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LONG-TERM (UP TO 2 YEARS) DYNAMIC 3D RADIOGRAPHIC ANALYSIS OF QUALITATIVE AND QUANTITATIVE CHANGES IN BONE TISSUE AROUND DENTAL IMPLANTS WITH EARLY FUNCTIONAL LOADING

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Abstract
Objective: This study aims to conduct a long-term (up to 2 years) analysis of the qualitative and quantitative changes in the peri-implant bone tissue under early functional loading protocols, utilizing 3D radiographic data. The secondary objective is to evaluate the dynamics of blood supply and implant stability to substantiate the efficacy of early loading. Methods: The study involved 90 patients, aged 25 to 61, with minor defects of the dental arches in the lower jaw. Patients were allocated into three groups: Group 1 (n=28) received two-stage screw-type implants with conventional loading; Group 2 (n=31) received implants with early functional loading (prostheses placed after 1 month); Group 3 (n=38) received traditional fixed partial dentures. All prosthetic constructions were metal-ceramic bridges. The evaluation included clinical-stomatoscopic examination, 3D radiography (CBCT), Laser Doppler Flowmetry (LDF) to assess blood microcirculation, and implant/tooth mobility tests. Assessments were performed at 1, 3, 6, 9, 12, and 24 months post-prosthesis placement. Results: The 3D radiographic analysis is expected to demonstrate that the early loading group (Group 2) exhibits comparable, if not superior, results in maintaining marginal bone levels and bone density compared to the conventional loading group (Group 1) over the 2-year period. LDF data will likely show an initial pronounced hyperemic response in Group 2, followed by a quicker stabilization of blood flow, suggesting an accelerated and robust healing process. Implant stability quotients are anticipated to show a minimal initial dip followed by a steady increase in the early loading group, reaching values comparable to the conventional group by the 6-month follow-up. Conclusion: Early functional loading of dental implants, when applied under controlled conditions and in properly selected cases, can be a predictable and effective treatment modality. It not only reduces the overall treatment time but may also positively stimulate the peri-implant bone, leading to successful long-term osseointegration and clinical outcomes. This study provides a multi-faceted approach, combining radiographic, hemodynamic, and stability data to validate this protocol.
Keywords: Dental implantation, early functional loading, 3D radiography, CBCT, osseointegration, Laser Doppler Flowmetry (LDF), implant stability.

АННОТАЦИЯ
Цель: Провести долгосрочный (до 2 лет) анализ качественных и количественных изменений периимплантатной костной ткани при ранней функциональной нагрузке с использованием данных 3D-рентгенографии. Второстепенной целью является оценка динамики кровоснабжения и стабильности имплантатов для обоснования эффективности ранней нагрузки. Методы: В исследовании приняли участие 90 пациентов в возрасте от 25 до 61 года с малыми дефектами зубных рядов нижней челюсти. Пациенты были разделены на три группы: Группа 1 (n=28) – двухэтапные винтовые имплантаты с отсроченной нагрузкой; Группа 2 (n=31) – имплантаты с ранней функциональной нагрузкой (протезирование через 1 месяц); Группа 3 (n=38) – традиционные мостовидные протезы.

Все протезные конструкции представляли собой металлокерамические мосты. Оценка включала клинико-стоматоскопический осмотр, 3D-рентгенографию (КЛКТ), лазерную допплеровскую флоуметрию (ЛДФ) для оценки микроциркуляции крови и тесты на подвижность имплантатов/зубов. Обследования проводились через 1, 3, 6, 9, 12 и 24 месяца после установки протезов. Результаты: Ожидается, что данные 3D-рентгенографии покажут, что группа с ранней нагрузкой (Группа 2) продемонстрирует сопоставимые, если не превосходящие, результаты по сохранению уровня краевой кости и плотности костной ткани по сравнению с группой с отсроченной нагрузкой (Группа 1) в течение 2-летнего периода. Данные ЛДФ, вероятно, покажут начальную выраженную гиперемическую реакцию в Группе 2 с последующей более быстрой стабилизацией кровотока, что свидетельствует об ускоренном и устойчивом процессе заживления. Ожидается, что показатели стабильности имплантатов покажут минимальное начальное снижение с последующим устойчивым ростом в группе с ранней нагрузкой, достигая значений, сопоставимых с группой с отсроченной нагрузкой к 6-му месяцу наблюдения. Заключение: Ранняя функциональная нагрузка на дентальные имплантаты при контролируемых условиях и у правильно подобранных пациентов может быть предсказуемым и эффективным методом лечения. Это не только сокращает общее время лечения, но и может положительно стимулировать периимплантатную кость, что приводит к успешной долгосрочной остеоинтеграции и клиническим результатам. Данное исследование представляет комплексный подход, сочетающий рентгенографические, гемодинамические данные и данные о стабильности для валидации этого протокола.
Ключевые слова: Дентальная имплантация, ранняя функциональная нагрузка, 3D-рентгенография, КЛКТ, остеоинтеграция, лазерная допплеровская флоуметрия (ЛДФ), стабильность имплантата.

INTRODUCTION

The rehabilitation of partially and fully edentulous patients with dental implants has become a cornerstone of modern dentistry, offering predictable and long-lasting results. The classic protocol for implant placement, as described by Brånemark, involves a two-stage surgical approach with a healing period of 3 to 6 months to allow for undisturbed osseointegration before functional loading. While this conventional loading protocol has demonstrated high success rates, it is associated with a prolonged treatment timeline and the need for patients to wear interim removable prostheses, which can be uncomfortable and functionally limiting.

In response to patient demands for shorter treatment times and immediate functional and aesthetic improvement, there has been a significant shift towards accelerated loading protocols, including immediate and early functional loading. Early functional loading, typically defined as loading that occurs between one week and two months after implant placement, aims to bridge the gap between immediate and conventional protocols. The primary challenge of this approach lies in achieving successful osseointegration while the implant is subjected to masticatory forces during the critical healing phase.

The success of any loading protocol is fundamentally dependent on the quality and quantity of the host bone and its adaptive response to mechanical stimuli. Functional loads, when appropriately managed, can act as a positive stimulus for bone remodeling, a concept known as Wolff's law. Conversely, excessive or premature loading can lead to micromotion at the bone-implant interface, disrupting the formation of a stable osseointegrated connection and resulting in fibrous encapsulation and implant failure. Therefore, understanding the biomechanical

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interactions between the implant, prosthesis, and surrounding bone is critical for optimizing treatment outcomes.

This necessitates a comprehensive and objective assessment of the peri-implant tissues over time. While traditional 2D radiography has been the standard for monitoring marginal bone levels, it provides limited information due to geometric distortion and anatomical superimposition. The advent of three-dimensional (3D) imaging techniques, particularly Cone-Beam Computed Tomography (CBCT), has revolutionized the evaluation of peri-implant bone. CBCT allows for a precise, multi-planar assessment of bone volume, density, and morphology, providing invaluable data for treatment planning and long-term monitoring.

Furthermore, the biological response to implant placement and loading is not limited to osseous changes. The vascular supply in the peri-implant area is crucial for healing and tissue maintenance. Laser Doppler Flowmetry (LDF) is a non-invasive technique that enables the real-time monitoring of microcirculatory blood flow, offering insights into the physiological processes of adaptation and healing around the implant.

This study, as outlined in the dissertation work of Akhmadjonov M.A., is designed to provide a comprehensive, long-term evaluation of the efficacy of early functional loading on dental implants. By integrating clinical, 3D radiographic, hemodynamic (LDF), and stability assessments, this research aims to scientifically substantiate the optimal timing for prosthetic loading and to develop a robust methodology for evaluating treatment effectiveness. The findings are expected to have significant practical implications, potentially validating a protocol that enhances patient satisfaction by shortening treatment duration while ensuring long-term clinical success.

LITERATURE REVIEW

The concept of osseointegration, defined as a direct structural and functional connection between ordered, living bone and the surface of a load-carrying implant, remains the biological foundation of implant dentistry. The debate over loading protocols—immediate, early, and conventional—has been a central theme in implant research for the past two decades.

Biomechanics of Osseointegration and Functional Loading The response of bone to mechanical loading is a complex biological process. According to the "mechanostat" theory proposed by Frost, bone adapts its mass and architecture to the mechanical demands placed upon it. Controlled mechanical strain within a physiological window stimulates bone formation and increases density. However, strains that are too low (disuse) can lead to bone resorption (atrophy), while excessive strains (overload) can cause microdamage, bone resorption, and ultimately, failure of osseointegration.

Early loading protocols challenge the traditional understanding of a quiescent healing period. Research suggests that controlled, early micromotion might not be detrimental and could even be beneficial for bone healing, a phenomenon termed "osteogenic stimulation." The key is the magnitude of this micromotion. It is generally accepted that micromotion below 50-150 μm allows for osseointegration, whereas movement exceeding this threshold leads to the formation of fibrous tissue. The success of early loading, therefore, depends on achieving high primary implant stability, which is influenced by surgical technique, implant design (e.g., screw-type implants), and bone quality.

3D Radiographic Assessment of Peri-Implant Bone Cone-Beam Computed Tomography (CBCT) has become the gold standard for three-dimensional assessment in implant dentistry. Unlike 2D periapical or panoramic radiographs, CBCT provides cross-sectional views, allowing for the precise measurement of marginal bone loss (MBL) on all aspects of the implant (buccal, lingual, mesial, and distal). This is crucial, as significant buccal bone resorption can be masked in 2D imaging.

Several studies have utilized CBCT to compare bone level changes between different loading protocols. A systematic review by Pjetursson et al. (2014) found that while some studies reported slightly more initial bone loss with immediate/early loading compared to conventional loading, the long-term differences were often not clinically significant, provided that high primary stability was achieved. Furthermore, CBCT can be used to assess changes in bone density (measured in Hounsfield Units or grayscale values) around the implant over time, providing a quantitative measure of bone remodeling and maturation in response to functional loading. This study's use of 3D radiography aligns with current best practices for objectively assessing bone-level changes.

Vascularization and Healing Dynamics The establishment of a robust vascular network around the implant is paramount for nutrient supply, waste removal, and the recruitment of osteogenic cells. The surgical trauma of implant placement inevitably disrupts the local vasculature. The subsequent revascularization process is a critical component of healing. Laser Doppler Flowmetry (LDF) offers a unique window into these physiological changes. Studies using LDF have shown a characteristic pattern of blood flow changes after surgery: an initial ischemic phase followed by a period of hyperemia (increased blood flow) that gradually returns to baseline as the tissue matures.

The influence of functional loading on this process is an area of active research. It is hypothesized that early functional loads may stimulate angiogenesis and accelerate the maturation of the microvascular network, contributing to faster and more robust bone healing. By comparing LDF measurements between early and conventional loading groups, this study aims to provide hemodynamic evidence to support this hypothesis.

Implant Stability Assessment Primary stability at the time of placement is a critical prerequisite for early loading. It is a mechanical measure of the implant's initial fixation in the bone. Secondary stability, on the other hand, is the biological stability that develops as osseointegration occurs. Resonance Frequency Analysis (RFA) is the most common objective method for measuring implant stability, providing a quantitative value known as the Implant Stability Quotient (ISQ).

A typical ISQ pattern after implant placement shows a high initial value (primary stability), followed by a slight dip at around 2-4 weeks as the initial mechanical stability is partially replaced by biological fixation. The ISQ then increases as osseointegration progresses. In early loading protocols, monitoring the ISQ is crucial to ensure that the implant is stable enough to withstand functional forces. The proposed study's plan to monitor stability before and after loading at various intervals will provide valuable data on the progression of osseointegration in the different patient groups.

MATERIALS AND METHODS

This study was designed as a prospective clinical trial to evaluate and compare the outcomes of three different treatment modalities for restoring minor edentulous spaces in the mandible.

Study Population The clinical part of the work was based on the examination and treatment of 90 patients aged between 25 and 61 years (55 women and 35 men). All patients presented with small, bounded (Kennedy Class III) defects in the dental arches of the lower jaw.

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Inclusion Criteria: Systemically healthy adults, good oral hygiene, adequate bone volume for implant placement without major augmentation, and willingness to comply with the follow-up schedule.
Exclusion Criteria: Uncontrolled systemic diseases (e.g., diabetes), active periodontal disease, heavy smoking (>10 cigarettes/day), parafunctional habits (bruxism), and background pathologies that could interfere with healing.
Group Allocation The 90 patients were allocated into three distinct groups:
Group 1 (Conventional Loading, n=28): This group received two-stage, intraosseous screw-type dental implants. Following a submerged healing period of 3 months, the implants were uncovered and restored with metal-ceramic fixed partial dentures.
Group 2 (Early Loading, n=31): This group received intraosseous screw-type implants. Metal-ceramic fixed partial dentures were placed and brought into function one month after implant surgery. A prerequisite for inclusion in this group was achieving an initial implant stability quotient (ISQ) of >65.
Group 3 (Control - Traditional Prosthodontics, n=38): This group served as the control and was treated with conventional tooth-supported metal-ceramic fixed partial dentures to restore the edentulous spaces.
In all groups, the final restorations were metal-ceramic bridges. The implants used in Groups 1 and 2 were of the same type and manufacturer (intraosseous screw-type implants).
Data Collection and Assessment Methods All patients were scheduled for follow-up examinations at 3, 6, 9, 12, and 24 months after the delivery of the final prosthesis. The following methods were used for data collection:
Clinical-Stomatoscopic Examination: This included a visual inspection of the peri-implant/peri-prosthetic soft tissues, assessment of plaque index, gingival index, and probing depths around implants and abutment teeth. Any signs of inflammation, pain, or prosthetic complications were recorded.
3D Radiographic Analysis: Cone-Beam Computed Tomography (CBCT) scans were taken immediately after prosthesis placement (baseline) and at the 6, 12, and 24-month follow-up appointments. High-resolution scans were used to perform the following measurements:
Marginal Bone Level (MBL): The vertical distance from the implant shoulder to the first bone-to-implant contact was measured on the mesial, distal, buccal, and lingual surfaces. The change in MBL from baseline was calculated for each time point.
Peri-implant Bone Density: Using the CBCT software, regions of interest (ROIs) were defined around the implant threads in the coronal, middle, and apical thirds. The mean grayscale value (as a proxy for bone density) was calculated for each ROI and tracked over time.
Laser Doppler Flowmetry (LDF): To assess the dynamics of blood microcirculation, LDF measurements were taken from the gingival tissue adjacent to the implants (Groups 1 and 2) and the pontic area (Group 3). A standardized probe was placed at a designated point, and blood perfusion units (BPU) were recorded at each follow-up visit.
Implant/Tooth Mobility Assessment: For implant groups (1 and 2), stability was measured using Resonance Frequency Analysis (RFA) to obtain an Implant Stability Quotient (ISQ) value. Measurements were taken at implant placement, at the time of prosthesis delivery, and at all subsequent follow-up appointments.
For the control group (3), the mobility of the abutment teeth was assessed using a Periotest device.

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5. Statistical Analysis: The collected data will be analyzed using appropriate statistical software. Descriptive statistics (mean, standard deviation) will be calculated for all parameters. Inferential statistical tests, such as ANOVA or Kruskal-Wallis test, will be used to compare the means between the three groups. Paired t-tests or Wilcoxon signed-rank tests will be used to analyze changes within each group over time. The level of significance will be set at $p < 0.05$.

RESULTS AND DISCUSSION

This section presents the anticipated results based on the study protocol and existing literature, followed by a discussion of their clinical implications. The data presented in the tables are hypothetical but reflect plausible outcomes of such a clinical trial.

Anticipated Radiographic Results (CBCT)

The primary outcome of this study is the change in marginal bone level (MBL) around the implants. It is hypothesized that the early loading group will show slightly more initial bone loss but will stabilize over the long term, resulting in clinically acceptable outcomes comparable to the conventional group.

Table 1: Hypothetical mean marginal bone loss (MBL) in mm (± SD) over 24 months

Time Point	**Group 1 (Conventional)**	**Group 2 (Early Loading)**	**p-value (Group 1 vs 2)**
Baseline (Prosthesis Delivery)	0.25 (± 0.15)	0.28 (± 0.18)	> 0.05
6 Months	0.65 (± 0.30)	0.85 (± 0.40)	< 0.05
12 Months	0.80 (± 0.35)	0.95 (± 0.45)	> 0.05
24 Months	0.90 (± 0.40)	1.05 (± 0.50)	> 0.05

The hypothetical data in Table 1 suggest that at the 6-month mark, the early loading group might exhibit statistically significantly higher MBL compared to the conventional group. This could be attributed to the initial bone remodeling response to functional forces being introduced earlier in the healing process. However, by the 12- and 24-month follow-ups, the rate of bone loss is expected to stabilize in both groups, with the difference becoming statistically non-significant. A mean MBL of around 1.0 mm after two years is well within the criteria for implant success. This finding would support the idea that after an initial adaptation phase, early loaded implants can maintain bone levels effectively over the long term.

Table 2: Hypothetical mean peri-implant bone density change (grayscale value ± SD) over 24 months

Time Point	**Group 1 (Conventional)**	**Group 2 (Early Loading)**	**p-value (Group 1 vs 2)**
Baseline (Prosthesis Delivery)	550 (± 80)	555 (± 85)	> 0.05
6 Months	580 (± 90)	610 (± 95)	< 0.05
12 Months	600 (± 95)	635 (± 100)	< 0.05
24 Months	615 (± 100)	645 (± 105)	> 0.05

The data in Table 2 hypothesize that early functional loading may act as a positive stimulus for bone densification. The early loading group is projected to show a more rapid and significant increase in peri-implant bone density within the first year compared to the conventional group.

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This supports the biomechanical principle that controlled loading encourages bone apposition and maturation, leading to a denser bone-implant interface. While the difference may level off by the 24-month mark, the enhanced density in the early stages could contribute to long-term stability. This directly aligns with the study's goal of understanding the structural changes occurring during adaptation to early loads.

Anticipated Hemodynamic and Stability Results

Table 3: Hypothetical mean laser doppler flowmetry (LDF) and implant stability quotient (ISQ) Values (± SD)

Time Point	LDF (Blood Perfusion Units)		ISQ (Resonance Frequency)	
	Group 1 (Conventional)	Group 2 (Early Loading)	Group 1 (Conventional)	Group 2 (Early Loading)
Baseline	18.5 (± 4.0)	25.0 (± 5.5)*	71 (± 5)	72 (± 5)
3 Months	22.0 (± 5.0)	20.0 (± 4.5)	73 (± 4)	70 (± 6)
6 Months	19.0 (± 4.2)	18.0 (± 4.0)	75 (± 4)	74 (± 5)
12 Months	17.5 (± 3.8)	17.0 (± 3.5)	77 (± 3)	76 (± 4)
24 Months	17.0 (± 3.5)	16.8 (± 3.3)	78 (± 3)	77 (± 4)

*Baseline for LDF in Group 2 is at 1 month (prosthesis delivery), showing post-surgical hyperemia. Baseline for Group 1 is at 3 months (prosthesis delivery).

The LDF results are expected to reveal a more pronounced hyperemic response in the early loading group at the time of prosthesis delivery (1 month), indicative of an active healing and remodeling process. This is followed by a faster return to baseline perfusion levels, suggesting an efficient and accelerated maturation of the peri-implant soft and hard tissues.

The ISQ values are anticipated to demonstrate the well-documented slight dip in stability for the early loading group around the 3-month mark, as biological stability begins to take over from primary mechanical stability. However, the key finding would be the subsequent steady increase, reaching levels comparable to the conventional loading group by 6-12 months. This would confirm that, despite being subjected to early functional forces, the implants achieve robust secondary stability and successful osseointegration.

Discussion and Clinical Significance The combined results from this multi-faceted investigation would provide strong evidence supporting the predictability of early functional loading protocols. The slightly higher initial bone loss observed in the early loading group can be interpreted as a physiological remodeling response to the early introduction of functional stimuli. The crucial finding is the subsequent stabilization of bone levels, which, when coupled with an observed increase in bone density, indicates a successful and healthy adaptation of the peri-implant bone. This aligns with the work of numerous researchers who have found that as long as micromotion is controlled, early loading does not jeopardize long-term implant survival.

The practical significance of these findings is substantial. An evidence-based protocol for early loading allows clinicians to significantly reduce the overall treatment time from implant placement to final restoration. This addresses a major patient-centric concern, improving patient satisfaction and acceptance of implant therapy. For a patient with a missing tooth in the aesthetic zone, reducing the period of wearing a temporary prosthesis by several months is a considerable advantage.

Furthermore, the study's methodology, which combines advanced 3D imaging with functional physiological assessment (LDF and RFA), provides a comprehensive model for evaluating

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implant success that goes beyond simple survival rates. By understanding the dynamics of bone remodeling and vascular healing, clinicians can make more informed decisions about which patients are suitable candidates for early loading and can better predict treatment outcomes. The development of a clear methodology for assessing treatment effectiveness, as stated in the project's aims, would be a valuable contribution to the field. This research would help to substantiate that early functional loading is not merely a faster option but a biologically sound procedure that can stimulate and enhance the healing process in the peri-implant bone.

CONCLUSION

Based on the proposed comprehensive clinical study, the following conclusions are anticipated:
Efficacy of Early Loading: The long-term (2-year) dynamic analysis is expected to confirm that early functional loading of dental implants is a viable and predictable treatment modality, demonstrating clinical and radiographic outcomes comparable to conventional loading protocols. The success of the protocol is contingent upon achieving high primary implant stability and careful case selection.
Bone Remodeling: 3D radiographic analysis will likely show that while early loading may lead to slightly greater initial marginal bone resorption during the first six months, the bone levels stabilize over time. More importantly, early loading is expected to positively stimulate an increase in peri-implant bone density, indicating a robust adaptive response to functional forces.
Physiological Response: Laser Doppler Flowmetry and Resonance Frequency Analysis data are predicted to demonstrate that the peri-implant tissues in the early loading group undergo an accelerated but physiologically sound healing process. An initial, controlled hyperemic response and a temporary dip in stability are followed by rapid maturation of the vascular supply and a steady increase in osseointegration, leading to excellent long-term implant stability.
Clinical Recommendations: The findings will provide a scientific basis for recommending the application of early functional loading in clinical practice for restoring minor defects in the mandible. This approach effectively shortens treatment duration, thereby enhancing patient satisfaction without compromising the long-term health and stability of the implant and surrounding tissues. The comprehensive assessment protocol used in this study can serve as a model for objectively monitoring and validating implant treatment outcomes.

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