Alveolar Bone Density and Width Affect Primary Implant Stability

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Primary implant stability (PIS) depends on surgical technique, implant design, and recipient bone characteristics, among other factors. Bone density (BD) can be determined in Hounsfield units (HUs) using cone beam computerized tomography (CBCT). Reliable prediction of PIS could guide treatment decisions. We assessed whether PIS was associated with recipient bone characteristics, namely, BD and alveolar ridge width (ARW), measured preoperatively by CBCT. We studied a convenience sample of 160 implants placed in 48 patients in 2016 and 2017. All underwent CBCT with a radiologic/surgical guide yielding values for ARW and BD. PIS measures used were the implant stability quotient (ISQ) from resonance frequency analysis and insertion torque (IT). IT was most influenced by the HU value at 0.5 mm outside the implant placement area, followed by the value within this area, and ISQ by the HU value at 0.5 mm outside the placement area, followed by implant placement site and apical ARW. ISQ values were significantly related to ARW in coronal ($P < .05$), middle ($P < .01$), and apical ($P < .01$) thirds. ISQs were higher with larger-diameter implants ($P < .01$). ISQ and IT were strongly correlated ($P < .001$). PIS in terms of ISQ and IT is positively correlated with edentulous alveolar ridge BD measured by CBCT, implying that implant stability may be predicted preoperatively. Wide alveolar ridges favored lateral PIS but did not affect rotational PIS. The most significant predictor of lateral and rotational PIS in our patients was the HU value at 0.5 mm outside the implant placement area.

Key Words: bone density, Hounsfield units, alveolar bone width, primary implant stability, insertion torque, ISQ

INTRODUCTION

Dental implants are becoming increasingly common and primary implant stability (PIS); although influenced by multiple factors, fundamentally depends on the surgical technique, implant design, and characteristics of the recipient bone.[1] In particular, it is plausible that the bone density (BD) at the placement site of the implant affects the PIS. Indeed, research has shown higher success rates in implants placed in higher-density bone.[2] In a recent study analyzing the prognosis of 6977 implants placed in humans, Zhou et al[3] related placement of implants in the posterior maxilla, where the cortical bone is thinner and the medullary soft, to greater failures in osseointegration. Reliable prediction of PIS before implant placement surgery could improve our understanding of the prognosis of our implant treatments, guide decisions on treatment, and improve our success rate.

BD can be assessed in Hounsfield units (HUs) using conventional computerized tomography (CT). Specifically, HU values have been found to be correlated with BD according to Misch's classification[2] and according to the classification of Lekholm and Zarb.[4] Furthermore, CT-based HU values were associated with the hydroxyapatite concentration of the extracellular bone matrix in an in vitro study,[5] and mineral BD measured by CT was significantly related to that found in histomorphometry of biopsies of implant placement sites in a clinical study with 23 patients.[6]

At the end of the 1990s, a new tomographic technique was developed especially for dental applications: cone beam CT (CBCT).[7,8] The beam, which is conical (rather than fan-shaped as in conventional CT), moves around the patient's head, and the data collected are processed to construct a volumetric image of the cylindrical field of view. Given the numerous advantages it offers over conventional CT, including shorter scan time, lower radiation exposure, and less distortion and magnification and that it can provide good-quality images, CBCT has become the main diagnostic radiology tool in implantology.[9]

The quantitative scale developed by Godfrey Newbold Hounsfield for describing radiodensity measured using CT has been modified for use in CBCT studies, enabling assessment of BD in HUs. On the other hand, various in vitro studies indicate that the grayscale values measured by CBCT may differ from those measured by medical CT and therefore should not be considered absolute values.[10] One of the most important sources of error is the large amount of scattered radiation produced by the volumetric exploration typical of CBCT systems. Scattered radiation generates more noise in the images and reduces the spatial uniformity of the

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densitometry values in HUs.[11] Despite these differences, it has been suggested that, similar to CT, CBCT is able to provide a useful preoperative assessment of the BD of the jaws (in HUs).[12]

Notably, patients in need of implant treatments increasingly demand predictable and rapid recovery of dental esthetics and masticatory function. Success in immediate loading procedures lies in achieving adequate PIS that ensures immobilization and subsequent osseointegration of the implant.[13] For this reason, it is essential to plan treatment carefully and assess the determinants of PIS inherent to each patient. In practical terms, radiologic datasets acquired by CT techniques can be digitized, downloaded to a personal computer, and visualized with specific software to measure the dimensions of anatomical structures and BD (in HUs). This allows treatment planning in three dimensions considering the patient's anatomy and visualization of expected results before surgery. Although a positive association has been found between BD and PIS, the scientific evidence supporting this relationship can be considered weak to moderate because of the quality of studies and great methodologic differences between them.[14] Furthermore, there is a huge range of macroscopic and microscopic implant designs, and it is reasonable to believe that each design has a predictable PIS according to the BD in the area of implant placement, assuming that the surgical protocol for drilling recommended by the manufacturer has been followed. That is, there is a need for more data establishing the relationship between BD and PIS for specific designs of implant.

Given this, the main objectives of this study were to assess whether PIS with a specific implant was significantly associated with the characteristics of the recipient bone in terms of BD and alveolar ridge width (ARW) measured preoperatively by CBCT and thereby investigate whether it may be possible to predict PIS by this type of radiologic analysis of the edentulous alveolar ridge before implant placement. The null hypothesis was that it is not possible to predict implant stability for a specific macroscopic design of implant with given dimensions before placement based on the availability and hardness of the bone in the edentulous alveolar ridge assessed by CBCT. The alternative hypothesis was that the PIS values of a specific implant are positively correlated with the amount and density of recipient bone available, and hence, are predictable before implant placement surgery using this type of tomography. Secondary objectives were to characterize patterns of BD and thickness in the recipient bone and explore the relationship between PIS and implant characteristics.

Materials and Methods

This observational clinical study was approved by the local ethics committee (reference ÉTICA-ULE-011-2017). A convenience sample was recruited from among candidates for rehabilitation of edentulous ridges with dental implants in the maxilla and mandible in 2016 and 2017, and patients were only included after they had provided written informed consent. The study was conducted in accordance with the principles of the Declaration of Helsinki.

Study population

Patients with uncontrolled systemic disease or history of bisphosphonate intake, radiotherapy, or chemotherapy treatments were excluded. All the patients were operated on by different surgeons. The sample size required to be able to justify extrapolation of our results to the target population, namely, candidates for dental implants in our geographical area, was estimated, using an equation created for this purpose.[15] Specifically, a power analysis was performed for HU values (within the area of implant placement and at 0.5 mm outside this area) with an α of 0.05 and a power of 0.80. This indicated that the number of implants needed was 130. Therefore, allowing for dropouts (10% losses), we estimated that we needed a sample of at least 145 implants. Finally, data were gathered on a total of 160 implants.

Definitions

The implant regions were defined as follows: posterior maxilla, between the upper first premolar and second molar on both sides; anterior maxilla, between the upper canines; posterior mandible, between the lower first premolar and second molar on both sides; anterior mandible, between the upper canines.

Intervention

Surgeons used different diameters and lengths of a single cylindrical implant design, the BEGO Semados S-Line (BEGO Implant Systems GmbH & Co. KG, Bremen, Germany); a BEGO Semados torque wrench (10-50 Ncm); and Osstell ISQ system (Osstell AB, Göteborg, Sweden) with SmartPegs Type 26 (Osstell AB). All patients underwent preoperative CBCT (Carestream 9300, Carestream Health, Rochester, NY) with a surgical splint that also served as a radiologic guide. The radiation dose was adjusted for patient's weight (591, 685, and 856 mGy/cm^2 for patients weighing $<$60, 60–90, and $>$90 kg, respectively). The BD and ARW were assessed using BTI Scan 3 software (BTI Biotechnology Institute SL, Miñano, Álava, Spain).

Preoperative bone characteristics: BD and ARW

A cross section was obtained at the alveolar crest corresponding to the area of implant placement marked by the radiologic/surgical guide, and an outline of the chosen implant (from the BTI Scan 3 database) was superimposed on this cross section, with an appropriate inclination (Figure 1). Subsequently, 3 lines (at the coronal, middle, and apical levels of the implant) were drawn perpendicular to the axial axis of the implant from the buccal to the lingual cortex. Using densitometric analysis, mean HU values were obtained within the area of implant placement and at 0.5 mm outside this area. Three variables were used to define the BD of the crestal cortical bone: the mean, maximum and minimum HU values in the first 3 coronal mm within the area of implant placement.

Primary implant stability: IT and ISQ

All the implants were inserted under the same conditions and at the same distance from the bone. The final IT was determined with the dynamometric torque wrench, categoriz-

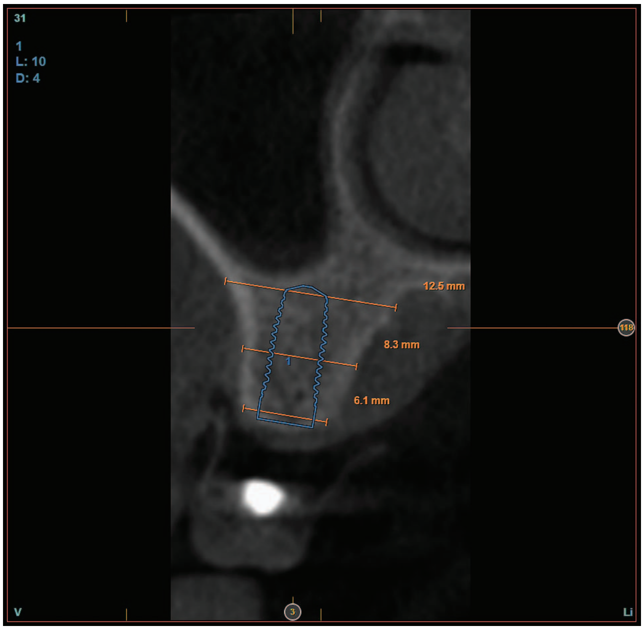

Figure 1. Preoperative imaging assessment and planning. Example of an outline of an implant (from the BTI Scan 3 database) superimposed, with an appropriate inclination, on a cross section at the alveolar crest corresponding to the area of implant placement.

ing this result into one of the following groups: IT $<$ 30 Ncm, IT between 30 and 50 Ncm, IT $>$ 50 Ncm. The implant stability quotient (ISQ) value was calculated with the Osstell ISQ system by screwing the SmartPeg Type 26 to the implant. Two readings were taken: one with the device in a buccolingual direction (ISQ-BL) and the other with it in a mesiodistal direction (ISQ-MD). The ISQ ranges from 0 to 100, with values $<$60 considered to indicate low stability, 60 to 69 considered medium stability, and $>$70 considered high stability (according to the manufacturer of the implant; https://www.osstell.com/clinical-guidelines/the-isq-scale/).

Statistical analysis

IBM SPSS Statistics for Windows, version 22.0 (Armonk, NY) was used for the statistical analysis, and $P < .05$ was considered significant. For the descriptive analysis, qualitative data were expressed using frequencies and percentages and quantitative data using means and standard deviations or minima and maxima. Contingency table analysis was performed with the statistical procedures appropriate for the types of data, namely, categorical (implant placement site, torque, bone type, implant diameter, and length) or quantitative (density in HUs, ISQ, and ARW) in each pair of variables. Specifically, when one variable was quantitative and the other categorical, we used a test for differences in the mean, with estimation of the size of the effect by means of R^2 (indicating the percentage of variance explained from 0%–100%); when both were quantitative, a scatterplot and Pearson's and Spearman's correlation coefficients were used; and when both were categorical, the χ^2 test of independence, with adjusted standardized residuals, to assess associations between categories, was used, whereas the strength of the association was estimated with the contingency coefficient. Help was obtained from an independent statistician, external to our working group, for designing the statistical analysis. Subsequently, the same statistician conducted the statistical analysis for the study.

RESULTS

Study population

Over the 2 years of the study, data were gathered on 160 implants placed in 48 patients, with an almost balanced sex ratio: 84 (52.5%) in men and 76 (47.5%) in women. The age of the patients ranged from 31 to 64 years, with a mean of 50 years. The mean age of men (50.68 years; 95% CI: 48.72–52.64) and women (48.96 years; 95% CI: 47.31–50.61) differed by 2 years, but this difference was not statistically significant ($P > .05$). Nearly half of the implants were placed in the posterior mandible (51.2%), with smaller numbers placed in the posterior maxilla (28.7%), anterior maxilla (10%), and anterior mandible (10%).

Preoperative bone characteristics: BD and ARW

In the inferential analysis, we found a statistically significant relationship between the site of implant placement and recipient alveolar ridge BD. Specifically, the highest values of mean BD were found in the anterior mandible and the lowest in the posterior maxilla ($P < .001$; Table 1). Similarly, we found a significant relationship between implant placement site and edentulous ARW, the largest mean widths being found in the 2 posterior regions and the smallest in the 2 anterior regions ($P < .001$; Table 1).

Primary implant stability: IT and ISQ

Notably, we found a strong relationship ($P < .001$) between the 2 variables used to assess PIS, namely, IT and ISQ. We observed significant relationships between both these parameters and all the variables considered that in some way define the BD of the edentulous alveolar ridge. Specifically, both IT and ISQ were strongly associated with the HU value at 0.5 mm outside the area of implant placement ($P < .0001$ in both cases). The univariate models exploring the effects on PIS in the present study indicate that the factors with the greatest effect on IT are the HU value at 0.5 mm outside the area of implant placement, which explained 39.8% of the variance, followed by the HU value within the area of implant placement, which explained 35.3% of the variance (Table 2). Similarly, in the multivariate linear model (with automatic selection), the factors with the greatest effect on the sum of the ISQ values were the HU value at 0.5 mm outside the area of implant placement followed by the site of implant placement and the apical ARW (Table 3).

Classifying the bone density using the HU value at 0.5 mm outside the area of implant placement, we found significant differences in implant stability by bone type, with large effect sizes. Specifically, lower-density bones (type 4) were associated with lower ISQ values (ISQ-BL $<$ 79 vs $\geq$79 and ISQ-MD $<$ 80 vs $\geq$80) than higher-density bones (type 1). Torque was more likely to be lower in lower-density bones (IT $<$ 30 Ncm in all cases of type 4 and 45.2% of type 3) and was higher in most

Table 1

Relationship between bone density of the recipient alveolar ridge and alveolar ridge width by anatomical implant placement site†

	Implant Placement Site				Analysis of Variance		
Variables	Posterior Maxilla (n = 46) Mean (SD)	Anterior Maxilla (n = 16) Mean (SD)	Posterior Mandible (n = 82) Mean (SD)	Anterior Mandible (n = 16) Mean (SD)	*F* Value	*P* Value	Effect Size: R^2
HUs inside	590.22 (233.48)	809.38 (205.93)	778.66 (287.39)	1062.50 (167.83)	14.55	.001**	21.9%
HUs 0.5 mm outside	668.48 (210.39)	921.88 (202.46)	917.68 (271.98)	1221.87 (195.76)	23.01	.001**	30.7%
Coronal width	7.32 (1.65)	6.31 (0.97)	6.88 (1.38)	6.19 (1.44)	3.47	.018*	6.3%
Middle width	9.04 (1.77)	8.47 (1.60)	10.17 (1.93)	8.01 (1.43)	10.09	.001**	16.2%
Apical width	11.05 (2.75)	11.41 (2.93)	11.47 (1.80)	9.79 (1.34)	2.70	.048*	4.9%

$^*P < .05$; $^{**}P < .01$.

†Inferential analysis: differences in the mean.

higher-density bones (IT > 50 Ncm in all cases of type 1 and 77.5% of type 2).

Significant relationships were found between all 3 measures of crestal cortical BD and both the PIS variables ($P < .001$ in all cases). Although the results showed no relation between ARW and IT, both ISQ values were significantly associated with the ARW in the coronal ($P < .05$), middle ($P < .01$), and apical ($P < .01$) thirds. Furthermore, wide alveolar ridges favored lateral PIS, but they had no effect on rotational PIS.

With the implant used, we found a positive association between implant diameter and ISQ values. Specifically, implants with a 4.1-mm diameter were associated with higher ISQs than those with diameters of 3.25 and 3.75 mm ($P < .01$). In contrast, we did not find significant relationships between implant diameter and IT or between implant length and PIS values.

Discussion

Using CBCT, we found that PIS values were positively correlated with the amount and density of bone available in the edentulous alveolar ridge, supporting the alternative hypothesis and rejecting the null hypothesis. Specifically, with Bego Semados S-line implants, we found lower IT (<30 vs >50 Ncm) and lower ISQ values (ISQ-BL <79 vs ≥79 and ISQ-MD <80 vs ≥80) in low-density bone (Misch type 4) than in higher-density bones (types 1 and 2). Furthermore, the variable with the greatest significance for predicting the lateral and rotational PIS of these implants was the HU value at 0.5 mm outside the area of implant placement.

Table 2

Univariate inferential analysis: effects of explanatory factors on implant insertion torque†

Explanatory Factor	Effect Size (%)	*P* Value
Site of implant placement	5.7	.081$^{\text{NS}}$
Implant diameter	3.3	.216$^{\text{NS}}$
Implant length	0.8	.698$^{\text{NS}}$
Coronal ARW	1.6	.274$^{\text{NS}}$
Middle ARW	2.4	.148$^{\text{NS}}$
Apical ARW	2.7	.027$^{\text{NS}}$
HUs within implant placement area	35.3	.001**
Type of bone inside implant placement area	28.9	.001**
HUs at 0.5 mm outside implant placement area	39.8%	.001**
Type of bone 0.5 mm outside	33.1	.001**
HUs in first 3 coronal mm within implant placement area	23.3	.001**
Maximum HUs in first 3 coronal mm within implant placement area	15.4	.001**
Minimum HUs in first 3 coronal mm within implant placement area	21.7	.001**

$^{**}P < .01$.

†ARW indicates alveolar ridge width; NS, not significant ($P > .05$).

In addition, in our study population, the greatest BD was found in the anterior mandible followed by the anterior maxilla, with significantly lower densities in the posterior mandible and the posterior maxilla. These results coincide with the patterns described by Misch[1] and Norton and Gamble.[4] In our patients, the ARW was significantly greater in posterior sections than anterior ones. Furthermore, narrow alveolar ridges were associated with significantly higher values of BD (type 1), as would be expected because of the closeness of the vestibular and lingual/palatal cortices, whereas wide ridges were associated with lower values of BD (type 4), which contained a greater volume of cancellous bone than narrower ridges.

There is considerable evidence that BD determines the PIS. This relationship has been studied previously, and the BD has been quantified in various ways, either subjectively (tactile sensation of bone resistance to drilling) or objectively (radiologic studies), with research having been conducted in humans in which BD was quantified in HUs through the use of CT or CBCT. In particular, HU values obtained with CT have been found to be significantly associated with ISQ values and sometimes also with IT.[16–19] In our study, type 4 bone was

Table 3

Predictive factors of the sum of implant stability quotients (in buccolingual and mesiodistal directions)†

			Adjusted R^2	
	Predictive Factor	*P* Value	Of the Factor	Of the Model
First	HUs at 0.5 mm outside the implant placement area	.001**	14.3%	14.3%
Second	Site of implant placement	.001**	11.3%	25.7%
Third	Apical alveolar ridge width	.001**	2.9%	28.6%

$^{**}P < .01$.

†Automated multivariate linear model.

associated with lower ISQ values than type 1 bone, and we also found that torque tended to be lower in lower-density bones (types 3 and 4). Given differences between studies, however, further research is needed to clarify the relationship between PIS, in particular, IT, and bone type.

Regarding the use of CBCT, Arisan et al[12] found a significant relationship between HU values calculated by CT or CBCT and PIS values in a sample of 108 implants. An important conclusion of that study was that the densitometric measurements made with CBCT are reliable and comparable to those made with CT scanners when the devices are properly calibrated. In relation to this, Sennerby et al[11] validated a CBCT system and found the BD at 1 mm outside the implant placement area to be strongly associated with ISQ ($P < .0002$) and IT ($P < .0001$). Fuster-Torres et al[20] obtained significant results only in the anteromandibular region, relating CBCT-based HU values within the implant placement area with IT ($P < .05$) and the BD with ISQ in males only ($P < .05$). Our study adds to the body of evidence on the use of CBCT for assessing BD before implant placement.

Specifically, our results indicate that the use of a calibrated CBCT system is reliable for performing densitometric measurements and studying relationships with PIS variables. Consistent with the results of Arisan et al[12] and Sennerby et al,[11] we found the periphery of the implant placement area to be the most interesting area for studying the effect of BD on PIS. A reasonable explanation is that PIS is determined by the bone surrounding the implant and not by the bone originally present in the area where the implant is to be placed.

In vitro studies[21–23] have shown the importance of cortical thickness for obtaining PIS when placing implants of different designs in blocks of rigid polyurethane foam. Furthermore, we found that the PIS was influenced as much by BD as by the thickness of the cortex. Marquezan et al[24] reached the same conclusion in a systematic review and meta-analysis on the influence of cortical thickness on the PIS of orthodontic miniscrews. BD and cortical thickness increase in the apical direction of the alveolar ridge, as described by Ohiomoba et al.[25] In our patients, we found strong relationships between the BD of the crestal cortical bone and PIS ($P < .001$). These results suggest, in agreement with the aforementioned studies, that the properties of the crestal bone are fundamental when it comes to achieving PIS.

Although cortical thickness is a key parameter as far as PIS is concerned, we found no scientific evidence in the literature that demonstrates a relationship between the overall ARW and PIS. Our multivariate explanatory models indicate that ISQ values but not IT were significantly associated with the ARW in the coronal ($P < .05$), middle ($P < .01$), and apical ($P < .01$) thirds. More studies are needed to explain this. On the other hand, we found that the BD at the periphery of the implant increased as the ARW decreased ($P < .001$), with the buccal and palatal/lingual cortical plates lying closer to the implant surface, despite the lack of a significant relationship between ARW and IT. Again, more studies are needed to investigate this issue.

Our results coincide with those of other studies with different methodologies of BD measurement. For example, Suer et al[26] found BD values of the alveolar ridge obtained by fractal analysis of panoramic radiographs of the premolar and mandibular molar area to be significantly associated with IT values ($P = .0005$) and ISQ ($P = .005$),[26] and similar results have been obtained by other authors.[27,28] Another methodology for quantifying BD is micro-CT analysis of bone microstructure in tissue obtained from a biopsy of the area where the implant is placed. Ribeiro-Rotta et al[29] demonstrated associations between variables defining the bone microstructure (architecture of the bone trabeculate and its density) measured by micro-CT and IT values ($P < 0.01$), and Fu et al[30] established a negative association between ISQ values and the different types of bone analyzed by stereomicroscopy ($P = .013$) and micro-CT ($P = .027$), although only in the maxilla.

We found a strong association ($P < .001$) between the IT and ISQ variables, in agreement with some previous studies,[31,32] although a review failed to confirm this association.[33] Although rotational PIS and lateral PIS are different concepts, both are affected by the same conditions and determine the success of the osseointegration of implants.

Various studies have sought to determine the relationship of PIS with the diameter and length of dental implants. Our results agree with those of Gómez-Polo et al,[34] who found a significant relationship between the diameters of 88 implants and ISQ values but found no relationship between implant length and PIS.[34] Karl et al[35] also found a relationship between implant diameter and the ISQ values, although only in the mandibular region ($P = 0.037$), as well as implant length and ISQ also in the anterior mandible ($P = 0$). Indeed, several studies have indicated that using longer implants increases the PIS.[36,37] In our case, the lack of a significant association with length may be because the most commonly used length measurements were 10 mm (77 implants) and 11.5 mm (52 implants); the difference between these lengths is relatively small and the corresponding implants taken together account for most cases in the study ($n = 129$). This can be considered a limitation of the study.

Indeed, we recognize that our study has various limitations. First, we used a convenience sample from a single geographical region. In particular, the study population is not representative of cases in which there is insufficient bone to fully accommodate an implant or those in which the radiological BD is altered, such as a postextraction alveolar socket that is healing by natural regeneration or bone regenerated with biomaterials. Furthermore, we used a single type of implant (Bego Semados S-line) in all cases, and hence, our findings may not be generalizable to other implant designs. On the other hand, our analysis is based on a relatively large sample of patients covering an age range typical of candidates for dental implants, and all patients had implants inserted under equivalent conditions, at the same distance from the bone level, and had imaging performed with the same system. Notably, we found no data in the literature on the relation between ARW and PIS, and our findings indicate an association between ARW and specifically ISQ (as defined in this study).

As we indicated earlier in the Discussion, further research is needed in this field to clarify and confirm the trends observed. Future studies should have a more robust design with large randomly selected samples. Furthermore, studies are required to assess the ability of BD to predict PIS with different implant designs, specifically investigating how the design influences the relationship between total ARW and ISQ values. We believe that it is important to improve our understanding of the way in which ARW affects PIS because this might help us improve the success rate of immediate loading implants.

Conclusions

In our study population, PIS assessed in terms of ISQ and IT was positively correlated with the BD of the edentulous alveolar ridge measured preoperatively by CBCT, rejecting our null hypothesis and supporting our alternative hypothesis. That is, our findings suggest that it may be possible to predict implant stability preoperatively by this type of radiographic study. Specifically, with the implant design studied, both IT and ISQ were lower in low-density bone, and the PIS was best predicted by BD in the periphery of the implant area. Wide alveolar ridges favored lateral PIS, although they seemed to have no effect on rotational PIS. Furthermore, greater PIS as reflected in higher ISQ values was associated with wider implants. There was a significant positive association between lateral and rotational PIS. Nonetheless, our results must be interpreted with caution given that we only studied 1 implant design and used a convenience sample. Further research is needed to help continue to improve the stability of dental implants.

Abbreviations

ARW: alveolar ridge width
BD: bone density
CBCT: cone beam computerized tomography
CT: computerized tomography
ISQ: implant stability quotient
ISQ-BL: implant stability quotient measured in a buccolingual direction
ISQ-MD: implant stability quotient measured in a mesiodistal direction
IT: insertion torque
PIS: primary implant stability

References

1. Al-Sabbagh M, Eldomiaty W, Khabbaz Y. Can osseointegration be achieved without primary stability? *Dent Clin North Am*. 2019;63:461–473.
2. Misch CE. Density of bone: effect on treatment planning, surgical approach, and healing. In: Misch CE, ed. *Contemporary Implant Dentistry*. St Louis, Mo: Mosby-Year Book; 1993:469–485.
3. Zhou N, Dong H, Zhu Y, Liu H, Zhou N, Mou Y. Analysis of implant loss risk factors especially in maxillary molar location: a retrospective study of 6977 implants in Chinese individuals. *Clin Implant Dent Relat Res*. 2019;21: 138–144.
4. Norton MR, Gamble C. Bone classification: an objective scale of bone density using the computerized tomography scan. *Clin Oral Implants Res*. 2001;12:79–84.
5. Maki K, Okano T, Morohashi T, Yamada S, Shibaski Y. The application of three-dimensional quantitative computed tomography to the maxillofacial skeleton. *Dentomaxillofac Radiol*. 1997;26:39–44.
6. Todisco M, Trisi P. Bone mineral density and bone histomorphometry are statistically related. *Int J Oral Maxillofac Implants*. 2005;20:898–904.
7. Makimoto Y, Matsuzaki K, Yoshida S, Nishitani H. Early clinical experience on cone-beam CT. *J Digit Imaging*. 1998;11:211–213.
8. Mozzo P, Procacci C, Tacconi A, Martini PT, Andreis IA. A new volumetric CT machine for dental imaging based on the cone-beam technique: preliminary results. *Eur Radiol*. 1998;8:1558–1564.
9. Jacobs R, Salmon B, Codari M, Hassan B, Bornstein MM. Cone beam computed tomography in implant dentistry: recommendations for clinical use. *BMC Oral Health*. 2018;18:88.
10. Naitoh M, Hirukawa A, Katsumata A, Ariji E. Evaluation of voxel values in mandibular cancellous bone: relationship between cone-beam computed tomography and multislice helical computed tomography. *Clin Oral Implants Res*. 2009;20:503–506.
11. Sennerby L, Andersson P, Pagliani L, et al. Evaluation of a novel cone beam computed tomography scanner for bone density examinations in preoperative 3D reconstructions and correlation with primary stability. *Clin Implant Dent Relat Res*. 2015;17:844–853.
12. Arisan V, Karabuda ZC, Avsever H, Özdemir T. Conventional multislice computed tomography (CT) and cone-beam CT (CBCT) for computer-assisted implant placement. Part I: relationship of radiographic gray density and implant stability. *Clin Implant Dent Relat Res*. 2013;15:893–906.
13. Tettamanti L, Andrisani C, Bassi MA, Vinci R, Silvestre-Rangil J, Tagliabue A. Immediate loading implants: review of the critical aspects. *Oral Implantol (Rome)*. 2017;10:129–139.
14. Marquezan M, Osório A, Sant'Anna E, Souza MM, Maia L. Does bone mineral density influence the primary stability of dental implants? A systematic review. *Clin Oral Implants Res*. 2012;23:767–774.
15. Martínez González MA, Sánchez-Villegas A, Faulin Fajardo J. *Bioestadística Amigable*. 3rd ed. Madrid, Spain: Ediciones Diaz de Santos S.A.; 2009.
16. Turkyilmaz I, Tumer C, Ozbek EN, Tözüm TF. Relations between the bone density values from computerized tomography, and implant stability parameters: a clinical study of 230 regular platform implants. *J Clin Periodontol*. 2007;34:716–722.
17. Turkyilmaz I, McGlumphy EA. Influence of bone density on implant stability parameters and implant success: a retrospective clinical study. *BMC Oral Health*. 2008;8:32.
18. Farré-Pagés N, Augé-Castro ML, Alaejos-Algarra F, Mareque-Bueno J, Ferrés-Padró E, Hernández-Alfaro F. Relation between bone density and primary implant stability. *Med Oral Patol Oral Cir Bucal*. 2011;16:e62–e367.
19. Herekar M, Sethi M, Ahmad T, Fernandes AS, Patil V, Kulkarni H. A correlation between bone (B), insertion torque (IT), and implant stability (S): BITS score. *J Prosthet Dent*. 2014;112:805–810.
20. Fuster-Torres MA, Peñarrocha-Diago M, Peñarrocha-Oltra D, Peñarrocha-Diago M. Relationships between bone density values from cone beam computed tomography, maximum insertion torque, and resonance frequency analysis at implant placement: a pilot study. *Int J Oral Maxillofac Implants*. 2011;26:1051–1056.
21. Hsu JT, Fuh LJ, Tu MG, Li YF, Chen KT, Huang HL. The effects of cortical bone thickness and trabecular bone strength on noninvasive measures of the implant primary stability using synthetic bone models. *Clin Implant Dent Relat Res*. 2013;15:251–261.
22. Divac M, Stawarczyk B, Sahrmann P, Attin T, Schmidlin P R. Influence of residual bone thickness on primary stability of hybrid self-tapping implants in vitro. *Int J Oral Maxillofac Implants*. 2013;28:84–88.
23. Wang TM, Lee MS, Wang JS, Lin LD. The effect of implant design and bone quality on insertion torque, resonance frequency analysis, and insertion energy during implant placement in low or low- to medium-density bone. *Int J Prosthodont*. 2015;28:40–47.
24. Marquezan M, Mattos CT, Sant'Anna EF, de Souza MM, Maia LC. Does cortical thickness influence the primary stability of miniscrews?: a systematic review and meta-analysis. *Angle Orthod*. 2014;84:1093–1103.
25. Ohiomoba H, Sonis A, Yansane A, Friedland B. Quantitative evaluation of maxillary alveolar cortical bone thickness and density using computed tomography imaging. *Am J Orthod Dentofacial Orthop*. 2017;151: 82–91.
26. Suer BT, Yaman Z, Buyuksarac B. Correlation of fractal dimension values with implant insertion torque and resonance frequency values at implant recipient sites. *Int J Oral Maxillofac Implants*. 2016;31:55–62.
27. Lee DH, Ku Y, Rhyu IC, et al. A clinical study of alveolar bone quality using the fractal dimension and the implant stability quotient. *J Periodontal Implant Sci*. 2010;40:19–24.
28. Veltri M, Ferrari M, Balleri P. Correlation of radiographic fractal analysis with implant insertion torque in a rabbit trabecular bone model. *Int J Oral Maxillofac Implants*. 2011;26:108–114.
29. Ribeiro-Rotta RF, de Oliveira RC, Dias DR, Lindh C, Leles CR. Bone tissue microarchitectural characteristics at dental implant sites part 2: correlation with bone classification and primary stability. *Clin Oral Implants Res*. 2014;25:e47–e53.
30. Fu MW, Fu E, Lin FG, Chang WJ, Hsieh YD, Shen EC. Correlation between resonance frequency analysis and bone quality assessments at

dental implant recipient sites. *Int J Oral Maxillofac Implants*. 2017;32:180–187.

31. Filho LC, Cirano FR, Hayashi F, et al. Assessment of the correlation between insertion torque and resonance frequency analysis of implants placed in bone tissue of different densities. *J Oral Implantol*. 2014;40:259–262.

32. Makary C, Rebaudi A, Sammartino G, Naaman N. Implant primary stability determined by resonance frequency analysis: correlation with insertion torque, histologic bone volume, and torsional stability at 6 weeks. *Implant Dent*. 2012;21:474–480.

33. Lages FS, Douglas-de Oliveira DW, Costa FO. Relationship between implant stability measurements obtained by insertion torque and resonance frequency analysis: A systematic review. *Clin Implant Dent Relat Res*. 2018;20:26–33.

34. Gómez-Polo M, Ortega R, Gómez Polo C, Martín C, Celemín A, del Río J. Does length, diameter or bone quality affect primary and secondary stability in self-tapping dental implants? *J Oral Maxillofac Surg*. 2016;74:1344–1353.

35. Karl M, Graef F, Heckmann S, Krafft T. Parameters of resonance frequency measurement values: a retrospective study of 385 ITI dental implants. *Clin Oral Implants Res*. 2008;19:214–218.

36. Bataineh AB, Al-Dakes AM. The influence of length of implant on primary stability: an in vitro study using resonance frequency analysis. *J Clin Exp Dent*. 2017;9:e1–e6.

37. Kong L, Sun Y, Hu K, et al. Bivariate evaluation of cylinder implant diameter and length: a three-dimensional finite element analysis. *J Prosthodont*. 2008;17:286–293.