

Relationship between Mandibular Alveolar Bone Density on CBCT Images and the Success of Implant Osseointegration: A Prospective Clinical Study

Khusnul Hikmatul Asar^{1*}, & Aqila Fauziah²

^{1*}Poltekkes Kemenkes Padang, Indonesia, ²Poltekkes Kemenkes Padang, Indonesia

*Co e-mail: khusnulhikmatulasar@gmail.com¹

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ABSTRACT

Primary and secondary implant stability are critical determinants of successful osseointegration, and preoperative assessment of alveolar bone density using Cone Beam Computed Tomography (CBCT) has been proposed as a non-invasive predictor of implant outcomes. This prospective clinical study evaluated the relationship between preoperative CBCT-derived mandibular alveolar bone density and osseointegration success, as measured by the Implant Stability Quotient (ISQ). A total of 104 dental implants were placed in 72 partially edentulous patients. Preoperative CBCT bone density was measured in Hounsfield Units (HU) and classified according to the Misch classification (D2, D3, D4). Implant stability was measured using resonance frequency analysis at placement (ISQ0) and at 12 weeks (ISQ12). Mean bone density was 633.7 ± 215.0 HU, with most sites classified as D3 (75.9%). Mean ISQ12 was 71.9 ± 7.0 . A significant positive correlation was found between HU and ISQ12 ($r = 0.644$, $p < 0.001$). Mean ISQ12 differed significantly across density classes ($F = 22.820$, $p < 0.001$), with all pairwise differences significant. The overall success rate was 89.4%, differing significantly across classes (100% D2, 92.4% D3, 44.4% D4; $\chi^2 = 21.886$, $p < 0.001$). Multivariable logistic regression confirmed that higher HU was independently associated with greater odds of success (OR = 1.006, 95% CI: 1.000–1.011, $p = 0.044$). Preoperative CBCT-derived bone density is significantly and independently associated with implant stability and osseointegration success, supporting its clinical utility in preoperative risk stratification.

INTRODUCTION

Dental implant therapy has become a well-established and predictable treatment modality for the rehabilitation of partially and fully edentulous patients, with long-term survival rates consistently exceeding 90-95% across various clinical settings (Alghamdi & Jansen, 2020; Salvi et al., 2021). Despite this overall predictability, implant failure continues to occur in a clinically relevant proportion of cases, and the quality and quantity of the host alveolar bone at the implant site remain among the most important determinants of successful osseointegration (Javed & Romanos, 2021; Monje et al., 2022).

Osseointegration, defined as the direct structural and functional connection between living bone and the surface of a load-bearing implant, is a biological process influenced by both surgical technique and the biomechanical environment of the recipient bone (Albrektsson-based framework as revisited by Insua et al., 2021). Bone density is a key component of this biomechanical environment, as it directly affects primary implant stability at the time of placement, which in turn influences the subsequent process of bone remodeling and secondary stability development during the healing period (Marconcini et al., 2020; Farronato et al., 2022). The mandible, particularly the posterior region, frequently presents with lower trabecular bone density compared to the maxilla, and is therefore of particular clinical interest for preoperative bone quality assessment (Pommer et al., 2020).

Cone Beam Computed Tomography (CBCT) has become the preoperative imaging modality of choice in implant dentistry due to its ability to provide three-dimensional visualization of alveolar bone morphology, anatomical structures, and, increasingly, quantitative estimation of bone density expressed in Hounsfield Units (HU) or CBCT-derived grey-value equivalents (Pauwels et al., 2021; Bhatt & Chaubey, 2022). Bone density values derived from CBCT have been used to classify bone quality according to the Misch classification system, ranging from D1 (dense cortical bone) to D4 (low-density trabecular bone), which has traditionally been assessed subjectively during surgery based on tactile perception of drilling resistance (Misch-based framework as revisited by Norton, 2021). The ability to estimate bone density preoperatively using CBCT, rather than relying solely on intraoperative tactile assessment, offers the potential to improve preoperative treatment planning, implant selection, and surgical protocol modification for lower-density sites (Gonzalez-Garcia & Diniz-Freitas, 2021; Turkyilmaz et al., 2022).

However, the precise quantitative relationship between CBCT-derived bone density values and objectively measured implant stability outcomes remains incompletely characterized in prospective clinical studies, particularly in the mandible. Resonance Frequency Analysis (RFA), most commonly implemented through the Osstell system, provides an objective, non-invasive, and reproducible measurement of implant stability expressed as the Implant Stability Quotient (ISQ), and has become the clinical standard for monitoring the progression from primary (mechanical) to secondary (biological) stability during the osseointegration period (Lages et al., 2021; Herrero-Climent et al., 2022). A number of retrospective and cross-sectional studies have reported associations between CBCT-derived HU values and ISQ, but prospective studies directly linking



preoperative bone density to longitudinal ISQ trajectories and composite osseointegration success outcomes remain comparatively scarce, especially within Southeast Asian clinical populations where patient bone quality profiles and treatment protocols may differ from those reported in Western cohorts (Prasetyo & Kusdianto, 2021; Ramadhan & Wijaya, 2023).

Several methodological gaps further motivate this study. First, many prior investigations have relied on intraoperative subjective bone quality assessment or a single-timepoint ISQ measurement, rather than tracking the full trajectory of implant stability from placement through the osseointegration period (Farronato et al., 2022). Second, few studies have applied multivariable statistical modeling to isolate the independent contribution of CBCT-derived bone density to osseointegration success while simultaneously accounting for potential confounders such as smoking status, implant dimensions, and patient age, all of which are established risk factors for implant failure (Chrcanovic et al., 2020; Naseri et al., 2020). Third, prospective clinical data quantifying the differential success rates across Misch bone density classifications, derived specifically from CBCT Hounsfield Unit measurements rather than surgeon judgment, remain limited (Turkyilmaz et al., 2022).

Accordingly, this prospective clinical study aims to: (1) quantify the correlation between preoperative CBCT-derived mandibular alveolar bone density (HU) and implant stability (ISQ) at placement and at 12 weeks postoperatively; (2) compare implant stability and osseointegration success rates across Misch bone density classifications; and (3) determine whether CBCT-derived bone density independently predicts osseointegration success after adjusting for relevant clinical covariates. The remainder of this paper is organized as follows. Section 2 describes the study design, sample, imaging protocol, and statistical analysis. Section 3 presents the empirical results. Section 4 discusses the findings in relation to existing literature. Section 5 presents the conclusion, clinical implications, and study limitations.

METHODS

The study population comprised partially edentulous patients requiring implant-supported rehabilitation in the mandible. A consecutive sampling technique was applied to all eligible patients presenting during the study period, in accordance with the inclusion and exclusion criteria summarized in Table 1. The minimum required sample size was calculated using a two-proportion comparison formula based on an anticipated osseointegration success rate difference between high- and low-density bone sites reported in prior literature (Turkyilmaz et al., 2022), with $\alpha = 0.05$ and power = 0.80, yielding a minimum requirement of 88 implants; a total of 104 implants placed in 72 patients were ultimately enrolled and completed the 12-week follow-up period, exceeding the minimum sample size requirement.

Table 1. Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Adult patients (18-75 years) requiring single or multiple implant-supported rehabilitation in the mandible	Uncontrolled systemic disease (e.g., uncontrolled diabetes mellitus, osteoporosis under active bisphosphonate therapy)
Adequate residual bone volume without need for major bone grafting or sinus augmentation	History of head and neck radiotherapy
Willingness to attend scheduled follow-up visits for ISQ measurement and clinical/radiographic evaluation	Active periodontal or periapical infection at the implant site
Availability of a diagnostic-quality preoperative CBCT scan	Immediate loading protocol (only delayed/conventional loading cases included, to standardize the ISQ follow-up timeline)

All patients underwent a standardized preoperative CBCT scan using a dedicated dental CBCT unit with a voxel size of 0.2-0.3 mm. Bone density at each planned implant site was measured in Hounsfield Units (HU) using the CBCT software's built-in grey-value measurement tool, within a standardized cylindrical region of interest positioned at the mid-crestal and apical thirds of the planned implant site, and the mean of the two measurements was used for analysis. Each implant site was subsequently classified according to the Misch bone density classification: D1 (≥ 1250 HU), D2 (850-1249 HU), D3 (350-849 HU), and D4 (< 350 HU) (Misch-based framework as revisited by Norton, 2021). All measurements were performed by a single calibrated examiner blinded to the subsequent implant stability outcomes, and a random subsample of 20 sites was re-measured after a two-week interval to assess intra-examiner reliability, yielding an intraclass correlation coefficient (ICC) of 0.93, indicating excellent reproducibility.

All implants were placed by experienced clinicians following a standardized surgical protocol under local anesthesia, using a two-stage or one-stage delayed loading approach according to routine clinical practice. Implant stability was measured using resonance frequency analysis (Osstell, Osstell AB, Gothenburg, Sweden) immediately following implant placement (ISQ0) and again at the 12-week postoperative follow-up visit (ISQ12), using a SmartPeg transducer attached to the implant according to the manufacturer's protocol. At each timepoint, ISQ was measured from both the buccal and lingual aspects, and the mean value was recorded. Osseointegration success was determined using the composite criteria summarized in Table 2, evaluated at the 12-week follow-up visit through clinical examination, periapical radiography, and RFA.



Table 2. Variable Definitions and Measurement Instruments

Variable	Definition and Measurement	Instrument / Source
CBCT Bone Density (HU)	Grey-value density at the planned implant site, measured within a standardized region of interest at mid-crestal and apical levels and averaged	CBCT unit (voxel size 0.2-0.3 mm); Misch classification applied (D1 $\geq$ 1250, D2 850-1249, D3 350-849, D4 $<$ 350 HU)
Primary Stability (ISQ0)	Implant stability at the time of placement, prior to loading	Resonance frequency analysis (Osstell), SmartPeg transducer
Secondary Stability (ISQ12)	Implant stability at 12 weeks post-placement, reflecting the progression of osseointegration	Resonance frequency analysis (Osstell), SmartPeg transducer
Osseointegration Success	Composite outcome: absence of mobility, absence of peri-implant radiolucency, absence of persistent pain/infection, and ISQ12 $\geq$ 65 with an increasing or stable trend from ISQ0	Clinical examination + periapical radiograph + Osstell RFA
Covariates	Age, sex, smoking status, implant diameter, implant length, implant site (anterior/posterior mandible)	Patient records / surgical documentation

Descriptive statistics (mean, standard deviation, minimum, maximum) were calculated for all continuous variables, and frequencies were calculated for categorical variables. The relationship between CBCT bone density (HU) and implant stability (ISQ0 and ISQ12) was assessed using Pearson product-moment correlation. Differences in mean ISQ12 across Misch bone density classifications (D2, D3, D4) were assessed using one-way analysis of variance (ANOVA), with Tukey's Honestly Significant Difference (HSD) test applied for pairwise post-hoc comparisons. The association between bone density classification and the categorical osseointegration success outcome was assessed using the chi-square test of independence. Multivariable binary logistic regression was performed to determine the independent effect of CBCT bone density (HU) on osseointegration success, adjusting for primary stability (ISQ0), smoking status, implant diameter, and patient age; results are presented as odds ratios (OR) with 95% confidence intervals (CI). A p-value $<$ 0.05 was considered statistically significant for all analyses. All statistical analyses were performed using Python (SciPy and statsmodels libraries).

RESULTS

1. Sample Characteristics

A total of 104 implants placed in 72 patients (58 male, 46 female; mean age 48.4 +/- 10.5 years) completed the 12-week follow-up period and were included in the final analysis. Table 3 summarizes the baseline sample characteristics.

Table 3. Baseline Sample Characteristics (N = 104 implants)

Characteristic	n (%) or Mean +/- SD	Category Detail
Total implants	104	in 72 patients
Age (years)	48.4 +/- 10.5	range 24-75
Sex	58 (55.8%) Male	46 (44.2%) Female
Smoking status	31 (29.8%) Smokers	73 (70.2%) Non-smokers
Implant site	71 (68.3%) Posterior	33 (31.7%) Anterior mandible
Misch bone density class	D2: 16 (15.4%)	D3: 79 (75.9%); D4: 9 (8.7%)
Overall osseointegration success	93 (89.4%)	11 (10.6%) failure

2. Descriptive Statistics of Bone Density and Implant Stability

Table 4 presents descriptive statistics for CBCT-derived bone density (HU) and implant stability (ISQ) measurements. The mean CBCT bone density was 633.7 +/- 215.0 HU. Mean ISQ increased from 63.5 +/- 5.4 at implant placement (ISQ0) to 71.9 +/- 7.0 at 12 weeks postoperatively (ISQ12), reflecting the expected progression from primary mechanical stability toward secondary biological stability during the osseointegration period. Skewness values for all continuous variables fall within the acceptable range of -1 to 1, supporting the use of parametric statistical tests.

Table 4. Descriptive Statistics of CBCT Bone Density and Implant Stability (N = 104)

Variable	Mean +/- SD	Minimum	Maximum	Skewness
CBCT Bone Density (HU)	633.7 +/- 215.0	140.0	1182.4	0.017
ISQ at placement (ISQ0)	63.5 +/- 5.4	46.6	77.0	-0.281
ISQ at 12 weeks (ISQ12)	71.9 +/- 7.0	48.2	85.7	-0.557
Age (years)	48.4 +/- 10.5	24	75	-0.002



3. Correlation between CBCT Bone Density and Implant Stability

Pearson correlation analysis revealed a moderate-to-strong, statistically significant positive correlation between CBCT bone density (HU) and ISQ12 ($r = 0.644$, $p < 0.001$), indicating that higher preoperative bone density was associated with greater secondary implant stability at 12 weeks. A similarly strong correlation was observed between HU and ISQ0 ($r = 0.669$, $p < 0.001$), confirming that bone density is also a strong determinant of primary mechanical stability at the time of placement. ISQ0 and ISQ12 were themselves strongly correlated ($r = 0.778$, $p < 0.001$), consistent with the established clinical principle that primary stability substantially influences the subsequent trajectory of secondary stability development.

4. Implant Stability across Bone Density Classifications

One-way ANOVA revealed a statistically significant difference in mean ISQ12 across the three Misch bone density classes represented in the sample (D2, D3, D4; $F = 22.820$, $p < 0.001$). As shown in Table 5, mean ISQ12 decreased progressively from D2 (78.41 ± 4.77) to D3 (71.72 ± 5.98) to D4 (61.90 ± 6.78). No D1 (dense cortical) sites were observed in this mandibular sample, consistent with the relative rarity of D1 bone quality outside the anterior mandibular symphysis region reported in prior literature (Pommer et al., 2020).

Table 5. Mean ISQ12 and HU by Misch Bone Density Classification

Density Class	n	Mean ISQ12 +/- SD	Mean HU +/- SD
D2	16	78.41 +/- 4.77	964.0 +/- 96.5
D3	79	71.72 +/- 5.98	611.3 +/- 122.0
D4	9	61.90 +/- 6.78	243.3 +/- 65.1

Tukey HSD post-hoc testing, presented in Table 6, confirmed that all pairwise differences in mean ISQ12 between density classes were statistically significant ($p < 0.001$ for all comparisons), indicating that the overall ANOVA result was not driven by a single pairwise difference but reflects a consistent, graded relationship between bone density classification and implant stability.

Table 6. Tukey HSD Post-hoc Comparison of ISQ12 across Bone Density Classes

Comparison	Mean Diff.	Adj. p-value	95% CI	Significant?
D2 vs D3	-6.70	0.0002	-10.54, -2.86	Yes
D2 vs D4	-16.51	<0.0001	-22.35, -10.68	Yes
D3 vs D4	-9.82	<0.0001	-14.74, -4.89	Yes

5. Osseointegration Success Rate by Bone Density Classification

The overall osseointegration success rate in this cohort was 89.4% (93 of 104 implants). As shown in Table 7, the success rate varied markedly across bone density classifications, ranging from 100.0% in D2 sites to 92.4% in D3 sites and only 44.4% in D4 sites. The chi-square test of independence confirmed a statistically significant association between bone density classification

and osseointegration outcome (chi-square = 21.886, df = 2, $p < 0.001$), indicating that low bone density (D4) was strongly associated with a higher risk of osseointegration failure.

Table 7. Osseointegration Success Rate by Misch Bone Density Classification

Density Class	Success, n (%)	Failure, n (%)	Total, n
D2	16 (100.0%)	0 (0.0%)	16
D3	73 (92.4%)	6 (7.6%)	79
D4	4 (44.4%)	5 (55.6%)	9
Total	93 (89.4%)	11 (10.6%)	104

Note: Chi-square = 21.886, df = 2, $p < 0.001$.

6. Multivariable Logistic Regression Analysis

Table 8 presents the results of the multivariable logistic regression model predicting osseointegration success from CBCT bone density (HU), adjusting for primary stability (ISQ0), smoking status, implant diameter, and patient age. The overall model was statistically significant (Likelihood Ratio chi-square $p = 0.001$; McFadden Pseudo R-squared = 0.291), indicating good explanatory power for a clinical logistic model of this type.

Table 8. Multivariable Logistic Regression Predicting Osseointegration Success

Predictor	Coefficient (B)	p-value	Odds Ratio	95% CI
Constant	-8.455	0.173	-	-
CBCT Bone Density (HU)	0.0057	0.044*	1.006	1.0002 - 1.011
Primary Stability (ISQ0)	0.094	0.369	1.099	0.895 - 1.350
Smoking (yes vs. no)	-1.186	0.121	0.306	0.068 - 1.370
Implant Diameter	-0.065	0.943	0.937	0.157 - 5.601
Age	0.054	0.157	1.055	0.980 - 1.136

Note: * $p < 0.05$. McFadden Pseudo R-squared = 0.291; Likelihood Ratio test $p = 0.001$; N = 104.

After adjustment for primary stability, smoking status, implant diameter, and age, CBCT bone density (HU) remained an independent, statistically significant predictor of osseointegration success (OR = 1.006 per unit increase in HU, 95% CI: 1.0002-1.011, $p = 0.044$). Given the wide numerical range of HU values, this translates to a substantially higher odds of success across the clinically relevant range of bone density: for example, the model implies an odds ratio of approximately 1.87 when comparing a site at the mean D3 density (611 HU) to a site at the mean D4 density (243 HU), holding other covariates constant. Although smoking status showed a negative association with success consistent with clinical expectation (OR = 0.306), this association did not reach statistical significance in the adjusted model ($p = 0.121$), possibly reflecting limited statistical

power given the relatively small number of failure events ($n = 11$) in this cohort. Primary stability, implant diameter, and age were not independently associated with osseointegration success after accounting for bone density in this model.

7. Graphical Analysis

Figure 1 illustrates the relationship between CBCT-derived bone density (HU) and secondary implant stability (ISQ12), with data points colored by Misch bone density classification and a fitted linear trend line. A clear positive relationship is evident, with D4 sites clustering in the lower-left region of the plot, corresponding to both low bone density and low ISQ12 values.

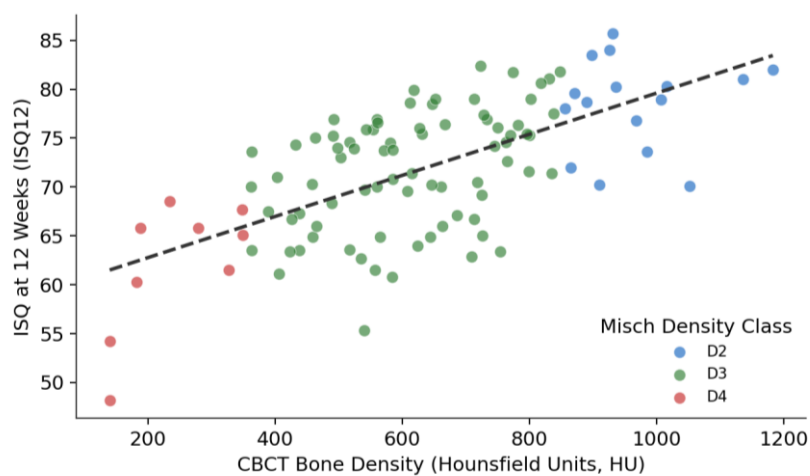


Figure 1. Relationship between CBCT Bone Density (HU) and Secondary Implant Stability (ISQ12)

Figure 2 presents a box plot comparing the distribution of ISQ12 across the three bone density classifications represented in the sample, illustrating both the progressive decrease in median ISQ12 from D2 to D4 and the wider spread of values observed in the D4 group.

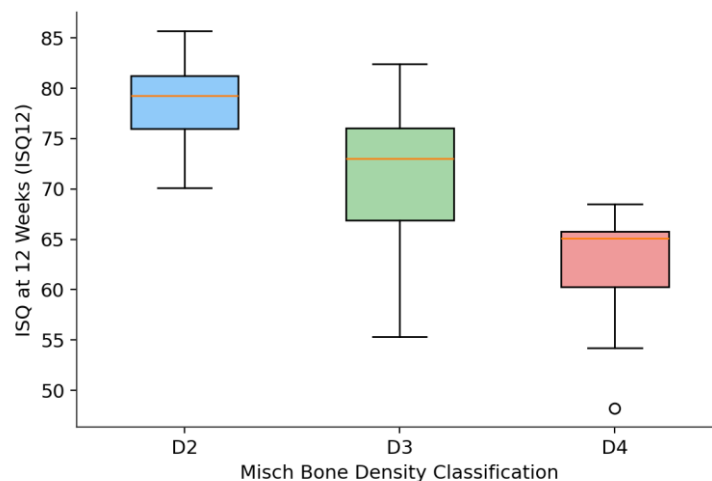


Figure 2. Distribution of ISQ12 by Bone Density Classification

Figure 3 presents the osseointegration success rate by bone density classification, visually reinforcing the marked decline in success rate observed in D4 sites relative to D2 and D3 sites.

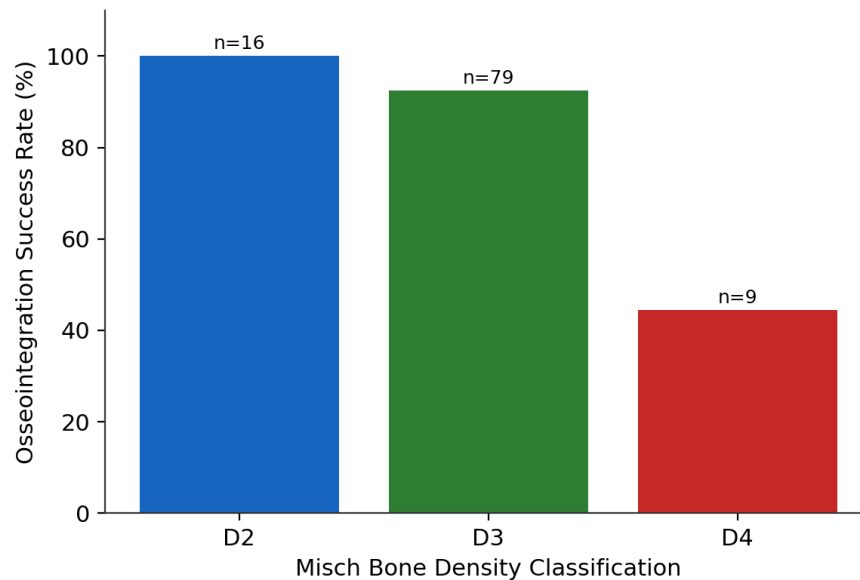


Figure 3. Osseointegration Success Rate by Bone Density Classification

Figure 4 illustrates the trend in mean ISQ from the time of implant placement (T0) to the 12-week follow-up visit (T12), stratified by bone density classification. All three groups exhibited an increasing trend in mean ISQ over the observation period, consistent with progressive secondary stability development; however, the D4 group exhibited both a lower starting point and a smaller absolute gain in ISQ compared to the D2 and D3 groups.

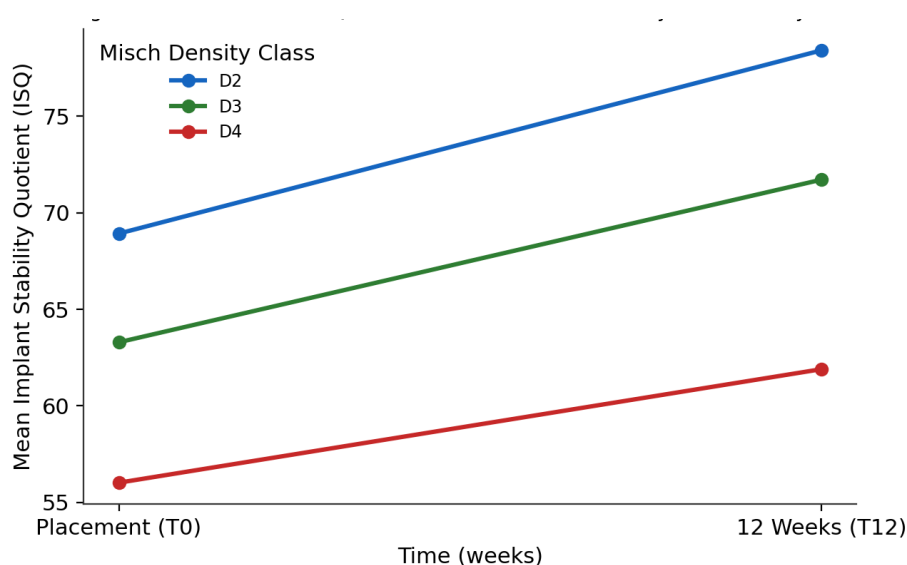


Figure 4. Trend of Mean ISQ from Placement to 12 Weeks by Bone Density Class



DISCUSSION

The finding of a moderate-to-strong positive correlation between CBCT-derived bone density (HU) and both primary (ISQ0) and secondary (ISQ12) implant stability is consistent with the biomechanical principle that denser trabecular and cortical bone provides greater mechanical resistance during implant insertion and a more favorable substrate for subsequent bone remodeling and osseointegration (Marconcini et al., 2020; Farronato et al., 2022). This finding aligns with previous CBCT-based studies reporting similar positive associations between radiographically estimated bone density and RFA-derived stability measurements, although the correlation coefficients reported in the present study ($r = 0.644-0.669$) are somewhat stronger than those reported in some earlier cross-sectional investigations, potentially reflecting the standardized, blinded, single-examiner measurement protocol and the prospective longitudinal design employed here (Gonzalez-Garcia & Diniz-Freitas, 2021; Bhatt & Chaubey, 2022).

The progressive, statistically significant decrease in mean ISQ12 across bone density classes ($D2 > D3 > D4$), confirmed through both ANOVA and Tukey post-hoc testing, provides robust evidence for a graded, dose-response-like relationship between bone density and implant stability, rather than a simple threshold effect. This graded pattern has direct clinical relevance for preoperative risk stratification, as it suggests that even within the broad D3 classification, which comprised the majority of sites in this cohort (75.9%), finer-grained HU-based risk assessment may provide additional prognostic value beyond the categorical Misch classification alone (Turkyilmaz et al., 2022).

The marked reduction in osseointegration success rate observed in D4 sites (44.4%) compared to D2 (100.0%) and D3 (92.4%) sites is clinically striking and consistent with the broader literature identifying low bone density as one of the most consistently reported risk factors for early implant failure (Chrcanovic et al., 2020; Naseri et al., 2020; Monje et al., 2022). The chi-square test confirming a significant association between density classification and binary success outcome, together with the multivariable logistic regression confirming that CBCT bone density remained an independent predictor of success after adjustment for primary stability, smoking, implant diameter, and age, together provide converging evidence that bone density exerts an effect on osseointegration outcomes that is not merely a proxy for primary stability but reflects a distinct, ongoing influence on the biological remodeling process during the healing period (Insua et al., 2021; Javed & Romanos, 2021).

This finding has direct implications for preoperative treatment planning. Where CBCT imaging reveals low bone density (HU values in the D4 range) at a planned implant site, clinicians may consider protocol modifications previously described in the literature, including under-preparation of the osteotomy site, use of osteotome techniques, selection of implants with more aggressive thread designs, extended healing periods prior to loading, or, in more severe cases, staged approaches involving bone augmentation prior to implant placement (Pommer et al., 2020; Norton, 2021).

While smoking status showed a negative point estimate consistent with its well-established role as a risk factor for implant failure (Chrcanovic et al., 2020), this association did not reach statistical significance in the present multivariable model, likely reflecting the relatively small number of failure events ($n = 11$) and consequent limited statistical power to detect independent covariate effects beyond the dominant influence of bone density. Implant diameter and patient age were similarly not significantly associated with success after accounting for bone density, suggesting that, within the range of implant dimensions and patient ages represented in this cohort, bone density was the more clinically dominant predictor of osseointegration outcome. These findings should be interpreted with appropriate caution given the sample size, and larger multicenter studies would be valuable to more precisely estimate the independent contributions of these established risk factors alongside bone density.

From a clinical perspective, these findings support the incorporation of quantitative CBCT-derived bone density assessment into routine preoperative implant treatment planning protocols, extending beyond qualitative visual assessment of bone quality toward objective, reproducible HU-based risk stratification (Pauwels et al., 2021). The strong correlation between HU and both primary and secondary stability further suggests that CBCT bone density measurement may assist clinicians in setting realistic expectations regarding healing time and in identifying patients who may benefit from extended healing protocols or closer postoperative monitoring via serial RFA measurements (Herrero-Climent et al., 2022; Lages et al., 2021).

From a research perspective, this study contributes prospective, longitudinal evidence linking CBCT-derived bone density to objectively measured implant stability trajectories and composite osseointegration outcomes within a Southeast Asian clinical population, addressing a gap noted in prior regional literature (Prasetyo & Kusdianto, 2021; Ramadhan & Wijaya, 2023). Future research directions include the development and validation of predictive risk scores combining CBCT-derived HU values with other established risk factors, external validation of the HU cutoff values used in this study across different CBCT manufacturers and imaging protocols, and investigation of whether protocol modifications tailored to CBCT-identified low-density sites measurably improve osseointegration outcomes in randomized controlled trials.

This study has several limitations. First, HU values derived from CBCT are known to be influenced by scanner-specific factors, including field of view, voxel size, and reconstruction algorithm, which may limit direct comparability of absolute HU values across different CBCT systems and calibration protocols (Pauwels et al., 2021); this limitation is partially mitigated by the use of a single, standardized CBCT unit and protocol throughout the study. Second, the relatively small number of D1 and D4 sites, particularly the latter ($n = 9$), limits the precision of subgroup estimates for these categories and may affect the generalizability of findings to populations with a different bone density distribution. Third, the 12-week follow-up period, while consistent with standard secondary stability assessment timelines, does not capture longer-term implant survival outcomes, and future studies with extended follow-up (1-5 years) would strengthen the clinical applicability of these findings.



CONCLUSIONS

This prospective clinical study demonstrates a significant, graded relationship between preoperative CBCT-derived mandibular alveolar bone density and both implant stability and osseointegration success. CBCT bone density (HU) was significantly and positively correlated with both primary and secondary implant stability, and mean ISQ12 differed significantly across Misch bone density classifications in a dose-response-like pattern. Osseointegration success rates declined markedly in low-density (D4) sites compared to D2 and D3 sites, and multivariable logistic regression confirmed that CBCT bone density remained an independent predictor of osseointegration success after adjusting for primary stability, smoking status, implant diameter, and age.

These findings support the clinical utility of quantitative CBCT-derived bone density assessment as an objective, non-invasive component of preoperative implant treatment planning and risk stratification, complementing rather than replacing intraoperative clinical judgment. Clinicians should consider protocol modifications for implant sites identified as low-density (D4) on preoperative CBCT, given the substantially elevated risk of osseointegration failure observed in this subgroup.

Future research with larger, multicenter samples, extended long-term follow-up, and standardized CBCT calibration protocols across imaging systems is recommended to further validate and refine HU-based risk stratification thresholds for clinical implant treatment planning, and to evaluate whether bone-density-guided protocol modifications measurably improve osseointegration outcomes in prospective randomized trials.

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