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ASSESSMENT OF BONE DENSITY & GINGIVAL CREVICULAR FLUID DERIVED BONE BIOMARKER (OSTEOCALCIN) IN BONE LEVEL & TISSUE LEVEL IMPLANTS: A RANDOMIZED CONTROL TRIAL

Dr. Anshuman Chaturvedi[1], Dr. Shivank*[2], Dr. Shitij Srivastava[3], Dr. Abhinav Shekhar[4], Dr. Love Kumar Bhatia[5]

[1]Department of Prosthodontics and Crown & Bridge, Sardar Patel Post Graduate Institute of Dental & Medical Sciences, Lucknow, Uttar Pradesh, India, Email ID: dranshuman.mds@gmail.com
[*2]Department of Prosthodontics and Crown & Bridge
Sardar Patel Post Graduate Institute of Dental & Medical Sciences, Lucknow, Uttar Pradesh, India, Email ID: shivank0810@gmail.com
3Department of Prosthodontics and Crown & Bridge, Sardar Patel Post Graduate Institute of Dental & Medical Sciences, Lucknow, Uttar Pradesh, India, Email ID: shitijsrivastava@gmail.com
[4]Department of Prosthodontics and Crown & Bridge, Sardar Patel Post Graduate Institute of Dental & Medical Sciences, Lucknow, Uttar Pradesh, India, Email ID: dentalo3doctor@gmail.com
[5]Department of Prosthodontics and Crown & Bridge, Sardar Patel Post Graduate Institute of Dental & Medical Sciences, Lucknow, Uttar Pradesh, India, Email ID: drlovebhatia12@gmail.com

ABSTRACT

Background: Immediate loading protocols in dental implantology have gained popularity due to reduced treatment time and improved patient satisfaction. However, the influence of implant design—particularly bone-level and tissue-level implants—on early osseointegration and peri-implant bone response remains insufficiently explored. The use of biochemical markers such as Osteocalcin, along with radiographic assessment using Cone Beam Computed Tomography, provides a comprehensive evaluation of peri-implant bone dynamics.

Aim: To compare peri-implant bone density and osteocalcin levels in gingival crevicular fluid around bone-level and tissue-level implants subjected to immediate non-functional loading.

Materials and Methods: A prospective randomized controlled split-mouth clinical trial was conducted on 30 patients (60 implant sites). Each patient received one bone-level implant (Group I) and one tissue-level implant (Group II). Immediate non-functional loading was performed within 48 hours. Osteocalcin levels were assessed at 2 weeks and 3 months using ELISA. Bone density (Hounsfield Units) and marginal bone loss were evaluated using CBCT. Statistical analysis was performed using SPSS version 21.0 with significance set at $p < 0.05$.

Results: At 2 weeks, osteocalcin levels and bone density were comparable between groups ($p > 0.05$). At 3 months, Group I demonstrated significantly higher osteocalcin levels (3.081 ± 0.259 ng/mL vs. 2.912 ± 0.134 ng/mL; $p = 0.002$) and greater bone density (619.90 ± 39.21 HU vs. 590.37 ± 49.17 HU; $p = 0.013$). Both groups showed significant intragroup increases over time ($p < 0.001$). Marginal bone loss was minimal and comparable between groups ($p > 0.05$).

Conclusion: Immediate non-functional loading is a reliable and predictable protocol for both implant designs. Bone-level implants demonstrated superior early biological and radiographic outcomes, indicating enhanced osseointegration. However, both implant types maintained excellent marginal bone stability.

KEYWORDS: Bone density; Bone-level implants; CBCT; Immediate loading; Osseointegration; Osteocalcin; Tissue-level implants

INTRODUCTION

Dental implantology has emerged as a cornerstone in modern prosthetic dentistry, offering a predictable and long-term solution for the rehabilitation of partially and completely edentulous patients [1]. Since the pioneering work of Per-Ingvar Brånemark, the concept of osseointegration—defined as a direct structural and functional connection between living bone and the surface of a load-bearing implant—has revolutionized restorative dentistry. Implant-supported prostheses provide superior functional efficiency, esthetics, and patient satisfaction compared to conventional treatment modalities such as removable dentures and fixed partial dentures [2]. The long-term success of dental implants is critically dependent on achieving and maintaining stable osseointegration, which is influenced by a complex interplay of biomechanical, biological, and patient-related factors [3].

Traditionally, implant placement protocols advocated a delayed loading approach, allowing a healing period of 3–6 months to ensure optimal osseointegration before prosthetic rehabilitation [4]. However, this prolonged treatment duration often resulted in patient discomfort, compromised esthetics, and reduced acceptance of implant therapy [5]. In response to these limitations, immediate and early loading protocols have gained widespread clinical acceptance [6]. Immediate non-functional loading, in particular, allows placement of a provisional restoration within 48 hours without occlusal contact, thereby minimizing mechanical stress while promoting early functional and psychological benefits for the patient.

Despite these advantages, concerns persist regarding the biological response of peri-implant tissues, especially in relation to early bone remodeling and implant stability [7].

One of the critical determinants of implant success is the preservation of peri-implant bone. Marginal bone loss and inadequate bone remodeling can compromise implant stability and lead to early or late implant failure [8]. Bone remodeling around implants is a dynamic process involving resorption and formation, which is influenced by factors such as implant design, surface characteristics, loading conditions, and host bone quality. Among these, implant macro-design—particularly the distinction between bone-level and tissue-level implants—plays a significant role in determining the biological and biomechanical behavior of peri-implant tissues [9].

Bone-level implants are placed at the level of the alveolar crest, allowing direct bone-to-implant contact and facilitating optimal load distribution within the surrounding bone [10]. In contrast, tissue-level implants are designed with a transmucosal collar that extends above the bone crest, promoting soft tissue adaptation and reducing microbial infiltration at the implant–abutment interface [11]. While both designs have demonstrated high survival rates, differences in crestal bone response, soft tissue stability, and stress distribution remain areas of ongoing investigation [12]. Existing literature presents conflicting evidence regarding which implant design provides superior outcomes, particularly under immediate loading conditions [12,13]. Therefore, a direct comparative evaluation of these implant systems under standardized clinical conditions is essential.

Radiographic assessment has traditionally been the primary method for evaluating peri-implant bone changes [14]. Advanced imaging modalities such as Cone Beam Computed Tomography enable three-dimensional evaluation of bone density and marginal bone levels, expressed in Hounsfield units (HU) [14]. Although CBCT provides valuable structural information, it has inherent limitations in detecting early biochemical changes associated with bone remodeling. Radiographic changes often become apparent only after significant mineral alterations have occurred, thereby limiting their sensitivity in early diagnosis of implant-related complications [15].

To overcome these limitations, recent research has focused on the use of biochemical markers to assess bone metabolism at the implant site. Among these, Osteocalcin has gained considerable attention as a reliable indicator of osteoblastic activity and bone formation [16]. Osteocalcin is a non-collagenous protein synthesized by osteoblasts during bone matrix formation and mineralization [17]. It is present in gingival crevicular fluid (GCF) or peri-implant sulcular fluid (PISF), making it a minimally invasive and site-specific biomarker for evaluating peri-implant bone remodeling [18]. Elevated levels of osteocalcin are indicative of active bone formation and may reflect successful osseointegration. Despite its potential clinical utility, the application of osteocalcin as a diagnostic tool in implant dentistry remains underexplored, particularly in the context of different implant designs and loading protocols [19].

Furthermore, the integration of radiographic and biochemical assessments offers a more comprehensive understanding of peri-implant tissue dynamics [11]. While CBCT-derived bone density provides quantitative information about mineralization, osteocalcin levels reflect the underlying biological activity of bone formation [12]. The correlation between these parameters may serve as a valuable predictor of implant success and stability. However, limited clinical studies have simultaneously evaluated both bone density and osteocalcin levels in a controlled comparative setting, highlighting a significant gap in the literature [13].

Another critical aspect influencing implant success is the biomechanical environment at the bone–implant interface [14]. Immediate loading introduces functional or non-functional forces during the early healing phase, which may affect primary stability and subsequent osseointegration. While controlled loading has been shown to stimulate bone formation through mechano- transduction, excessive stress can lead to micromovement, fibrous encapsulation, and implant failure [15]. The extent to which implant design modulates these biomechanical forces and influences biological responses remains inadequately understood.

In this context, the present randomized controlled trial is designed to evaluate and compare the biological and radiographic outcomes of bone-level and tissue-level implants under immediate non-functional loading conditions. By assessing peri-implant bone density using CBCT and quantifying osteocalcin levels in gingival crevicular fluid through enzyme-linked immunosorbent assay (ELISA), this study aims to provide a dual-dimensional analysis of osseointegration. Additionally, evaluation of marginal bone loss will further enhance the understanding of early implant stability and peri-implant tissue response.

The novelty of this study lies in its integrative approach, combining biochemical and radiographic parameters to assess peri-implant bone health. Unlike previous studies that have focused primarily on clinical or radiographic outcomes, this investigation emphasizes the biological processes underlying osseointegration. The split-mouth randomized design further strengthens the study by minimizing inter-individual variability and allowing direct comparison within the same patient. In summary, although both bone-level and tissue-level implants are widely used in clinical practice, there remains a lack of definitive evidence regarding their comparative performance under immediate loading conditions, particularly in terms of bone metabolism and density changes. The incorporation of osteocalcin as a biomarker, alongside CBCT-based bone density assessment, provides a novel and comprehensive framework for evaluating implant success. The findings of this study are expected to contribute to evidence-based clinical decision-making, guiding the selection of implant design and loading protocols to optimize patient outcomes and enhance the predictability of implant therapy.

MATERIALS & METHOD

Study Design

This study was designed as a prospective, randomized controlled clinical trial with a split-mouth design to evaluate peri-implant bone health in bone-level and tissue-level implants under immediate non-functional loading. The split-mouth approach enabled intra-individual comparison, thereby reducing variability and improving the reliability of outcomes. Study Setting and Ethical Approval The study was conducted in the Department of Prosthodontics and Crown & Bridge

at Sardar Patel Postgraduate Institute of Dental and Medical Sciences, Lucknow. Ethical approval was obtained from the Institutional Ethical Committee and Research Advisory Council prior to commencement of the study. All procedures adhered to the principles of the Declaration of Helsinki, and written informed consent was obtained from all participants.

Sample Size Calculation

Sample size estimation was performed using G*Power software, considering a significance level of 5% ($\alpha = 0.05$) and power of 80% ($\beta = 0.20$). Based on expected differences in bone density and osteocalcin levels, a minimum of 25 implant sites per group was required. To improve statistical validity, 30 sites per group (total 60 sites) were included.

Participant Selection

Thirty systemically healthy patients aged between 21 and 60 years with bilateral maxillary premolar edentulous areas were enrolled.

Inclusion Criteria

- Patients aged 21–60 years
- Adequate bone volume for implant placement
- Good systemic health
- Implant Stability Quotient (ISQ) ≥ 60
- Willingness to participate and comply with follow-up

Exclusion Criteria

- Systemic diseases affecting bone metabolism
- History of radiotherapy or chemotherapy
- Immunocompromised conditions
- Pregnancy or lactation
- Poor oral hygiene or non-compliance
- Intake of calcium or vitamin D supplements

Randomization and Allocation

A split-mouth design was employed in which each patient received:

- Group I: Bone-level implant (30 sites)
- Group II: Tissue-level implant (30 sites)

Implants were placed contralaterally under identical clinical conditions to ensure standardization.

Preoperative Assessment

All patients underwent detailed clinical and radiographic evaluation. Radiographic assessment was performed using Cone Beam Computed Tomography to evaluate bone density and anatomical conditions. Routine hematological investigations were conducted to ensure fitness for surgery.

Surgical Procedure

Implant placement was performed under local anesthesia (2% lignocaine with epinephrine 1:80,000) following standard aseptic protocols. A crestal incision was made, and a full-thickness mucoperiosteal flap was reflected to expose the alveolar ridge.

Sequential osteotomy was carried out according to manufacturer instructions. In Group I, bone-level implants were placed at the crestal bone level **(figure 1.a)**, while in Group II, tissue-level implants were positioned with a transmucosal collar above the bone crest **(figure 1.b)**. Primary stability was achieved in all cases, and care was taken to avoid trauma to adjacent structures.

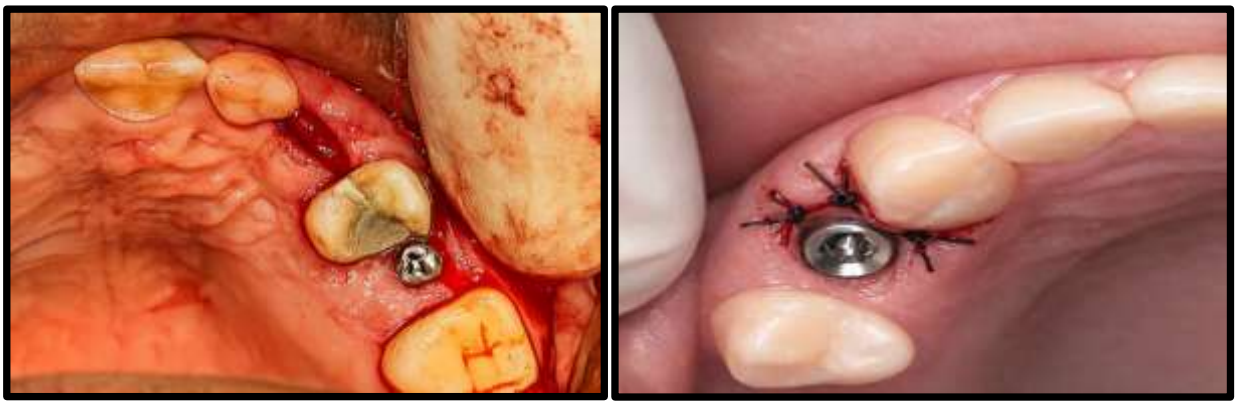


Figure 1.a: bone level implant placement; **(b)** tissue level implant placement

Immediate Non-Functional Loading Protocol

Within 48 hours of implant placement, immediate non-functional loading was performed **(figure 2)**. Open-tray impressions were made, and temporary screw-retained prostheses were fabricated using bis-acrylic composite material.

Figure 2: immediate non-functional loading protocol performed

The prosthesis was adjusted to eliminate occlusal contacts in centric and eccentric movements, ensuring non-functional loading conditions. Implant stability was assessed using resonance frequency analysis, and only implants with ISQ ≥ 60 were included.

Collection of Peri-Implant Sulcular Fluid

Peri-implant sulcular fluid (PISF) was collected at 2 weeks and 3 months postoperatively. The implant site was isolated, and sterile periopaper strips were inserted into the sulcus for 30 seconds. Contaminated samples were discarded. Samples were stored in Eppendorf tubes containing phosphate-buffered saline and preserved at −80°C until analysis.

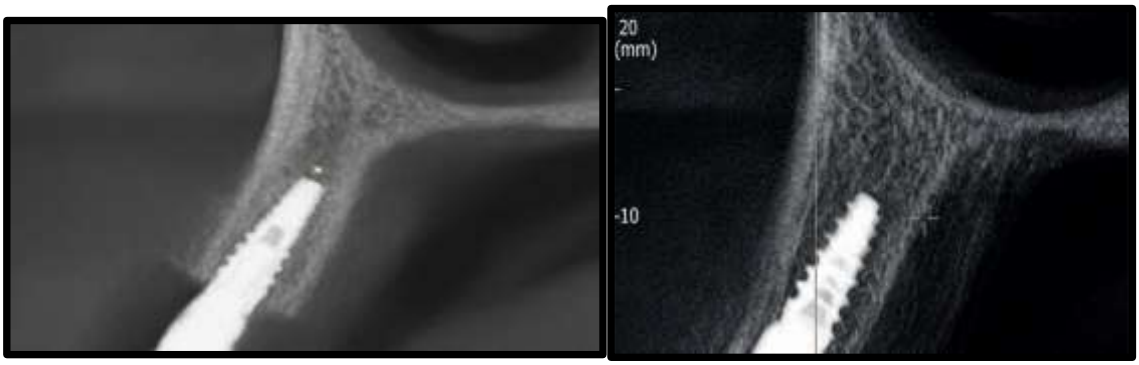
Biochemical Analysis

Quantification of Osteocalcin levels was performed using enzyme-linked immunosorbent assay (ELISA). Samples were processed through vortexing and centrifugation prior to analysis. Osteocalcin concentration (ng/mL) was used as a biomarker of bone formation and remodeling.

Radiographic Assessment

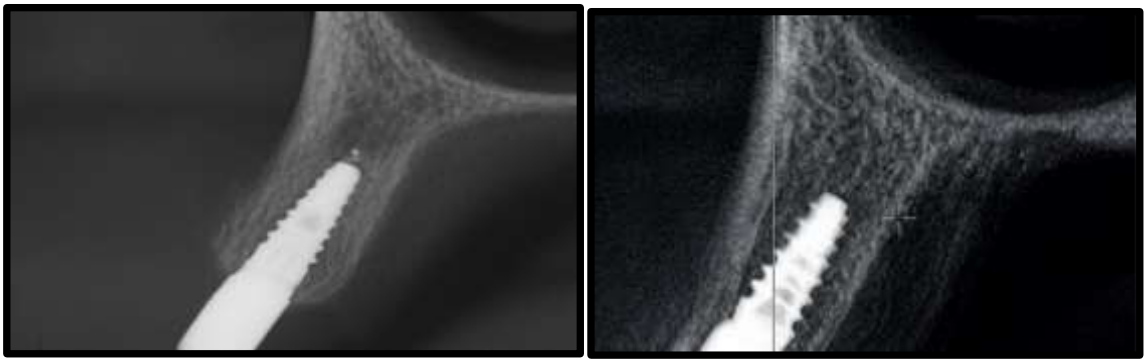
CBCT scans were obtained at baseline, 2 weeks **(figure 3. a, b)**, and 3 months **(figure 4. a,b)**. Bone density was measured in Hounsfield Units (HU) using standardized imaging parameters.

Peri-implant bone loss was evaluated by measuring the distance from the implant platform to the first bone-to-implant contact at mesial and distal aspects.



(a) (b)

Figure 3. CBCT post implant placement at 2 weeks; (a) tissue level; (b) bone level



(b) (b)

Figure 4. CBCT post implant placement at 3 months; (a) tissue level; (b) bone level

Outcome Measures

The primary outcome of the present study was the quantification of osteocalcin levels in peri-implant sulcular fluid, which served as a biochemical marker of bone formation and remodeling activity. Secondary outcome measures included the assessment of peri-implant bone density expressed in Hounsfield Units (HU) using Cone Beam Computed Tomography, evaluation of marginal bone loss in millimeters, and analysis of the correlation between biochemical parameters (osteocalcin levels) and radiographic findings (bone density and bone loss).

Statistical Analysis
Statistical analysis was performed using SPSS version 21.0. All quantitative data were expressed as mean ± standard deviation. Intergroup comparisons between bone-level and tissue-level implants were conducted using the independent t-test, while intragroup comparisons over time were analyzed using the paired t-test. For data not following a normal distribution, non-parametric tests were applied, including the Mann–Whitney U test for intergroup comparisons and the Wilcoxon signed-rank test for intragroup analysis. A p-value of less than 0.05 was considered statistically significant for all analyses.

RESULTS
A total of **30 patients (60 implant sites)** were included in this split-mouth randomized controlled trial. The mean age of participants was **37.23 ± 11.27 years (range: 21–57 years)**. Among them, **18 (60%) were males** and **12 (40%) were females**.

b) Comparison of Osteocalcin Levels
Table 1 presents the comparison of osteocalcin levels between bone-level implants (Group I) and tissue-level implants (Group II) at 2 weeks and 3 months. At 2 weeks, no statistically significant difference was observed between the groups ($p = 0.066$), indicating comparable early osteoblastic activity. However, at 3 months, Group I demonstrated significantly higher osteocalcin levels than Group II ($p = 0.002$), suggesting enhanced bone formation and superior early osseointegration in bone-level implants.

Table 1: Intergroup Comparison of Osteocalcin Levels (ng/mL)

Time Point	Group I (Mean ± SD)	Group II (Mean ± SD)	t-value	p-value
2 Weeks	1.622 ± 0.239	1.712 ± 0.115	1.875	0.066
3 Months	3.081 ± 0.259	2.912 ± 0.134	3.177	**0.002***

Intragroup Changes in Osteocalcin
Table 2 shows the intragroup changes in osteocalcin levels from 2 weeks to 3 months for both implant types. Both groups exhibited a highly significant increase ($p < 0.001$), indicating active bone remodeling over time. Group I showed a greater mean and percentage increase (89.95%) compared to Group II (70.05%), reflecting a more pronounced osteoblastic response in bone-level implants.

Table 2: Intragroup Comparison of Osteocalcin Levels

Group	Mean Change	SD	% Change	t-value	p-value
Group I	1.459	0.334	89.95%	23.929	<0.001*
Group II	1.199	0.133	70.05%	49.234	<0.001*

c) Comparison of Bone Density
Table 3 compares peri-implant bone density between the two groups. At 2 weeks, bone density values were nearly identical with no statistically significant difference ($p = 0.901$). At 3 months, Group I showed significantly higher bone density than Group II ($p = 0.013$), indicating improved mineralization and maturation of peri-implant bone in bone-level implants.

Table 3: Intergroup Comparison of Bone Density (HU)

Time Point	Group I (Mean ± SD)	Group II (Mean ± SD)	t-value	p-value
2 Weeks	481.70 ± 19.20	482.50 ± 29.45	0.125	0.901
3 Months	619.90 ± 39.21	590.37 ± 49.17	2.572	**0.013***

Intragroup Changes in Bone Density
Table 4 illustrates the changes in bone density within each group over time. Both groups demonstrated a statistically significant increase from 2 weeks to 3 months ($p < 0.001$). Group I exhibited a greater mean increase (138.20 HU) and higher percentage change (28.69%) compared to Group II (107.87 HU; 18.27%), suggesting enhanced bone maturation in bone-level implants.

Table 4: Intragroup Comparison of Bone Density

Group	Mean Change (HU)	SD	% Change	t-value	p-value
Group I	138.20	42.04	28.69%	18.007	<0.001*
Group II	107.87	45.83	18.27%	12.891	<0.001*

d) Comparison of Marginal Bone Loss
Table 5 presents the comparison of marginal bone loss between the two groups. At both 2 weeks and 3 months, no statistically significant differences were observed ($p = 1.000$ and $p = 0.734$, respectively). The values remained extremely low in both groups, indicating excellent preservation of peri-implant bone irrespective of implant design.

Table 5: Intergroup Comparison of Marginal Bone Loss (mm)

Time Point	Group I (Mean ± SD)	Group II (Mean ± SD)	Z-value	p-value

2 Weeks	0.0000 ± 0.000	0.0000 ± 0.000	0.000	1.000
3 Months	0.0004 ± 0.007	0.0003 ± 0.0007	0.339	0.734

Intragroup Changes in Marginal Bone Loss

Table 6 shows intragroup changes in marginal bone loss over time. Although both groups demonstrated statistically significant increases from 2 weeks to 3 months ($p < 0.05$), the absolute changes were negligible (<0.001 mm), indicating that the observed differences are not clinically relevant and that both implant types maintain excellent bone stability.

Table 6: Intragroup Comparison of Marginal Bone Loss

Group	Mean Change (mm)	SD	Z-value	p-value
Group I	0.0004	0.007	2.428	0.015*
Group II	0.0003	0.0007	2.251	0.024*

DISCUSSION

The present randomized controlled clinical trial aimed to evaluate peri-implant bone response by assessing both biochemical and radiographic parameters in bone-level and tissue-level implants subjected to immediate non-functional loading. The findings demonstrated that while both implant designs exhibited favorable outcomes, bone-level implants showed significantly higher osteocalcin levels and greater bone density at 3 months, indicating enhanced early osseointegration. Marginal bone loss, however, remained minimal and comparable between the two groups. These findings provide important insights into the biological and clinical behavior of implant designs under immediate loading conditions.

Osteocalcin as a Biomarker of Osseointegration

Osteocalcin, a non-collagenous protein synthesized by osteoblasts, plays a crucial role in bone matrix formation and mineralization. In the present study, osteocalcin levels increased significantly from 2 weeks to 3 months in both groups, with significantly higher values observed in bone-level implants at 3 months. This suggests a more pronounced osteoblastic activity and bone remodeling response around bone-level implants.

These findings are consistent with the study by Keshari et al. [3], who reported increased osteocalcin levels in immediately loaded implants, indicating enhanced bone formation during early healing. Similarly, Rastogi et al. [15] demonstrated that osteogenic biomarkers, including osteocalcin, are significantly elevated in peri-implant crevicular fluid during the early phases of osseointegration, supporting their role as sensitive indicators of implant stability. Fujimoto et al. [16] also established a positive correlation between osteocalcin levels and implant stability, reinforcing its diagnostic value.

In contrast, some studies have suggested that osteocalcin levels may not differ significantly between implant designs. However, these discrepancies could be attributed to differences in study design, loading protocols, and sample characteristics. The present study's split-mouth design strengthens the validity of the findings by minimizing inter-patient variability.

The higher osteocalcin levels observed in bone-level implants may be explained by their placement at the crestal bone level, allowing direct bone-to-implant contact and enhanced mechanical stimulation, which promotes osteoblastic activity through mechanotransduction. This is in agreement with the biological principles described by Albrektsson et al. [17], who emphasized that controlled mechanical loading enhances bone remodeling and osseointegration.

Bone Density Changes and Radiographic Correlation

Bone density assessment using CBCT revealed a significant increase in both groups over time, with bone-level implants demonstrating significantly higher density at 3 months. This finding indicates superior mineralization and maturation of peri-implant bone in bone-level implants.

These results are in agreement with Mounir et al. [10], who reported that CBCT-derived Hounsfield units are reliable indicators of bone density changes and correlate with implant stability. Similarly, Myra et al. [18] demonstrated that increased bone density values are associated with improved osseointegration and long-term implant success.

The greater increase in bone density observed in bone-level implants may be attributed to their biomechanical advantage. By being positioned at the crestal bone level, these implants facilitate better load transfer and stress distribution, thereby stimulating bone remodeling. This aligns with the findings of Pecora et al. [19], who highlighted the importance of implant design in optimizing stress distribution and enhancing primary stability.

However, some studies, such as those by Canullo et al. [7], have reported comparable bone density outcomes between bone-level and tissue-level implants, suggesting that factors such as surgical technique, implant surface characteristics, and patient-specific variables may play a more significant role than implant design alone. This highlights the multifactorial nature of osseointegration.

Marginal Bone Loss and Clinical Stability

One of the most important findings of this study was the negligible marginal bone loss observed in both groups, with no statistically significant intergroup difference. Although intragroup comparisons showed statistically significant changes, the absolute values were clinically insignificant (<0.001 mm), indicating excellent peri-implant bone preservation.

These findings are consistent with the systematic review by Chrcanovic et al. [5], which concluded that immediate loading protocols do not adversely affect marginal bone levels when proper case selection and surgical protocols are followed. Similarly, Monje et al. [4] reported comparable marginal bone stability between immediate and delayed loading protocols.

Interestingly, some studies have suggested that tissue-level implants may exhibit reduced crestal bone loss due to their

transmucosal design, which minimizes bacterial infiltration at the implant-abutment interface (Canullo et al., [7]). However, the present study did not demonstrate any significant difference between the two designs, indicating that immediate non-functional loading does not compromise marginal bone stability irrespective of implant type. This finding supports the concept proposed by Gallucci et al. [6], who emphasized that implant success is more dependent on proper surgical technique, primary stability, and occlusal management than on implant design alone The results of the present study are largely consistent with contemporary literature supporting immediate loading protocols. Studies by Pitman et al. [2] and Kumar et al. [11] have demonstrated that immediate loading can achieve comparable success rates to delayed loading, provided adequate primary stability is achieved. However, the present study adds a novel dimension by integrating biochemical and radiographic parameters. While most previous studies have focused on clinical or radiographic outcomes alone, this study highlights the importance of combining biomarkers such as osteocalcin with CBCT-based bone density assessment to provide a more comprehensive understanding of osseointegration. In contrast to studies that reported no significant difference between implant designs, the present study demonstrated superior biological activity and bone density in bone-level implants, suggesting that implant design may play a more significant role during the early healing phase than previously thought.

Clinical Implications

The findings of this study have important clinical implications. The higher osteocalcin levels and bone density observed in bone-level implants suggest that they may be more suitable for cases requiring rapid osseointegration, such as immediate loading protocols or compromised bone conditions. At the same time, the comparable marginal bone loss between the two groups indicates that both implant designs are clinically safe and effective.

The use of osteocalcin as a biomarker provides clinicians with a non-invasive method to monitor bone remodeling and implant stability, potentially enabling early detection of implant failure.

Limitations of the Study

Despite its strengths, the present study has several limitations. First, the follow-up period was limited to 3 months, which reflects early healing but does not provide insights into long-term implant survival and bone remodeling. Second, the sample size, although statistically adequate, was relatively small and may not represent the broader population.

Third, only one biomarker (osteocalcin) was evaluated. Bone remodeling is a complex process involving multiple biochemical markers, and the inclusion of additional markers such as alkaline phosphatase, osteopontin, or inflammatory cytokines could provide a more comprehensive understanding.

Fourth, CBCT-derived Hounsfield units, although widely used, may be influenced by imaging parameters and may not always accurately reflect true bone density.

Future Recommendations

Future studies should include larger sample sizes and longer follow-up periods to evaluate the long-term performance of implant designs. Multi-center trials would enhance the generalizability of findings.

Additionally, future research should focus on evaluating multiple biomarkers to better understand the biological processes underlying osseointegration. The integration of advanced imaging techniques with biochemical analysis could further improve diagnostic accuracy.

Studies investigating the effect of systemic conditions, bone quality variations, and different loading protocols on biomarker expression and bone density are also recommended.

CONCLUSION

Within the limitations of the present randomized controlled clinical trial, it can be concluded that both bone-level and tissue-level implants subjected to immediate non-functional loading demonstrate favorable biological and radiographic outcomes, indicating that immediate loading is a predictable and clinically viable treatment approach.

However, bone-level implants exhibited significantly higher levels of Osteocalcin and greater increases in peri-implant bone density over the 3-month follow-up period, suggesting enhanced early osseointegration and osteoblastic activity compared to tissue-level implants. Despite these differences, marginal bone loss remained minimal and comparable between the two implant designs, indicating that both systems are equally effective in preserving peri-implant bone stability under controlled loading conditions.

The findings of this study highlight the importance of implant design in influencing early biological responses, while also reinforcing that immediate non-functional loading does not adversely affect peri-implant bone health when appropriate case selection and surgical protocols are followed. Furthermore, the use of biochemical markers such as osteocalcin, in conjunction with radiographic assessment using Cone Beam Computed Tomography, provides a comprehensive and sensitive approach for evaluating osseointegration.

Clinically, bone-level implants may be preferred in situations requiring enhanced early bone formation and stability, whereas both implant designs can be successfully utilized without compromising marginal bone integrity. Future long-term studies incorporating larger sample sizes and multiple biomarkers are recommended to validate and expand upon these findings.

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