Conventional Multi-Slice Computed Tomography (CT) and Cone-Beam CT (CBCT) for Computer-Assisted Implant Placement. Part I: Relationship of Radiographic Gray Density and Implant Stability

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ABSTRACT

Purpose: The relationship of conventional multi-slice computed tomography (CT)- and cone beam CT (CBCT)-based gray density values and the primary stability parameters of implants that were placed by stereolithographic surgical guides were analyzed in this study.

Materials and Methods: Eighteen edentulous jaws were randomly scanned by a CT (CT group) or a CBCT scanner (CBCT group) and radiographic gray density was measured from the planned implants. A total of 108 implants were placed, and primary stability parameters were measured by insertion torque value (ITV) and resonance frequency analysis (RFA). Radiographic and subjective bone quality classification (BQC) was also classified. Results were analyzed by correlation tests and multiple regressions ($p < .05$).

Results: CBCT-based gray density values (765 ± 97.32 voxel value) outside the implants were significantly higher than those of CT-based values (668.4 ± 110 Hounsfield unit, $p < .001$). Significant relations were found among the gray density values outside the implants, ITV (adjusted $r^2 = 0.6142$, $p = .001$ and adjusted $r^2 = 0.5166$, $p = .0021$), and RFA (adjusted $r^2 = 0.5642$, $p = .0017$ and adjusted $r^2 = 0.5423$, $p = .0031$ for CT and CBCT groups, respectively). Data from radiographic and subjective BQC were also in agreement.

Conclusions: Similar to the gray density values of CT, that of CBCT could also be predictive for the subjective BQC and primary implant stability. Results should be confirmed on different CBCT scanners.

KEY WORDS: computed tomography, cone beam, dental implants, gray density, implant stability, stereolithography

INTRODUCTION

Rapid advances in diagnostic imaging and computer-aided treatment planning had a major impact on implant dentistry. By the implementation of the three-dimensional tomographic data to a dedicated computer software, the clinician may thoroughly analyze and plan a "virtual implant surgery," which can then be transferred to patients' mouth via a stereolithographic (SLA) surgical guide.[1] Structural characteristics of the recipient alveolar bone can also be assessed on the cross-sectional tomographic images prior to the surgery, and this may not only help to refrain the compromised zones but also assist clinician in deciding to employ standard or modified surgical techniques to sustain the primary stability – a critical perquisite for the osseointegration – upon implant insertion.[2,3] The attainment of this stability is related to the frictional resistance between screw threads of the implant body

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and the osteotomy walls, which is quantified on the basis of rotational moment force called insertion torque value (ITV).[4] Alternatively, the noninvasive, reproducible, resonance frequency analysis (RFA) can be utilized for objective quantification of the implant stability,[5] which could also be used as an indicator in deciding whether to initiate or delay the loading of implants.[6] Both ITV and RFA were found to be associated with the radiographic bone density as shown by the quantification of the gray density values from the conventional computed tomography (CT) images, which were expressed in Hounsfield unit (HU).[7,8]

As a result of reduced radiation dose and affordability, cone beam CT (CBCT) became widely used for the oral and maxillofacial imaging compared with the CT. The first generation of CBCT devices, which utilize an image-intensifier detector based on the charge coupling device or complementary metal oxide semiconductor technology, was highly sensitive and provided cross-sectional images even with a radiation dose (0.62 mGy)[9] similar that of a panoramic X-ray. The resulting images were sufficient for the visual examination[10,11] but unfortunately included artifacts such as halation[12] or beam hardening effects[13] and were inferior to the CT in terms of the dimensional accuracy and soft tissue depiction.[14] Later, the use of flat-panel detectors in CBCT devices improved the spatial resolution,[15] gray density range, and contrast (dynamic range),[16] as well as the pixel/noise ratio.[17] Dimensional accuracy was also comparable with the CT,[18] and the applicability in SLA guide production was demonstrated.[19] In contrast to the CT, the gray density values of the CBCT images (voxel value [VV]) are not absolute[20] and the relationship between the implant stability parameters is scarce. Being a key determinant for implant success,[21] the prediction of anticipated primary stability prior to the insertion of an implant may serve as a valuable tool in the clinical implant dentistry. The aim in the first part of this study was, therefore, to investigate the relevance of the gray density values of the implant recipient bone areas with the primary stability of corresponding implants that were placed by CT- or CBCT-derived SLA guides. The corroboration of software-rated radiographic (radiographic BQC) and subjective bone quality classification perceived by the surgeon during the implant osteotomy (subjective BQC) was also investigated.

MATERIALS AND METHODS

The study was approved by the Ethical Committee of İstanbul University and conducted in accordance with the Helsinki Declaration of 1975, as revised in 2008. Results from the previous studies were used to determine the sample size[8,22] with the help of a software (nQuery Advisor, Statistical Solutions, Saugus, MA, USA). Using the mean of reported effect sizes: $r = 0.664$, $r = 0.659$, and $r = 0.583$ (for between HU and RFA, HU and ITV, and RFA and ITV, respectively), a minimum of 48 implants per group was calculated to detect a minimum correlation coefficient (r^2) of 0.20 between the gray density value and RFA, gray density value and ITV, and RFA and ITV with a power of 80% at the $\alpha = 0.05$ level. This sample size was also sufficient for the analysis of deviations between the planned and placed implants, which were explored in the second part of this study. A dropout rate of 10% was also accounted. Accordingly, 46 consecutive patients who applied to the Department of Oral Implantology, Faculty of Dentistry, Istanbul University between March 2009 and April 2010 for the treatment of edentulism via implant-supported fixed prosthesis was informed about the study, and written approval was obtained from 39 volunteers. The use of single-type mucosa-supported SLA guides were beneficial in terms of reducing surgery duration, postoperative complications,[23] and deviations between the planned and placed implants[24] and therefore only such type of SLA guides were used. All patients were initially evaluated by panoramic X-ray and oral examination. A bone caliper (Osseometer, Oraltronics, Bremen, Germany) was used to determine the alveolar bone thickness under local infiltrative anesthesia in the canine and molar areas bilaterally. Measurements were taken 2 to 3 mm below the tip of the alveolar crest. Patients exhibiting a bone thickness of ≥5 mm and an attached mucosa width of ≥4 mm were decided as suitable for the flapless implant surgery using mucosa-supported SLA guides.[23] Patients with unhealthy systemic health status, parafunctional habits, poor oral hygiene, insufficient alveolar bone volume, uncontrolled diabetes, current irradiation to head or neck, psychological disorders, or alcohol or tobacco or drug abuse were excluded. Consequently, the patient group was consisted of 11 individuals with 18 edentulous jaws. A radiopaque scan prosthesis that represented the final prosthetic outline was produced using an acrylic and $BaSO_4$ mixture.

Afterwards, referring to a computer-generated randomization list (Quickcalcs, GraphPad Software Inc., San Diego, CA, USA), the patients were randomly assigned to be scanned by a conventional multi-slice CT (CT group) or a CBCT device (CBCT group).

Image Acquisition and Planning of the Implants on the Software

A multi-slice CT device (Siemens Somatom Sensation 64, Siemens AG Medical Solutions, Erlangen, Germany) using the setting of 130 kV, 83 mA, 0.25-mm-slice thickness was used and a daily calibration was performed in order to ensure that the air was defined as −1,000 HU by the CT scanner. A CBCT scanner (Iluma, 3M Imtec Imaging, Ardmore, OK, USA) using a standard setup of 120 kV, 3.8 mA with an exposure time of 40 seconds was used for the imaging of six patients in the CBCT group. The CBCT has a 24.4 × 19.5 cm amorphous-silicon, flat-panel image detector and offers a cylindrical volume of reconstruction up to 21.1 × 14.2 cm with a 14-bit gray density and 0.0936 mm voxel size. In contrast to the CT, the CBCT scanner employs factory-defined gray density attenuation. All acquired data were saved in Digital Imaging and Communications in Medicine (DICOM) format. The DICOM data were processed and a virtual three-dimensional model was reconstructed following the segmentation of bone and the scanning prosthesis by a technician trained in the post-tomographic imaging analysis and segmentation using specific software (Simplant Pro, Materialise Dental, Leuven, Belgium). Any visual or technical consequences were noted. The images were transferred to another computer to be used by the clinicians for planning the final positions of the implants using the same software without segmentation abilities (Simplant Planner, Materialise Dental). A clinician experienced in the computer-aided planning and placement of implants (V.A.) examined the images and planned the final positions of the implants with the help of the axial and sagittal images as well as referring to the three-dimensional model of the jaw bone and the scan prosthesis. A total of 108 implants (64 in the maxilla and 44 in the mandible) were planned according to the following strategy. Because a fixed prosthetic restoration was predicted for all patients, the distribution of implants was spread along the edentulous arch in the anterior-posterior aspect. Nevertheless, the availability of sufficient alveolar bone width and height was less frequent in the posterior aspect especially in the mandible. Thus, the majority of implants was in the anterior jaw region and supported by bilateral single posterior implants. This was done to reduce the occurrence of cantilevers and concomitant stresses. In addition, considering the possible deviations, a safety margin of 1 mm was sustained in the vestibule-palatinal direction in the surrounding alveolar bone. Accordingly, 3.5-mm narrow-diameter implants were also planned in the edentulous spaces showing insufficient bone width for a 4.0-mm standard-diameter implant. All implants were positioned in the best possible position regarding the prosthetic conformity and the recipient alveolar bone. The length of the planned implants varied between 8 and 12 mm. Longer implants were avoided to prevent any possible overheating of the apical bone portion during osteotomy.

TABLE 1 Radiographic Bone Quality Classification (Radiographic BQC) Thresholds of Misch[25] and Lekholm and Zarb[26] (as Reviewed by Norton and Gamble[27]) in Accordance with the HU

	Bone Density according to Misch Classification[25]	Bone Density according to Lekholm and Zarb Classification[26] as Reviewed by Norton and Gamble[27]
D1	>1,250	>850
D2	850–1,250	700–850
D3	350–850	500–700
D4	150–350	0–500
D5	<150	<0

Measurement of Gray Density (HU and VV) Values

The implant planning software (Simplant Planner) allows the quantification of gray density for the recipient bone volume as well as the outer milimetric circumference radius of the planned implant. Referring the implant axis, the gray scale along the 25 axial slices (along the body of the virtual implant that has been defined by the planning software) is averaged and displayed in the “bone density” window. The expressed values are also classified as “D1, D2, D3, D4, and D5” according to the threshold values defined by Misch[25] and Lekholm and Zarb[26] (as revised by Norton and Gamble’s[27] BQC (Table 1). In recognition of the previous similar studies,[27–29] the gray density value of the bone surrounding the planned implant volume was

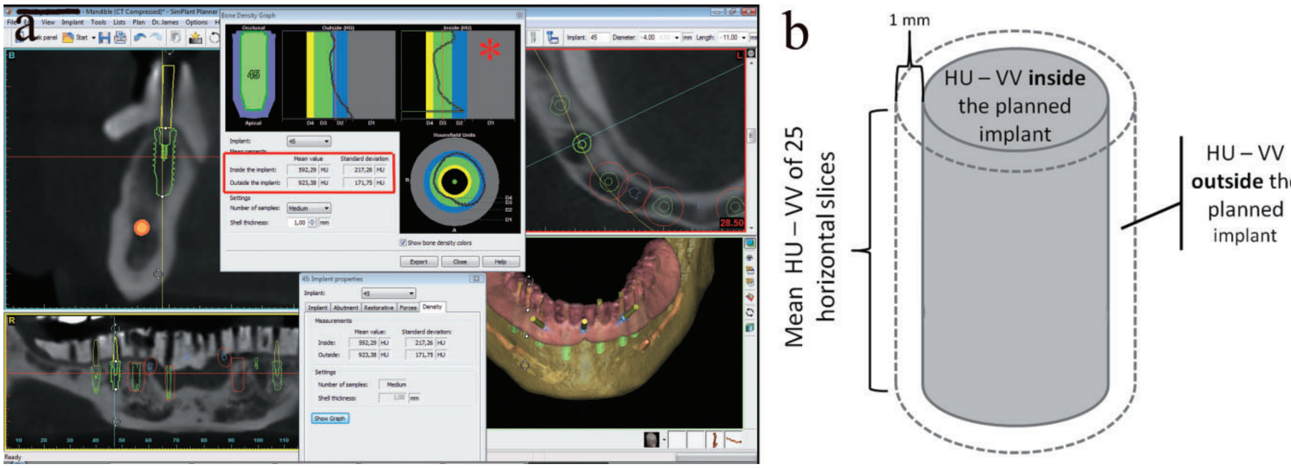

Figure 1 Measurement of gray density values of planned implants in CT (HU) and CBCT groups (VV). *A*, Following the planning of the implants, the "bone density" feature of the software was used to quantify the gray density inside and outside the implant (*red rectangle*). The software also classifies the bone quality according to the measured gray density value inside and outside the implant (*asterisk*). *B*, Schematic description of the gray density measurements inside and outside (1 mm outer shell) of the three-dimensional implant volume.

considered valuable because the bone within the planned implant volume is removed by the osteotomy, and the implant is anchored by being screwed to the surrounding bone. Therefore the quantified gray density values inside and outside the planned implant volume (outer 1-mm circumferential shell) was measured by an independent oral radiologist (H.A.) and expressed as HU and VV in CT and CBCT groups, respectively (Figure 1). Radiographic BQC outside the planned implant volume was also recorded as it was shown to be associated with the subjective BQC.[27] The final positions of the implants were confirmed, and the plan was saved and sent to the production facility (Materialise Dental).

The positions of the placed implants often deviates from the original planning because of technical consequences associated with the SLA template-guided surgery.[24] To ascertain an absolute match of the measured variables, implants yielding deviations outside of the gray density measurement area (implant diameter + 1 mm circumferential zone) were excluded, and the remaining implants were analyzed separately.

Implant Surgery

Surgical step of this study was explained in detail at the second part of this study. Briefly, the guides were seated over the mucosa and fixed with the osteosynthesis screws, and the mucotomy and osteotomy were completed using the special drill kit of the SLA guide manufacturer (SAFE drills, Materialise Dental). Care was taken to prevent overheating of the bone during the osteotomy through the designated holes on the SLA guide. Subjective BQC perceived during drilling (according to Misch)[25] through the holes of the SLA guide was scored by the surgeons (V.A. and C.K.). Following the completion of the osteotomy, the previously planned parallel-walled, self-tapping implants with a narrow tip (SPI Element, Thommen Medical, Waldenburg, Switzerland) were inserted through the guide via a torque-controlled handpiece connected to a torque-limiting surgical motor (Implantmed, W&H, Sazlburg, Austria). Peak torque achieved upon embedding of the implant body in the socket was recorded in newton-centimeters. The guide was removed by unscrewing the osteosynthesis screws and the magnetic transducer (Smartpeg type 21 and 22, Osstell AB, Gothenburg, Sweden) was screwed onto the implants and the RFA values were recorded by the RFA device (Ostell Mentor, Osstell AB) in a wireless manner (Figure 2).

Statistical Analysis

The similarity of the implant dimensions (length and diameter) and the number of implants placed per jaw was analyzed by the *t*-test on statistical software (Graphpad Prism, GraphPad Software, CA, USA). Descriptive statistics consisting of mean, standard deviation, minimum–maximum, and 95% confidence interval was calculated for all measured values. Distribution was not normal in some data sets as determined

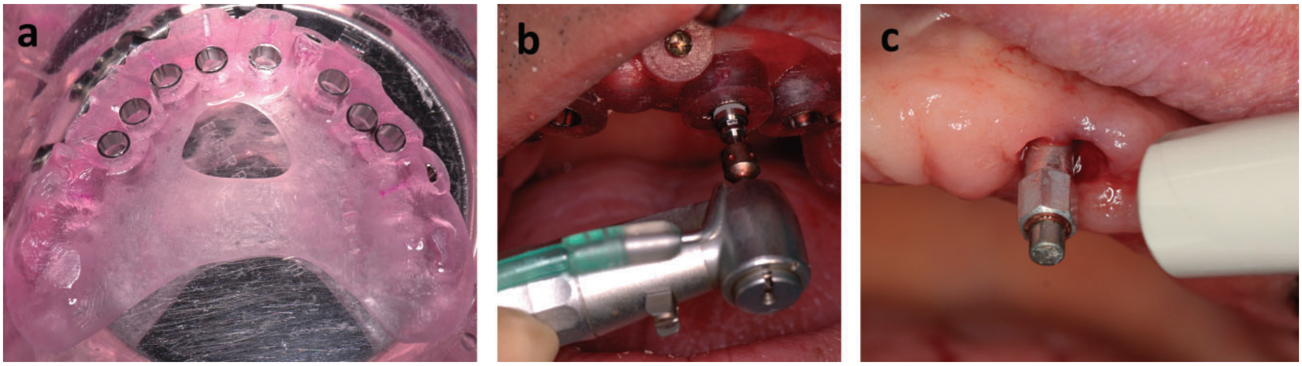

Figure 2 *A*, Mucosa-supported SLA guides used in the study. A perforation was prepared in the palatal aspect of the guide so that the anesthesia could be administered while the guide is fixed in the mouth. *B*, Implants were inserted through the guide, and the ITV was measured by the torque-controlled handpiece or the manual hand ratchet of the implant system. *C*, RFA was measured in a wireless manner.

by D'Agostino Pearson Omnibus normality test; thus, parametric and nonparametric tests were utilized where appropriate. Kruskal-Wallis test followed by Dunn's multiple comparison posttest was used to analyze the gray density values (HU and VV) inside and outside the implants. The dependence between gray density values, ITV, RFA, subjective BQC, and radiographic BQC obtained from the planning software was initially analyzed by the Spearman correlation test. With regard to the issue of dependent measurements,[30] the relation between ITV, RFA, radiographic and subjective BQC, and the gray density values were analyzed on multiple regression models. A logarithmic transformation (square root) was performed on non-normal data sets (VV outside the implants, HU inside the implants, and radiographic BQC) for the multiple regression analysis. Data in CT and the CBCT groups were analyzed on separate models. Implant stability (ITV and RFA) was attained as the fixed factor (criterion variable), and gray density value inside and outside the implants, radiographic BQC, and subjective BQC, as well as the implant length and diameter were attained as independent variables (predictor variables). The absence of multicollinearity was confirmed in the models that were found acceptable. A statistical software (SPSS 16, SPSS Inc., Chicago, IL, USA) was used for the multiple regression analysis and any p level below .05 was accepted as statistically significant in all statistical tests.

RESULTS

All surgeries were completed uneventfully. All placed implants were of exactly the same size of those planned on the software. The length and the diameter of the implants were similar between the jaws ($p = .16$ and $p = .20$ for implant length and diameter, respectively). Hence, the number of implants that each jaw received was between six and eight and was similar between the jaws ($p = .56$). In the CT group, mean gray density value inside and outside the implant were 380.4 (SD 114.6) and 668.4 HU (SD 110), respectively. In the CBCT group, mean gray density value were 417.4 (SD 116.5) and 765 VV (SD 97.32) inside and outside the implant, respectively (Table 2). The differences of the gray density values between the CT and CBCT groups were statistically significant (Kruskal-Wallis: 124.5, $p = .00012$). Gray density values measured outside the implants were

TABLE 2 Descriptive Statistics of Measured Gray Density Values for Inside and Outside of the Implants in CT and CBCT Groups

	CT Group (HU), $n = 53$		CBCT Group (VV), $n = 55$	
	Inside the Implant	Outside the Implant	Inside the Implant	Outside the Implant
Mean (SD)	380.4 (114.6)	668.4 (110.3)	417.4 (116.5)	765 (97.32)
Min–max	167–816	201–989	229–949	525–1,042
95% CI	344–416.8	637.7–699.1	361.4–473.6	732.5–799.3

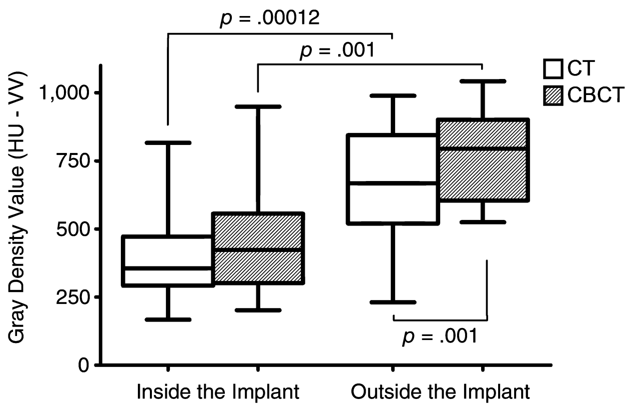

Figure 3 Gray density values inside and outside the planned implants in CT and CBCT groups.

significantly higher than those measured inside the implants ($p = .00012$ and $p = .001$ for CT and CBCT groups, respectively). In addition, the CBCT-based gray density value outside the implants was significantly higher than that of CT-based value ($p = .001$) (Figure 3). The difference of the gray density inside the implants, however, was not statistically significant between the CT and CBCT groups. Descriptive statistics of the gray density values inside and outside the implants, which were planned in the maxilla or mandible, are in Table 3. Except the maxillary implants in the CBCT group (mean 307.6 [SD 94.3] and 409.9 VV [SD 216.4] inside and the outside the implant, respectively), the gray density values outside the implants (727.8 [SD 154.8], 356.8 HU [SD 95.4] and 844.7 [SD 132], 409.9 VV [SD 216.4] in the mandible and maxilla, respectively) were significantly higher than those values inside the implants (608.9 [SD 188.6], 276.4 HU [SD 112.6] and 722.6 [SD 163.3], 370.6 VV SD 94.3 in the mandible and maxilla, respectively) ($p = .00132$ and $p = .00013$ for implants in CT and CBCT groups, respectively, and $p = .0015$ for the maxillary implants in the CT group). In the mandible, CBCT-based values inside (mean 722.69 VV [SD 163.3]) and outside the planned implants (mean 844.7 VV [SD 163.3]) were significantly higher than the CT-based values inside and outside the implants (mean 608.9 [SD 188.6] and 727.8 HU [SD 154.8]) inside and outside the implant, respectively) ($p = .001$ and $p = .00014$ for inside and outside the implants, respectively). In the maxilla, the differences of CT- and CBCT-based gray density values inside the implants were not statistically significant. In the CBCT group, however, values outside the implants (mean 409.9 VV [SD 216.4]) were significantly higher than those of implants in the CT group (mean 356.8 HU [SD 95.4]; $p = .0014$; Figure 4).

The majority of the implant recipient bone was subjectively classified as D1 (29.63 and 23.33%) and D2 (48.14 and 63.33% in CT and CBCT groups, respectively), whereas D4 was observed rarely (3.7 and 3.33% in CT and CBCT groups, respectively; Table 4). The frequency of subjective BQC was similar between the CT and the CBCT groups (Mann-Whitney *U* test: $p = .56$, $p = .81$, $p = .36$, and $p = .78$ for D1, D2, D3, and D4 classifications, respectively). Compared with the subjective BQC, the radiographic BQC (according to Misch classification[25]) generally revealed lower grades for all types of bone in the CT and CBCT groups. In the CT group, Spearman correlation analysis revealed significant relations between the subjective and radiographic BQC of Misch[25] ($\rho = 0.39$, $p = .041$) and Lekholm and Zarb[26] ($\rho = 0.64$, $p = .014$). In the CBCT group, however, a significant correlation was present only between the subjective BQC and radiographic BQC according to Lekholm and Zarb[26] ($\rho = 0.59$, $p = .021$; Figure 5).

Upon insertion, all implants reached to a sufficient primary stability as revealed by a mean ITV of 28.58 (SD 0.68) and 28.89 Ncm (SD 5.55) for CT and CBCT groups, respectively. The corresponding RFA values were also high (mean 63.65 [SD 5.65] and 65.96 [SD 5.11] implant stability quotient [ISQ] in CT and CBCT groups, respectively; Table 5). The ITV and RFA values were similar between the CT and the CBCT groups (Mann-Whitney *U*: 16.46, $p = .23$ and Mann-Whitney U: 26.45, $p = .32$ for ITV and RFA values, respectively).

Spearman correlation test revealed a statistically significant weak correlation between ITV and RFA in both groups ($\rho = 0.11$, $p = .036$ and $\rho = 0.14$, $p = .026$ for CT and CBCT groups, respectively). In the CT group, significant correlations were not only found between the gray density values and ITV ($\rho = 0.11$, $p = .031$ and $\rho = 0.25$, $p = .036$ for HU inside and outside the implants, respectively), but also between the gray density values and RFA ($\rho = 0.019$, $p = .044$ and $\rho = 0.316$, $p = .011$ for HU inside and outside the implants, respectively). In the CBCT group, however, the gray density values measured only for the outside of the implants were correlated with the ITV ($\rho = 0.21$, $p = .028$) and RFA ($\rho = 0.292$, $p = .024$).

According to the deviation measurements performed in Part II, 32 implants (13 in CT and 19 in CBCT) were positioned outside the gray density

TABLE 3 Descriptive Statistics of the Gray Density Values Inside and Outside the Planned Implants in Maxilla and Mandible

	CT Group (HU)				CBCT Group (VV)			
	Mandible (n = 25)		Maxilla (n = 28)		Mandible (n = 21)		Maxilla (n = 34)	
	Inside the Implant	Outside the Implant	Inside the Implant	Outside the Implant	Inside the Implant	Outside the Implant	Inside the Implant	Outside the Implant
Mean (SD)	608.9 (188.6)	727.8 (154.8)	276.4 (112.6)	356.8 (95.4)	722.6 (163.3)	844.7 (132)	370.6 (94.3)	409.9 (216.4)
Min–max	298–816	491–989	167–561	201–596	406–949	525–1,042	229–341	242–625
95% CI	516.4–681.4	684.7–770.9	289.4–402.6	302.2–416.9	656.1–788.4	894.2–756.4	286.4–384.4	314.2–505.4

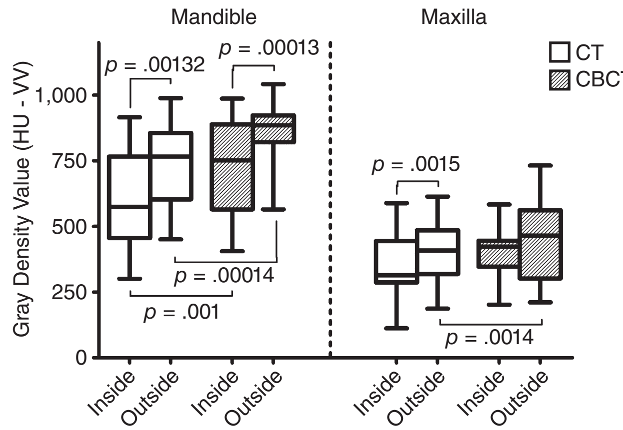

Figure 4 Box plots of gray density values (HU and VV for CT and CBCT groups, respectively) inside and outside of the planned implants in the maxilla and mandible (inside: inside the implant, outside: outside the implant).

measurement area (implant diameter + 1-mm circumferential zone) by revealing linear deviations higher than 1 mm. To provide an absolute match of the gray density values and the stability parameters, these implants (as well as with four implants which deviation measurement was not possible) were excluded, and remaining 70 implants were analyzed separately by averaging the gray density values measured inside and outside the implants. Mean gray density value for these implants were 527.22 HU (SD 109.21) and 597.21 VV (SD 119.43) for CT and CBCT groups, respectively, and the differences was statistically significant (Kruskal-Wallis: 101.5, $p = .022$). Spearman correlation analysis revealed significant relations between the subjective and radiographic BQC of Misch[25] ($\rho = 0.25$, $p = .036$ and $\rho = 0.28$, $p = .046$) and Lekholm and Zarb[26] ($\rho = 0.56$, $p = .008$ and $\rho = 0.41$, $p = .009$ for CT and CBCT groups, respectively) in both groups. Also, a weak correlation between the ITV and gray density value was observed in the CT ($\rho = 0.11$, $p = .038$) and CBCT groups $\rho = 0.21$, $p = .038$). Also, a weak correlation of the RFA and the gray density values was determined in the CBCT group ($\rho = 0.23$, $p = .041$).

In both groups, significant models emerged for ITV ($F_{3.933} = 7.9398$, $p = .0001$, adjusted $r^2 = 0.6142$ and $F_{4.486} = 6.986$, $p = .0021$, adjusted $r^2 = 0.5166$) and RFA ($F_{4.568} = 5.6785$, $p = .0017$, adjusted $r^2 = 0.5642$ and $F_{5.689} = 8.1589$, $p = .0031$, adjusted $r^2 = 0.5423$ for CT and CBCT groups, respectively). According to these models, gray density values (HU and VV) outside the implants and radiographic BQC according to Lekholm and Zarb[26]

TABLE 4 Frequency Table (%) of Perceived Subjective BQC during Surgery and Software-Rated Radiographic BQC according to Misch[25] and Lekholm and Zarb[26] (as Revised by Norton and Gamble)[27]

Bone Quality	CT Group (%)			CBCT Group (%)		
		Radiographic BQC			Radiographic BQC	
	Subjective BQC	Misch[25]	Lekholm and Zarb[26]	Subjective BQC	Misch[25]	Lekholm and Zarb[26]
D1	29.63	0	13.46	23.33	0	10
D2	48.14	21.15	61.53	63.33	13.33	40
D3	18.51	42.30	17.30	10	60	43
D4	3.70	36.53	7.69	3.33	26.66	3.33
D5	0	–	0	0	–	3.33

were the common predictor variables for ITV and RFA in both CT and CBCT groups. Subjective BQC was also related with the ITV in both groups ($p = .042$ and $p = .041$ for CT and CBCT groups, respectively; (Tables 6 and 7). In step with the emerged models, scatter plot graphics were depicted to visualize the relationship among the gray density values (HU and VV) outside the implants and RFA and ITV (Figures 6 and 7).

DISCUSSION

The relationship of CT- and CBCT-based gray density values (HU and VV) and corresponding objective (ITV, RFA, and radiographic BQC) and subjective[25] primary implant stability parameters were analyzed in this study. The use of SLA guides in conjunction with the special planning software yielded accurate match of gray density values and corresponding stability parameters of the actual implants. The similarity of implant dimensions between the CT and CBCT groups also proved the comparability of the measured variables (ITV and RFA were proved to be affected by the implant dimensions[8,28]). Accurate discrimination of the correlating parameters was endorsed by deploying multiple regression models.

Prediction of the primary stability prior to the insertion of implant may be of a critical importance especially when multiple implants are planned in an edentulous jaw. As a result of the disuse atrophy, the mineral content of the alveolus in totally edentulous jaws may have decreased dramatically resulting in an increased risk of implant placement into the compromised areas.[31] In view of this fact, the relationship of CT-based gray density values (HU) and the primary implant stability parameters was previously explored by many studies,[7,8,27,29,32] but such analysis based on CBCT-based values (VV) is scarce.[33] The inconsistency of the CBCT-based gray density values (even on the same specimen) also poses a significant concern.[13,16] Using an earlier version of the currently utilized software, Norton

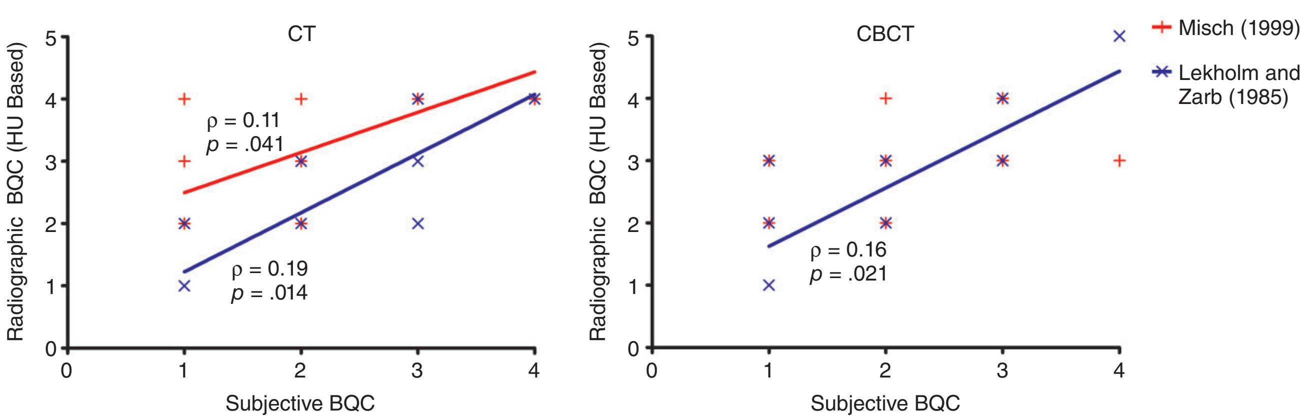

Figure 5 Relation between subjective (perceived during osteotomy) and software-rated BQC according to Misch[25] and Lekholm and Zarb[26] (as revised by Norton and Gamble[27]) in the CT and CBCT groups.

TABLE 5 Insertion Torque Value (ITV) and Resonance Frequency Analysis (RFA) Values of Implants in the CT and CBCT Groups

		CT Group	CBCT Group
ITV (Ncm)	Mean (SD)	28.58 (5.68)	28.89 (5.55)
	Min–max	15–35	15–35
	95% CI	27.12–30.05	37.37–30.40
RFA (ISQ)	Mean (SD)	63.65 (5.65)	65.96 (5.11)
	Min–max	51–75	54–74
	95% CI	62.19–65.11	64.57–67.36

and Gamble[27] measured the gray density values of 139 implant recipient areas and reported values between 77 and 1,421 HU in which the subjective quality scores were in correlation with the gray density values outside the designated implant areas. Ikumi and Tsutsumi[28] measured the gray density value of 59 implants planned on the software and found values between 208 and 1,099 HU. A strong dependency was found between the ITV and gray density value measured outside the corresponding implants. Shapurian and colleagues[29] reported CT-based gray density values ranging between −240 and 1,159 HU out of 219 edentulous segments, but a statistical dependency with the subjective density score was detected only in type 4 bone. In agreement with the present study, the authors recorded an increase in the HU where cortical bone is engaged in the outer circumference of the implant.

In a series of clinical studies, Turkyilmaz and colleagues[8] utilized the bundled software of a CT scanner and reported gray density values differing from 271 to 1,231 HU in 230 implants, 528 to 1,231 HU in 100 implants,[34] 199 to 1,231 HU in 300 implants,[32] and 278 to 1,227 HU in 158 implants.[35] They also reported strong correlations among the gray density of the designated implant area and ITV and RFA of the parallel-walled, self-tapping implants. Song and colleagues[33] used a CBCT machine for *per*-surgical quantification of the gray density around 61 implant osteotomy holes that revealed values between 107 and 904 VV. RFA of the placed implants was strongly correlated with the measured gray density value and the thickness of the cortical bone around implants.

The recorded gray density values ranging from 167 to 989 HU and 229 to 1,042 VV in this study were comparable with those of aforementioned studies, and the discrepancies are most likely to result from the variations of implant recipient areas and utilized methodology as well as with the demographic characteristics of the study population. As opposed to those studies where a single arbitrary chosen cross-sectional image of the designated implant area (implant represented by a rectangle) was referred for the quantification of the gray

TABLE 6 Emerged Multiple Regression Models in the CT Group

Variables	Coefficient (β)	SE	*t* Ratio	*p*
Model 1 in CT group*				
ITV (criterion variable)	4.188	9.55	0.43	.041
Gray density (HU) outside the implant	0.0178	0.006	2.208	.0017
Gray density (HU) inside the implant	0.087	0.045	1.786	.0056
Radiographic BQC according to Lekholm and Zarb[26]	−3.289	1.303	2.525	.036
Radiographic BQC according to Misch[25]	−1.16	0.056	1.563	.045
Subjective BQC	−1.117	0.051	1.414	.042
Model 2 in CT group†				
RFA (criterion variable)	5.1568	6.45	0.89	.037
Gray density (HU) outside the implant	0.0898	0.045	3.565	.026
Radiographic BQC according to Lekholm and Zarb[26]	−2.165	1.596	1.896	.041

*Adjusted $r^2 = 0.6142$; sum of squares, 695.96; SD of residuals, 3.933; F = 7.9398; $p = .0001$. Predictor variables implant length ($p = .12$) and implant diameter ($p = .46$) were not significant in this model.
†Adjusted $r^2 = 0.5642$; sum of squares, 346.98; SD of residuals, 4.568; F = 5.6785; p = .0017. Predictor variables radiographic BQC according to Misch[25] ($p = .086$), gray density (HU) inside the implant ($p = .087$), implant length ($p = .22$), and implant diameter ($p = .18$) were not significant in this model.

TABLE 7 Emerged Multiple Regression Models in the CBCT Group

Variables	Coefficient (β)	SE	*t* Ratio	*p*
Model 1 in CBCT group*				
ITV (criterion variable)	3.866	8.88	0.38	.036
Gray density (VV) outside the implant	0.0236	0.139	1.976	.008
Subjective BQC	−2.116	0.956	1.965	.041
Radiographic BQC according to Lekholm and Zarb[26]	−2.148	1.022	1.356	.046
Model 2 CBCT group†				
RFA (criterion variable)	3.1156	3.56	0.89	.033
Gray density (VV) outside the implant	1.112	1.855	2.583	.0021
Radiographic BQC according to Lekholm and Zarb[26]	−2.123	0.897	3.567	.046

*Adjusted $r^2 = 0.5166$; sum of squares, 576.45; SD of residuals, 4.486; $F = 6.986$; $p = .0021$. Predictor variables radiographic BQC according to Misch[25] ($p = .46$), gray density (VV) inside the implant ($p = .057$), implant length ($p = .087$), and implant diameter ($p = .32$) were not significant in this model.
†Adjusted $r^2 = 0.5423$; sum of squares, 386.22; SD of residuals, 5.689; $F = 8.1589$; $p = .0031$. Predictor variables, gray density (VV) inside the implant ($p = .057$), radiographic BQC according to Misch[25] ($p = .091$), implant length ($p = 0.36$), and implant diameter ($p = .088$) were not significant in this model.

density values,[7,8,32,36] the methodology of the present study is rather sophisticated, and because of the use of SLA guides, the results could be regarded precise. Descriptive analysis of CT- and CBCT-based gray density values in the anterior and posterior jaw zones was not intended in this study because such an attempt would necessitate a larger sampling group allocated according to a descriptive strategy. Yet, the recorded

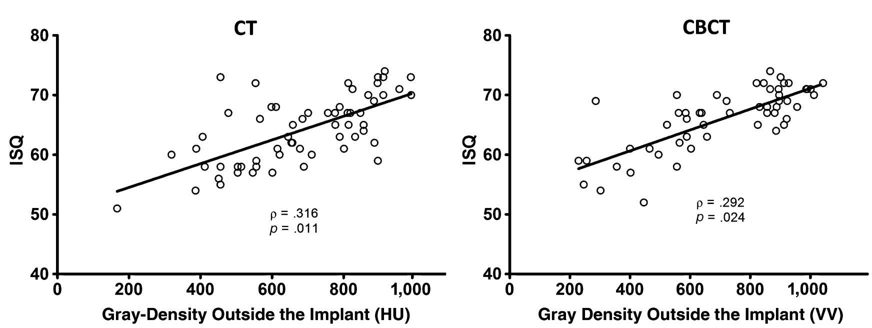

Figure 6 Dependency between the gray density values outside the implants and RFA (ISQ).

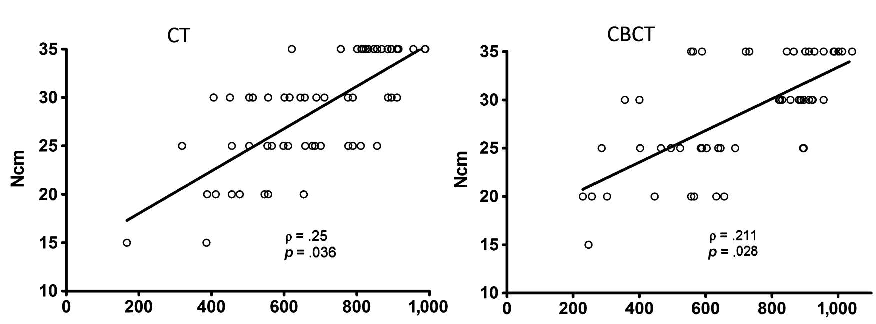

Figure 7 Dependency between the gray density values outside the implants and ITV (Ncm).

CT- and CBCT-based values were coherent in both jaws, and as found in the aforementioned studies, the values in mandible were significantly higher. Because of confrontation of the implants' outer wall into the cortical bone in the vestibular and palatinal aspect, gray density values outside the implants were found to be significantly higher than those values measured inside the implants. The lack of statistical significance between the gray density values inside and outside the maxillary implants of the CBCT group could be related to wider geometry of the maxillary alveolus that could have apposed the implants (and the outer 1-mm layer) solely to the trabecular bone especially in the posterior zone.

As reported in many in vitro studies,[37] the gray density values measured in the CBCT group (VV) was generally higher than those measured from the CT group (HU). The reason of this phenomenon was attributed to various technical factors such as X-ray beam hardening, scattered radiation,[38] and "projection data discontinuity-related effect,"[13] all of which add up in yielding a decrease in the dynamic contrast of the CBCT scanners (8 to 14-bit) compared with multi-slice CT (16-bit).[13] With the increase of the radio-opacity (mineral content), the effect of beam hardening is more pronounced.[39] This could also explain the significant differences of between the HU and VV outside the implants (cortical bone). Implants are confronted by the highly mineralized cortical bone (in the vestibular and palatinal aspect) in the outer 1-mm layer and therefore quantified by a higher gray density value (VV) by the CBCT scanner. In the trabecular, low-density maxillary bone (inside the implant), the CT- and CBCT-based values were rather similar. Nonetheless, cadaver studies revealed strong correlations of CT- and CBCT-based gray density values[17] even with the use of an earlier image intensifier-based CBCT system.[40] The results of the present study taken together with the previous reports reveals that the gray density in the 1 mm outside perimeter of the planned three-dimensional implant volumes yields higher values on CBCT images (VV) than those of CT images (HU). Clinicians should be aware of this fact and account for its possible implications in clinical decision making.

Aside from these differences, both type of gray density values were in correlation with the ITV and RFA in this study. This was also the case in other similar clinical investigations where moderate to strong correlations ($r < 0.56$–0.768 and $r < 0.31$–0.882 for ITV and RFA, respectively) were reported[7,8,32,34,35] especially for the parallel-walled, self-tapping implants revealing the strongest dependency with ITV ($r = 0.882$) and RFA ($r = 0.786$).[32] Mean ITV and RFA values measured in this study were lower than those reported in similar studies, and these differences were likely to result from the variations of macro design and thread pitch of the employed implant systems.[41] RFA values were shown to be decreased by the extension of the supracrestal implant collar.[22,42] It should also be noted that the weakness of the correlations in this study would be a mathematical consequence of the employed minimum sample size, and these relations may even get stronger in larger populations.[30]

From a statistical point of view, pairwise comparison of gray density values, ITV, RFA, and radiographic and subjective BQC could be biased by the violation of the assumptions: the measurements are from the same implant thus are not independent.[30] In view of this fact, multiple regression models were utilized in addition to the pairwise comparison tests for the analysis of the relationship between the gray density values and implant stability parameters. In both groups, ITV was found to be associated with the gray density values measured outside the implants. Additionally, the radiographic BQC of Lekholm and Zarb[26] and the subjective BQC perceived during surgery[25] were found to be associated with the ITV. This is of particular importance, as the perception of subjective bone quality would be – theoretically – impossible because of the friction between the drills and metal sleeves. Even so, the present results reveal that the prediction of bone "hardness" is possible through the radiographic BQC of Lekholm and Zarb (as revised by Norton and Gamble)[27] attained by the planning software. Nevertheless, the past experience of the surgeons on the SLA guides in this study should be noted as a key factor in achieving this result. The present findings are also confirmatory to the results of a previous cadaver study where the measured CT-based gray density value was strongly correlated with the subjective BQC perceived during surgery.[43] According to the present findings, it can be claimed that either by using CT or CBCT, the anticipated subjective BQC (according to Misch)[25] can be estimated preoperatively by means of the gray density values around 1 mm perimeter of the planned implant. Nevertheless, novice clinicians should be aware of the potential bias and altered tactile sensation regarding the subjective assessment of the BQC because of the presence of guide cylinders around the rotating instruments.

In contrast to ITV, the RFA was not related with the surgeons' subjective BQC[25] scores. Instead, the gray density values outside the implants and radiographic BQC (performed by the software) were associated with the RFA. RFA was shown to be influenced by many variables such as implant design, length, diameter, sink depth, bone density, and the surgical technique,[22] all of which may complicate clarification of any possible relations to the preoperatively measured gray density value to the ITV and RFA. The outcome regarding the relation of RFA and the gray density values measured outside the implants may also be accepted as confirmatory to those of Song and colleagues[33] whose data revealed a correlation of the RFA values with the cortical bone thickness at the shoulder of the implant.

Guided implant surgery using tomography-derived SLA templates is a relatively new technology and prone to complications throughout the sequence.[44] Deviation from planning poses a significant risk and clinicians should account for its adverse implications especially when flapless techniques are intended.[45]

The results of the present study demonstrate significant relations between the primary implant stability parameters and the gray density values obtained not only by a 64-slice CT but also by a 14-bit CBCT scanner equipped with a flat-panel detector. CBCT yielded higher gray density values than CT, and the gray density values measured from the outer 1-mm layer of software-planned implants demonstrated stronger associations with the measured variables in both groups. Lower radiation dose and costs may render CBCT preferable. However, the outcome would vary among different scanners and implant designs that should be elucidated by further studies.

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