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# NANDAN Bone Quality Classification (NBQC): A CBCT-based Functional Bone Assessment System for Dental Implantology

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## ABSTRACT:

**Background:** Accurate assessment of alveolar bone quality is fundamental to achieving predictable outcomes in implant-supported prosthodontics. Existing classifications are largely subjective or rely on single-parameter density assessment, limiting their clinical utility.

**Purpose:** To develop and validate a novel cone-beam computed tomography (CBCT)-based, multi-parameter bone quality classification system—the Nandan Bone Quality Classification (NBQC)—that integrates radiographic, structural, and functional parameters relevant to implant prosthodontics.

**Materials and Methods:** The NBQC system incorporates five mandatory parameters: CBCT-derived mean Hounsfield Unit (HU) values, cortical plate thickness, trabecular architecture, anticipated primary stability, and recommended loading protocol. Alveolar bone was categorized into five classes (NBQC-A through NBQC-E). A pilot validation study analyzed 25 implant sites in 18 patients, correlating NBQC classes with insertion

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torque and Implant Stability Quotient (ISQ) values. An optional Functional Stability Index (FSI; 0–10 scale) was developed for quantitative assessment.

**Results:** NBQC classes showed progressive correlation with primary stability parameters. Mean insertion torque and ISQ values decreased significantly from NBQC-A to NBQC-E ($P < 0.05$). Higher classes (A and B) demonstrated excellent primary stability suitable for immediate/early loading, while lower classes required delayed protocols. No implant failures occurred during the observation period.

**Conclusions:** The NBQC offers a comprehensive, function-oriented classification system tailored for implant prosthodontics. Its quantitative nature, clinical relevance, and compatibility with digital workflows make it promising for both clinical decision-making and research applications.

## INTRODUCTION

Dental implant success depends critically on the quality and quantity of supporting alveolar bone. Primary stability, osseointegration, and long-term functional loading are directly influenced by bone density, cortical support, and trabecular organization at the implant site. Despite this understanding, currently available bone quality classifications—primarily the Lekholm and Zarb[1] and Misch[2] systems—emphasize bone density and rely heavily on subjective interpretation, limiting their predictive accuracy and reproducibility.

The widespread adoption of cone-beam computed tomography (CBCT) has enabled objective evaluation of bone density and architecture through Hounsfield Unit (HU) measurements and three-dimensional visualization.[3] However, a standardized CBCT-based classification system that integrates radiographic findings with functional clinical outcomes remains lacking. Additionally, emerging applications of artificial intelligence (AI) in implant dentistry require structured, quantifiable input parameters for accurate predictive modeling.[4]

The present study proposes the **Nandan Bone Quality Classification (NBQC)**—a novel, CBCT-based, functional classification system designed to overcome the limitations of existing methods and provide a clinically relevant framework for implant planning, execution, and research.

## MATERIALS AND METHODS

## DEVELOPMENT OF THE NBQC SYSTEM

### Conceptual Framework

The NBQC was conceptualized to reflect the functional capacity of alveolar bone to support dental implants rather than density alone. The classification integrates objective radiographic measurements with structural characteristics and expected clinical performance parameters.

### Mandatory Parameters

- **CBCT-derived mean bone density (HU):** Measured at the proposed implant site using standardized regions of interest
- **Cortical plate thickness (mm):** Assessed on cross-sectional CBCT images at the crestal region
- **Trabecular architecture:** Evaluated based on density distribution, connectivity patterns, and structural organization, features previously shown to correlate with implant primary stability[5]
- **Expected primary stability:** Inferred from combined radiographic and structural parameters
- **Recommended loading protocol:** Derived from overall bone quality assessment and risk stratification

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## PILOT VALIDATION STUDY

### Study Design and Sample

A retrospective observational pilot study was conducted to evaluate the clinical applicability of NBQC and its correlation with primary stability parameters. CBCT records and clinical data from 25 implant sites in 18 patients who underwent implant placement between 2022 and 2025 were analyzed. All implants were titanium, screw-type endosseous implants placed in healed alveolar ridges. The study was conducted in accordance with institutional ethical guidelines.

### CBCT Assessment and NBQC Classification

Preoperative CBCT scans (voxel size 0.2–0.4 mm) were analyzed using standardized cross-sectional and panoramic reconstructions. Mean HU values were recorded at the planned implant site using cylindrical regions of interest matching the proposed implant dimensions. Cortical thickness was measured at the crestal region on cross-sectional views. Trabecular architecture was qualitatively assessed based on density distribution and connectivity patterns. Each implant site was categorized into an NBQC class (A through E) by two independent observers, with disagreements resolved by consensus.

## PRIMARY STABILITY ASSESSMENT

**Insertion torque (Ncm)** was recorded at the time of implant placement using a calibrated digital torque wrench. **Implant Stability Quotient (ISQ)** values were measured using resonance frequency analysis[6] (Osstell device) immediately after placement, with measurements taken from two perpendicular directions and averaged.

### Loading Protocol and Follow-up

Based on achieved primary stability and NBQC classification, implants were either immediately loaded (within 1 week), early loaded (6–8 weeks), or conventionally loaded (≥12 weeks). Successful early loading was defined as absence of pain, mobility, peri-implant radiolucency, or implant loss during the initial 3-month loading period.

### Statistical Analysis

Descriptive statistics (mean, standard deviation, range) were calculated for insertion torque and ISQ values across NBQC classes. One-way analysis of variance (ANOVA) was used to compare mean insertion torque and ISQ values among different NBQC classes, followed by post-hoc Tukey tests for pairwise comparisons. Pearson correlation analysis assessed the relationship between NBQC class (ordinal) and primary stability parameters. Statistical significance was set at $P < 0.05$. All analyses were performed using SPSS version 26.0.

## RESULTS

### The NBQC Classification System

The five-class NBQC system, integrating HU range, cortical thickness, trabecular architecture, anticipated primary stability, recommended loading protocol, and characteristic clinical presentation, is summarized in Table 1.

**Table 1.** Nandan Bone Quality Classification (NBQC)

| NBQC Class | HU Range | Cortical Thickness | Trabecular Architecture | Primary Stability | Recommended Loading | Clinical Characteristics |
|---|---|---|---|---|---|---|
| **NBQC-A** | >1250 HU | ≥ 2.5 mm | Cortical-dominant, minimal marrow spaces | Excellent | Immediate loading | Dense cortical bone, common in mandibular anterior |
| **NBQC-B** | 900–1250 HU | 1.8–2.4 mm | Dense, well-interconnected trabeculae | High | Immediate/Early loading | Thick cortex with dense trabecular core |

| NBQC Class | HU Range | Cortical Thickness | Trabecular Architecture | Primary Stability | Recommended Loading | Clinical Characteristics |
|---|---|---|---|---|---|---|
| **NBQC-C** | 500–900 HU | 1.2–1.7 mm | Moderately organized trabeculae | Moderate | Early loading | Moderate cortex, typical posterior mandible |
| **NBQC-D** | 250–500 HU | <1.2 mm | Sparse, poorly connected trabeculae | Low | Delayed loading | Thin cortex, common in posterior maxilla |
| **NBQC-E** | <250 HU or grafted | Absent or immature | Disorganized or immature trabeculae | Very low | Staged approach | Severely atrophic or recently grafted bone |

**Distribution of NBQC Classes**

Among the 25 implant sites analyzed, 3 (12%) were classified as NBQC-A, 8 (32%) as NBQC-B, 7 (28%) as NBQC-C, 5 (20%) as NBQC-D, and 2 (8%) as NBQC-E. The majority of sites (72%) fell within NBQC-B and NBQC-C categories, representing bone of good to moderate quality.

**Correlation with Insertion Torque**

Mean insertion torque values demonstrated a progressive decrease from NBQC-A to NBQC-E (Table 2). NBQC-A and NBQC-B sites demonstrated significantly higher insertion torque values (>35 Ncm) compared with NBQC-D and NBQC-E sites (<25 Ncm; $P < 0.05$). One-way ANOVA revealed statistically significant differences in mean insertion torque among NBQC classes ($F = 12.43$, $P = 0.001$).

**Correlation with ISQ Values**

ISQ values followed a similar trend, with NBQC-A and NBQC-B exhibiting higher primary stability (ISQ >70) compared to lower classes. One-way ANOVA revealed statistically significant differences in mean ISQ values among NBQC classes ($F = 15.67$, $P < 0.001$). Pearson correlation analysis showed a strong positive correlation between NBQC class and ISQ values ($r = 0.78$, $P < 0.001$).

**Loading Protocol and Early Loading Outcomes**

Early or immediate loading was successfully performed in all NBQC-A (3/3) and NBQC-B (8/8) cases and in the majority of NBQC-C cases (5/7). NBQC-D and NBQC-E sites required delayed loading protocols (≥12 weeks). No implant failures, mobility, or significant marginal bone loss were recorded during the early loading observation period (mean follow-up: 4.2 months).

**Table 2.** Correlation of NBQC Classes with Primary Stability Parameters

| NBQC Class | No. of Implants | Mean Insertion Torque (Ncm) ± SD | Mean ISQ Value ± SD | Loading Protocol Applied |
|---|---|---|---|---|
| **NBQC-A** | 3 | 48.3 ± 3.2 | 77.3 ± 2.1 | Immediate |
| **NBQC-B** | 8 | 38.8 ± 4.5 | 72.4 ± 3.8 | Immediate/Early |
| **NBQC-C** | 7 | 29.6 ± 5.2 | 65.1 ± 4.6 | Early |
| **NBQC-D** | 5 | 19.4 ± 4.8 | 55.8 ± 5.2 | Delayed |
| **NBQC-E** | 2 | 12.5 ± 2.1 | 46.5 ± 3.5 | Staged |

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**Functional Stability Index (FSI)**

To enhance objectivity and facilitate statistical and AI-based analysis, an optional **Functional Stability Index (FSI)** was developed to provide a quantitative score for bone quality assessment.

**Scoring Components**

**1. Mean HU Value (0–4 points)**

- >1250 HU: 4 points
- 900–1250 HU: 3 points
- 500–900 HU: 2 points
- 250–500 HU: 1 point
- <250 HU: 0 points

**2. Cortical Thickness (0–3 points)**

- ≥2.5 mm: 3 points
- 1.8–2.4 mm: 2 points
- 1.2–1.7 mm: 1 point
- <1.2 mm: 0 points

**3. Trabecular Connectivity (0–2 points)**

- Dense, well-connected: 2 points
- Moderate connectivity: 1 point
- Sparse, poorly connected: 0 points

**4. Risk Factor Modifier (0–1 point)**

- Absence of systemic/local risk factors: 1 point
- Presence of compromising factors: 0 points

**Total FSI Score: 0–10**

**Clinical Interpretation**

- **FSI 8–10:** Excellent bone quality, suitable for immediate loading
- **FSI 5–7:** Good to moderate bone quality, suitable for early loading
- **FSI <5:** Poor bone quality, delayed or staged loading recommended

## DISCUSSION

Accurate assessment of alveolar bone quality remains a cornerstone for predictable implant-supported prosthodontic outcomes. The NBQC system addresses critical limitations of existing classifications by integrating CBCT-derived objective measurements with functional clinical parameters. In this pilot validation, a clear progressive correlation was observed between NBQC classes and primary stability indicators, consistent with previous reports linking bone density to insertion torque and resonance frequency outcomes,[7,8] and supporting the clinical relevance of this classification approach.

**Comparison with Existing Classifications**

Traditional classifications by Lekholm and Zarb[1] (based on panoramic radiography and tactile sensation during drilling) and Misch[2] (emphasizing bone density) have provided valuable frameworks but lack the precision and reproducibility afforded by modern CBCT imaging, a limitation that has prompted subsequent CT-based revisions of the original systems.[9] The NBQC system leverages objective HU measurements, precise cortical thickness quantification, and three-dimensional trabecular assessment, offering superior reproducibility and clinical predictability, consistent with prior work correlating CBCT-derived bone parameters with primary implant stability outcomes.[10,11,12,13]

**Clinical Significance**

From a prosthodontic perspective, NBQC provides direct clinical utility in several domains. First, it assists in **treatment planning** by identifying sites requiring bone augmentation or modified surgical protocols. Second, it guides **implant selection**, as larger diameter or surface-modified implants may be indicated in lower NBQC classes. Third, it standardizes **loading protocol decisions**, reducing the risk of premature loading failures. Finally, it facilitates **risk stratification** for patient communication and informed consent.

The system is particularly valuable in challenging anatomical regions such as the posterior maxilla, where bone quality is often compromised[14] and implant survival has been reported to be lower in low-density, type IV bone,[15] and in medically complex patients where healing capacity may be reduced. Unlike density-only classifications, NBQC's multi-parameter approach better reflects the biomechanical behavior at the bone–implant interface, in keeping with systematic-review evidence that bone density alone is an incomplete predictor of primary stability.[16]

**Integration with Digital Workflows**

The quantitative nature of NBQC makes it compatible with digital implant planning software and suitable for integration into AI-based predictive models.[4] The optional FSI score provides a continuous variable that can be incorporated into statistical analyses, machine learning algorithms, and outcome prediction models, facilitating evidence-based decision support systems, an approach supported by growing evidence on the clinical utility of resonance frequency analysis in implant dentistry.[17]

**Limitations and Future Directions**

This pilot study has several limitations that warrant consideration. The sample size of 25 implant sites is relatively small, limiting statistical power for subgroup analyses. The observation period for early loading outcomes was limited to 3–4 months, precluding assessment of long-term prosthetic success and marginal bone maintenance. Additionally, CBCT-derived HU values may vary across different imaging systems and reconstruction protocols, necessitating potential calibration or standardization procedures.[18]

Variability in CBCT equipment represents a recognized challenge. Future iterations may incorporate system-specific correction factors or relative density measurements to enhance cross-platform reliability. Moreover, the qualitative assessment of trabecular architecture introduces some subjectivity; ongoing work involves developing automated image analysis algorithms to quantify trabecular parameters objectively.

Future research should focus on prospective multicenter validation with larger cohorts, long-term follow-up assessing prosthetic complications and marginal bone loss,[19] integration of patient-related variables (systemic health, smoking, parafunctional habits), and development of AI-driven predictive models incorporating NBQC parameters. Comparative studies with existing classifications would further establish the clinical superiority and cost-effectiveness of the NBQC approach.

**CONCLUSIONS**

The Nandan Bone Quality Classification (NBQC) represents a novel, CBCT-based, function-oriented system designed to enhance implant-supported prosthodontic decision-making. The pilot validation demonstrated meaningful correlations between NBQC classes and primary stability parameters, underscoring its clinical applicability and predictive value.

**Key advantages of the NBQC system include:**

- Multi-parameter assessment providing comprehensive bone quality evaluation
- Objective, reproducible measurements based on CBCT data
- Direct clinical relevance for loading protocol decisions
- Quantifiable FSI score suitable for statistical and AI applications
- Compatibility with digital implant planning workflows

NBQC has the potential to serve as a standardized framework for clinical practice, facilitate evidence-based treatment planning, improve communication among interdisciplinary teams, and enable future AI-driven predictive models in prosthodontics. Continued validation and refinement through multicenter research will establish its role as a valuable tool in contemporary implant dentistry.

## CLINICAL RELEVANCE

**Scientific rationale for the study:** Existing bone quality classifications lack objective, multi-parameter assessment compatible with modern CBCT imaging and digital workflows.

**Principal findings:** The NBQC system demonstrates strong correlation with primary stability parameters and provides clinically relevant guidance for loading protocol decisions.

**Practical implications:** NBQC offers a standardized, reproducible framework for bone quality assessment that can improve treatment planning, reduce complications, and facilitate research in implant prosthodontics.

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