between
cortical axial RBD and medular axial RBD
(r = 0.702, P < 0.001). The regression
equation (1) was obtained:

\[
\text{Cortical paraxial RBD} = 311.059 + 0.724 \cdot \text{Medular paraxial RBD.} 
\]  

Mean RBD values for the upper maxilla vs.
the mandible with respect to the axial RBD,
cortical paraxial RBD, and medular paraxial

Fig. 1. (a) Analysis of mean radiographic bone density (RBD) value along the major axis of the planned implant corresponding to bone biopsy no. 16. [b] Measurement of paraxial cortical and paraxial medular RBD of bone biopsy no. 25. (c) Measurement of axial RBD at the planned implant site corresponding to bone biopsy 33.

Fig. 2. (a) Micro-computed tomography (CT). 2D Sagittal view of bone biopsy no. 24 by micro-CT. (b) Micro-CT. 2D coronal view of bone biopsy no. 33 by micro-CT. (c) Micro-CT. 3D reconstruction of bone biopsy no. 50.
RBD were: 483 vs. 469 (P = 0.861), 554 vs. 718 (P = 0.02); and 373 vs. 486 (P = 0.11), respectively (Table 1). The analysis of the variance (ANOVA) test was used to compare mean density values among groups. No statistically significant differences among groups were observed for variables: axial RBD (P = 0.395) and medular paraxial RBD (P = 0.275). In relation to the variable cortical paraxial RBD, a statistically significant difference (P = 0.025) was observed between groups 2 (posterior upper maxilla) and 3 (anterior mandible). A Student’s t-test for independent variables was used to analyze if there was any difference between groups 1 + 2 (upper maxilla) and 3 + 4 (mandible). A statistically significant difference (P = 0.02) was observed for the variable cortical paraxial RBD between the upper maxilla and the mandible. No differences in terms of RBD were observed between the upper maxilla and the mandible for variables axial RBD and medular paraxial RBD.

Mean values for each analyzed variable in relation to micro-structural properties are shown in Table 2. Values for the whole series are displayed in Table 3. Tb.Th was positively correlated with axial RBD (r = 0.574, P < 0.001) and BV/TV (r = 0.711, P < 0.001). Tb.Sp was negatively correlated with axial RBD (r = -0.684, P < 0.001), BV/TV (r = -0.846, P < 0.001), Tb.Th (r = -0.379, P = 0.017), Tb.N (r = -0.773, P < 0.001), and FD (r = -0.566, P < 0.001). Tb.N was positively correlated with axial RBD (r = 0.511, P < 0.001), BV/TV (r = 0.601, P < 0.001), and FD (r = 0.830, P < 0.001). As an index showing inverse connectivity, Tb.Pf was higher as the trabecules were less connected and showed a negative correlation with axial RBD (r = -0.7, P < 0.001), BV/TV (r = -0.801, P < 0.001), Tb.N (r = -0.827, P < 0.001), and FD (r = -0.68, P < 0.001). SMI was negatively correlated with axial RBD (r = -0.704, P < 0.001), BV/TV (r = -0.706, P < 0.001), Tb.N (r = -0.735, P < 0.001), and FD (r = -0.557, P < 0.001). FD and DA did not show any correlation neither with any of the micro-structural variables analyzed by micro-CT nor with axial RBD analyzed by CBCT (Table 4).

Figure 3 shows direct relationship between axial RBD and BV/TV. A high positive Pearson’s correlation coefficient (r = 0.858, P < 0.001) was observed between these two main variables. The regression equations (2) and (3) were obtained:

### Table 1. Means and SD of variables: axial radiographic bone density (RBD), cortical paraxial RBD and medular paraxial RBD, categorized by groups

<table>
<thead>
<tr>
<th>Group</th>
<th>Group 2 (n = 11)</th>
<th>Group 3 (n = 6)</th>
<th>Group 4 (n = 7)</th>
<th>Total (n = 39)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial RBD</td>
<td>445.2 ± 205.1</td>
<td>483.7 ± 223.9</td>
<td>466.6 ± 211.8</td>
<td>472.9 ± 212.0</td>
</tr>
<tr>
<td>Cortical paraxial RBD</td>
<td>628.0 ± 164.4</td>
<td>753.4 ± 209.6</td>
<td>688.5 ± 223.9</td>
<td>688.5 ± 212.9</td>
</tr>
<tr>
<td>Medular paraxial RBD</td>
<td>408.2 ± 183.2</td>
<td>443.1 ± 261.5</td>
<td>524.3 ± 169.5</td>
<td>411.3 ± 211.1</td>
</tr>
</tbody>
</table>

### ANOVA: Axial RBD

<table>
<thead>
<tr>
<th>Sum of squares</th>
<th>Degrees of freedom</th>
<th>Mean quadratic</th>
<th>F</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inter-groups</td>
<td>1,389,755.12</td>
<td>3</td>
<td>46,191.714</td>
<td>1.021</td>
</tr>
<tr>
<td>Intra-groups</td>
<td>1,584,007.393</td>
<td>35</td>
<td>45,257.354</td>
<td>0.395</td>
</tr>
<tr>
<td>Total</td>
<td>1,592,754.513</td>
<td>38</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### ANOVA: Medular paraxial RBD

<table>
<thead>
<tr>
<th>Sum of squares</th>
<th>Degrees of freedom</th>
<th>Mean quadratic</th>
<th>F</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inter-groups</td>
<td>175,103.57</td>
<td>3</td>
<td>58,367.685</td>
<td>1.346</td>
</tr>
<tr>
<td>Intra-groups</td>
<td>1,517,538.420</td>
<td>35</td>
<td>43,358.241</td>
<td>0.275</td>
</tr>
<tr>
<td>Total</td>
<td>1,692,641.990</td>
<td>38</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### ANOVA: Cortical paraxial RBD

<table>
<thead>
<tr>
<th>Sum of squares</th>
<th>Degrees of freedom</th>
<th>Mean quadratic</th>
<th>F</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inter-groups</td>
<td>440,183.414</td>
<td>3</td>
<td>146,727.805</td>
<td>3.766</td>
</tr>
<tr>
<td>Intra-groups</td>
<td>1,363,592.770</td>
<td>35</td>
<td>38,959.793</td>
<td>0.019</td>
</tr>
<tr>
<td>Total</td>
<td>1,803,776.184</td>
<td>38</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Multiple comparisons

**Variable dependiente: cortical paraxial RBD**

<table>
<thead>
<tr>
<th>(I) Group</th>
<th>(J) Group</th>
<th>Difference between means (I-J)</th>
<th>Typical error</th>
<th>Significance</th>
<th>95% Confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>174.3788</td>
<td>78.3525</td>
<td>0.136</td>
<td>-36.930, 385.688</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>-60.4952</td>
<td>90.3493</td>
<td>0.908</td>
<td>304.159, 183.168</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>-174.3788</td>
<td>78.3525</td>
<td>0.136</td>
<td>-385.688, 36.930</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>-299.6955 (†)</td>
<td>100.1753</td>
<td>0.025*</td>
<td>-569.859, -29.532</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>125.3167</td>
<td>95.4331</td>
<td>0.084</td>
<td>-492.248, 22.500</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>-234.8740</td>
<td>109.8134</td>
<td>0.934</td>
<td>-231.335, 360.978</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>60.4952</td>
<td>90.3493</td>
<td>0.908</td>
<td>-183.168, 304.159</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>234.8740</td>
<td>95.4331</td>
<td>0.084</td>
<td>-22.500, 492.248</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>-64.8214</td>
<td>109.8134</td>
<td>0.934</td>
<td>-360.978, 231.335</td>
</tr>
</tbody>
</table>

Group 1: anterior upper maxilla; group 2: posterior upper maxilla; group 3: anterior mandible; group 4: posterior mandible. The analysis of the variance (ANOVA) test was used to compare means between groups. No statistically significant differences between groups were observed for variables: axial RBD (P = 0.395) and medular paraxial RBD (P = 0.275). In relation to variable cortical paraxial RBD, a statistically significant difference (P = 0.025) was observed between groups 2 (posterior upper maxilla) and 3 (anterior mandible). Difference between means is significant at P = 0.05.
In the present series, 19 of 21 biopsies (90.47\%) that presented density values upper than 450 showed BV/TV upper than 50\%. Because of its high discriminative power, 450 was chosen as the threshold density value below which most of the BV/TV values were lower than 50\%, and over which most of the BV/TV values were upper than 50\%. As presented previously, axial RBD was positively correlated with TbTh, Tb.N, and FD, while negatively correlated with Tb.Sp, SMI, and Tb.Pf (Table 4). By introducing a density value of 500 in the regression equation [3] (independent variable: Axial RBD), resultant estimated BV/TV was also upper than 50\%.

Thus, globally considered RBD upper than 450 was associated with BV/TV upper than 50\%, Tb.Th upper than 0.2 mm, Tb.Sp lower than 0.3 mm and Tb.N upper than 2. These correlations could be mathematically expressed and provided a reliable approach to the microstructure of the maxillary bones from the pre-operative density value estimations by CBCT. The regression equations [4], [5], [6], [7], and [8] were obtained:

\[
\text{Tb.Th} = 0.134 + 0.00019 \cdot \text{Axial RBD}. \quad (4)
\]

\[
\text{Tb.Sp} = 0.468 - 0.00033 \cdot \text{Axial RBD}. \quad (5)
\]

\[
\text{Tb.N} = 1.234 + 0.002 \cdot \text{Axial RBD}. \quad (6)
\]

\[
\text{SMI} = 3.18 - 0.006 - \text{Axial RBD}. \quad (7)
\]
These regression equations led us to estimate values of micro-structural variables of the analyzed bone from given density values by CBCT. For instance, for a given mean density value of 200 by CBCT corresponding to soft bone, we could expect to observe a bone with a BV/TV of approximately 28%, with Tb.Th and separation of 0.17 and 0.40 mm, respectively, and also Tb.N of 1.63, positive SMI equal to 1.98, and inverse connectivity of 5.41 in the micro-CT analysis. In contrast, for denser bones with a mean density value of 800, we should observe a BV/TV upper than 71%, with a Tb.Th and Tb.Sp of 0.28 and 0.2 mm, respectively, and also Tb.N of 2.83, negative SMI equal to -1.62 and negative inverse connectivity of -9.27 (Table 5).

Discussion

In relation to the emission of radiation, CBCT has a mean absorbed radiation of 12 mSV or 0.62 mGy (Sukovic 2003). This dosage is 25% of that corresponding to a conventional panoramic radiography. In addition, medical CT-scan generates radiation 40–60 times upper than CBCT. In fact, due to the high radiation dosage received by the patient, Sukovic (2003) has questioned the routine use of medical CT-scan for the study of the maxillary bones in implant surgery. Otherwise, CT-scan images are mathematically

$$Tb.Pf = 10.306 - 0.02447 \cdot \text{Axial RBD}.$$  (8)
reconstructed from a limited number of exist-
ing cuts. Thus, small spaces between two con-
secutive cuts are lacking information. They are adjusted by the software algorithm, result-
ing in errors up to 1–1.5 mm. In con-
trast, CBCT avoids these errors by the accu-
mulation of data from a 360° rotation of the X-ray source around the head of the patient. Magnification and distortion are minimal, with error less than 0.1 mm [Hashimoto & Kawashima 2006].

These properties of CBCT allowed us to analyze its reliability to pre-operatively char-
acterize bone density in the site of dental implants instead of using the classical medical CT-scan. In fact, few series are available concerning the study of RBD by CBCT with density values, instead of the well-known Hounsfield units (HU) by medical CT-scan. Recently, Isoda et al. [2011], in an experimen-
tal study with 18 implants inserted into 18 fresh femoral heads of swine, also used den-
sity values provided by CBCT to analyze bone density and its relationship with implant stability. They found a mean density value of 591 [range: 98–902], which is relatively close to mean 478 [range: 144–653] observed in the present series. Discrepancies may be attributable to the difference in the origin of bone in terms of specie and loca-
tion. Otherwise, to our knowledge no previ-
ous studies concerning the relationship between RBD assessed by CBCT and the micro-
structural properties of the maxillary bones assessed by micro-CT have been per-
formed. This fact is more remarkable consid-
ering that all bone biopsies in the present series were extracted from living patients undergoing dental implant rehabilitation. The present results refer to the analyzed type of CBCT and not others, and caution has to be taken while extrapolating results.

Globally considered for the present series, cortical RBD was 150% upper than medular RBD at the implant recipient site in the present series, showing a mean density value of 608 in contrast to 411. Cortical RBD and me-
dular RBD were positively correlated \( (r = 0.702) \) and the mathematical relationship allows us to calculate the value of one variable from a given value of the other variable, as expressed in the Results section. Park et al. [2008], in a study on 63 medical CT-scans of the upper maxilla and mandible, evaluated RBD by HU, showing values in the cortical bone between 810 and 940 HU for the upper maxilla, and between 810 and 1580 HU for the mandible. They concluded that mandibular cortical bone was denser than cortical bone of the upper maxilla, whereas cancellous bone has similar densities in both mandible and the upper maxilla. Similar results have been observed previously [Shapu-
nian et al. 2006; Turkylmaz et al. 2007]. These data, qualitatively considered, are sim-
ilar to those observed in the present series for RBD evaluated by CBCT. In our series, RBD from cortical bone of the mandible was significantly higher than that corresponding to the upper maxilla \( (P = 0.019) \), although this difference was not observed for the can-
cellous bone.

Our data supports a high positive correla-
tion between RBD assessed by CBCT and BV/TV by micro-CT \( (r = 0.858) \). A threshold den-
sity value of 450 was established over which most of the biopsies \( (90.47\%) \) showed BV/TV upper than 50%, and below which most of them \( (83.33\%) \) showed BV/TV lower than 50%. Positive correlation between axial RBD and Tb.Th \( (r = 0.574) \), and negative between axial RBD and Tb.Sp \( (r = -0.654) \) are equally signed than those between BV/TV and Tb.Th \( (r = 0.711) \) and between BV/TV and Tb.Sp \( (r = -0.846) \), which can also be explained by the positive correlation between axial RBD and BV/TV. Tb.Pf and SMI were negatively correlated with RBD \( (r = 0.704, \text{ respectively}) \), as it was observed between BV/TV and Tb.Pf \( (r = -0.801) \) and between BV/TV and SMI \( (r = -0.706) \), which can also be explained by the high correlation between RBD and BV/TV. Most of the biopsies \( (89.95\%) \) with mean density values upper than 450 presented negative Tb.Pf values, corre-
sponding to denser maxillary bones, as Tb.Pf is considered an inverse connectivity factor.

Regression equations reported in the results section allows the clinician to pre-
operatively estimate the micro-structure of the maxillary bones from a particular mean density value assessed by CBCT at the implant recipient site. Several items such as Tb.Th and separation (Tb.Sp) or, for instance, the number of times that a trabecule is crossed by others per unit of length (Tb.N), as well as the preponderance of trabecular morphology could be estimated from the mean density value of a particular region of interest with CBCT. These equations are based on a limited number of cases and thus have some limitations. However, they are the first reported approach to obtain a general view of the osseous micro-structure even prior to the micro-CT analysis of bone speci-
men. Future studies with larger series may provide more acute mathematical expressions that highlight the relationship between RBD and the micro-structural properties of maxillary bones. Even, whether the density values obtained by the CBCT device used in the present study could be extrapolated to other devices requires further analyses.

The reliability of stereolithographic surgi-
cal guides from CBCT images to transfer the information of the planned treatment has been shown [Nickenberg & Eitner 2007]. A discrep-
ancy from 0.2 mm to 1.45 mm in translation and from \( 1^\circ \) to \( 7.25^\circ \) in rotation between the planned implant and the inserted implant has been reported among series [Fortin et al. 2002; Di Giacomo et al. 2005]. These differences are considered quite acceptable among authors. This previous con-
dition led us to establish a safe methodology: [1] to accurately insert the implant at the planned implant recipient site; and [2] to obtain a 2-mm-width cylindrical bone biopsy from the core of the planned implant site with a high precision; and consequently [3] to compare mean density values from CBCT with the micro-structure of the bone by micro-CT at the site of dental implants.

Otherwise, the accuracy of micro-CT to properly analyze the micro-structure of the bone has been assessed by direct comparison with conventional histomorphometry, show-
ing a correlation upper than 0.7 [Kuhn et al. 1990; Müller et al. 1996; Fajardo et al. 2009], although several advantages for the first have been reported: [1] direct measurements of 3D trabecular morphology without interferences of stereologic 2D models [Hildebrand & Rüegsegger 1997]; [2] the volume of the ana-

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### Table 5. Estimated values for all micro-structural variables of micro-computed tomography from different given values of radiographic bone density (RBD) using the obtained regression equations (3), (4), (5), (6), (7) and (8) reported in the results section.

<table>
<thead>
<tr>
<th>Variable</th>
<th>0</th>
<th>200</th>
<th>400</th>
<th>600</th>
<th>800</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>BV/TV (%)</td>
<td>14.2</td>
<td>28.65</td>
<td>43.05</td>
<td>57.45</td>
<td>71.85</td>
<td>86.25</td>
</tr>
<tr>
<td>Tb.Th (mm)</td>
<td>0.13</td>
<td>0.17</td>
<td>0.21</td>
<td>0.24</td>
<td>0.28</td>
<td>0.32</td>
</tr>
<tr>
<td>Tb.Sp (mm)</td>
<td>0.46</td>
<td>0.40</td>
<td>0.33</td>
<td>0.27</td>
<td>0.20</td>
<td>0.13</td>
</tr>
<tr>
<td>Tb.N</td>
<td>1.23</td>
<td>1.63</td>
<td>2.03</td>
<td>2.43</td>
<td>2.83</td>
<td>3.23</td>
</tr>
<tr>
<td>SMI</td>
<td>3.18</td>
<td>1.98</td>
<td>0.78</td>
<td>-0.42</td>
<td>-1.62</td>
<td>-2.82</td>
</tr>
<tr>
<td>Tb.Pf</td>
<td>10.30</td>
<td>5.41</td>
<td>0.51</td>
<td>-4.37</td>
<td>-9.27</td>
<td>-14.16</td>
</tr>
</tbody>
</table>

| BV/TV, bone volumetric fraction; Tb.Th, trabecular thickness; Tb.Sp, trabecular separation; Tb.N, trabecular number; Tb.Pf, trabecular pattern factor; SMI, structural model index. |
lyzed material is higher; [3] analyses are faster as no decalcification is needed; [4] the technique is non-destructive and biopsies can be used in further analyses or mechanic tests; and [5] mineralization of bone can be estimated by the comparison of X-ray attenuation with that for hydroxyapatite [Fajardo et al. 2009]. Although it was not the main objective of the present study, preservation of the integrity of bone biopsies by micro-CT allowed further study of the same specimens by conventional histomorphometric analysis. Correlation of micro-CT and conventional histomorphometry for the present series of maxillary bone biopsies will be subject of a future specific work.

Conclusions

Radiographic bone density assessed by the presented Cone-beam CT [CBCT] has a high positive correlation with BV/TV assessed by micro-CT at the recipient site of dental implants within the maxillary bones. This tool allows the clinician to pre-surgically determine which areas of the maxillary bones correspond to the osseous micro-structure with highest density, by measuring RBD, and so to know which areas would better suit the placement of dental implants. The present study provides a prior approach to the micro-structure features of healthy maxillary in humans, but more clinical studies are necessary to validate the usefulness of density values obtained by this type of CBCT and others for determining bone density within the maxillary bones prior to dental implant insertion.

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Conflict of interests

None.

References


