E-ISSN 2250-0944
ISSN 2250-1150
doi: 10.31838/ijprt/15.02.577

Research Article

Impact of Pre-operative Metabolic Markers and Mineral Homeostasis on the Predictability of Dental Implant Osseointegration

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Received: 19.09.25, Revised: 24.11.25, Accepted: 14.12.25

ABSTRACT

Effective osseointegration is a long-term highly important factor in the survival of dental implants, and is affected by both surgical procedure and implant design, as well as by the metabolic condition of the system as an individual aspect of the patient. This cross-sectional observational study was carried out to assess the predictive value of pre-operative metabolic markers and mineral homeostasis on dental implant osseointegration. 100 patients who were aged 25-60 years and were in need of dental implant placement were recruited through a consecutive sampling method. The research itself took place at the Department of Oral and Maxillofacial Surgery of a Margalla College of Dentistry, Margalla Institute of Health Sciences, Rawalpindi. The pre-operative metabolism testing included the level of fasting blood glucose, HbA1c, serum vitamin D, calcium, phosphorus, and alkaline phosphatase. The instruments used in data collection were the Patient Demographic and Medical History Proforma (PDMHP), Pre-operative Metabolic and Mineral Profile Assessment Form (PMMPAF), Implant Stability Evaluation Sheet (ISES) with the help of resonance frequency analysis, and Radiographic Osseointegration Assessment Form (ROAF) based on periapical radiographs and cone-beam computed tomography. Clinical and radiographic assessments of the results of the process of osseointegration were measured at follow-up and compared with the metabolic and mineral profiles before surgery. The results are that metabolic markers and mineral homeostasis disruptions might have adverse implications for the implant osseointegration. Regular pre-operative screening of metabolism could optimize the treatment plan and increase the predictability and long-term effectiveness of dental implant treatment.

Keywords: Dental Implant, Osseointegration, Metabolic Marker, Mineral Homeostasis.

INTRODUCTION

Dental implants has become the treatment choice in the replacement of missing teeth and has recorded high rates of functional and esthetic success in dental implant therapy. Osseointegration can be described as the direct structural and functional relationship between living bone and the surface of a dental implant, and this will largely determine the success of dental implants in the long run. Osseointegration gives implants the mechanical stability and load-bearing ability needed to live [1]. In spite of the technological progress in implant design and surgical practice, early implants do not succeed, and may be related to systemic aspects, metabolic conditions and mineral homeostasis that affect the bone healing process [2].

The bone remodeling surrounding implants is a biologically complicated process that entails the integration of osteoblastic and osteoclastic functions and actions. Vitamin D is one of the systemic factors that are crucial in the metabolism of calcium and phosphates, the regulation of osteoblastic differentiation, and bone mineralization. The deficiency of vitamin D has been associated with the retarded formation of bones and can undermine the formation of a stable implant-bone interface [3,4]. Even though clinical and experimental

evidence has been reviewed several times to determine the role of vitamin D in the process of osseointegration, the results are inconsistent, and additional clinical tests must be conducted to explain the influence [5].

The bone metabolism also has important implications for the use of metabolic markers like glycemic control. Poorly managed diabetes mellitus has been found to negatively impact wound healing, osteoblast activity and the formation of a chronic inflammatory state, which may lead to impaired bone regeneration and stability of the implant [6,7]. In the experimental and clinical literature, high fasting blood glucose and glycated hemoglobin (HbA1c) concentrations have been linked to poor bone quality and slower rates of osseointegration [8].

Besides vitamin D and glycemic status, mineral homeostasis, including serum calcium, phosphorus, and alkaline phosphatase levels, is an indicator of bone turnover and remodeling. The imbalances in these mineral parameters can be a sign of systemic metabolic dysfunction that can affect peri-implant bone healing [9,10]. The incorporation of these serum markers into pre-operative screening procedures could contribute to the improvement of the predictive capacity of patients prone to impaired osseointegration [11].

Although the identified significance of these metabolic and mineral factors is a well-known fact, they are not regularly measured during pre-operative implant examination. Systematic reviews and clinical trials have shown that well-designed clinical studies are required to gain a better idea about the impact of pre-operative metabolic profiles on implant outcomes and how they can be used to predict the outcomes by developing predictive models that would be used by clinicians to make decisions [12,13]. Also, there is an interaction between age, bone density, and systemic comorbidities with metabolic status, which underlies the necessity of an individual approach to determining treatment planning [14,15].

The proposed research is expected to investigate the predictability of dental implant osseointegration using pre-operative metabolic markers and mineral homeostasis. The study will also help in improving the clinical outcomes in the field of implant dentistry by offering a deeper insight into the role of systemic factors on the implant healing process and using key serum biomarkers, such as glycemic indices and mineral levels, as tools for achieving a better understanding of the role of systemic factors on the immune response to implantation.

LITERATURE REVIEW

The success of dental implants has to be determined by surgical and implant design technology as well as by the metabolic and systemic factors that can influence the quality and the process of bone osseointegration. The recent research stresses the importance of pre-operative assessment of the metabolic condition as a predictor of the outcome of implants. An example is that bone turnover markers such as alkaline phosphatase, osteocalcin, and parathyroid hormone have been linked to the differences in early implant stability [16,17]. These biochemical indicators help to give an indication of the strength of the bone remodeling, which is essential at early stages of healing after the implantation.

A number of clinical studies have emphasized the relevance of glycemic control to the implant osseointegration. Diabetics who are well controlled have the same implant success rate as non-diabetic patients, and poorly controlled diabetes is associated with a slow rate of osseointegration and high failure rates [18,19]. The level of HbA1c above 7% has been especially involved in bone healing impairment, and there is a necessity of metabolic screening before operation [20].

The mineral homeostasis, especially the serum calcium and phosphorus homeostasis, is important in the process of peri-implant bone mineralization. Reduced bone density at the sites of implantation has been linked to low serum calcium, and increased phosphorus could be considered to depict abnormal bone turnover [21,22]. Vitamin D metabolites continue to play a major role in the regulation of these minerals; however, recent research indicates that other factors, including magnesium and zinc, also determine bone microarchitecture and the potential to integrate the bone [23].

Local bone features, in addition to systemic biomarkers, play significant predictive roles in implant success. Bone volume, bone density, and cortical thickness at the planned site of implantation are important data, which cone-beam computed tomography (CBCT) and radiographic examination can offer [24]. Research has established that increased bone density is associated with increased primary stability and speedy osseointegration [25].

The interaction of implant healing and inflammatory markers is also studied by emerging research. Higher levels of C-reactive protein (CRP) and pro-inflammatory cytokines like IL-6 and TNF-alpha have been implicated in poor osseointegration and peri-implant bone loss especially in patients with metabolic disorders [26,27]. The knowledge of these inflammatory processes will enable clinicians to tell who is at risk of early failure of the implant.

The nutritional condition, comprising trace elements and other vitamins other than vitamin D, has been reported to influence bone regeneration. Calcium, magnesium and vitamin K2 supplementation have shown beneficial results in animal and human trials in terms of bone formation and implant stability [28,29]. Such data support the idea of a comprehensive method of assessing the patient before surgery on implants.

Lastly, recent developments with predictive modeling have integrated clinical, radiographic, and biochemical factors in determining the probability of the survival of implants. The machine learning algorithms that rely on pre-operative metabolic and mineral data have demonstrated encouraging findings on detecting patients who are at risk of implant complications, and this could be the future of personalized implant therapy [30].

METHODOLOGY

This research was conducted as a cross-sectional observational study to determine the effects of pre-operative metabolic indicators and mineral homeostasis on the predictability of dental implant osseointegration. Research was carried out in oral and maxillofacial surgery department of a Margalla College of Dentistry, Margalla Institute of Health Sciences, Rawalpindi, over a period of six months.

100 patients with an age range of 25-60 years who need dental implants were recruited through a consecutive sampling method. Patients with controlled systemic conditions were included, but patients with uncontrolled diabetes mellitus, metabolic bone diseases, chronic kidney disease, long-term corticosteroid therapy, head and neck radiotherapy history, periodontal disease, active and heavy smoking were excluded to reduce confounding effects on bone healing and osseointegration.

Standardized data collection tools were used to conduct pre-operative assessment. The Patient Demographic and Medical History Proforma was used to capture demographic data and medical history about the patient. The Pre-operative Metabolic and Mineral Profile Assessment Form was used to determine metabolic and mineral status, and contained such laboratory investigations as fasting blood glucose, glycated hemoglobin (HbA1c), serum vitamin D, serum calcium, serum phosphorus, and alkaline phosphatase. Blood samples were taken in a standardized environment and tested in the hospital laboratory based on the regular biochemical protocols.

All the dental implants were done in accordance with a standardized procedure of surgery, administered by fully trained oral surgeons under general anesthesia. Implant preparation and implant placement were done as per the requirements of the manufacturer. The post-operative guidelines and medications were unified for all patients to minimize differences in healing processes.

The follow-up period was used in evaluating the outcome of the Osseointegration, both clinically and radiographically. Resonance frequency analysis was utilized to do a clinical evaluation, and results were displayed on the Implant Stability Evaluation Sheet. Periapical radiographs and cone-beam computed tomography were used to conduct radiographic evaluation of marginal bone levels and implant bone interface, which was checked by periapical radiographs, which were recorded based on the Radiographic Osseointegration Assessment Form. The success or compromise of the OI of implants was identified by predetermined clinical and radiographic criteria.

Statistical Package of Social Sciences (SPSS) software was used in entering and analyzing data. The level of metabolic markers and descriptive statistics were summarized using descriptive statistics. The chi-square test was employed to identify the associations among the categorical variables, and an independent samples t-test was employed to compare the level of mean metabolic markers of the successful and compromised groups in the case of (osseointegration) success. The binary logistic regression was conducted to determine the significant predictors of compromised osseointegration. A p-value under 0.05 was deemed to be statistically significant.

RESULTS

Table 1. Demographic Characteristics (n = 100)

Variable	Category	Frequency	Percent
Age Group	25–34	28	28.0
	35–44	34	34.0
	45–54	26	26.0
	≥55	12	12.0
Gender	Male	58	58.0
	Female	42	42.0

The demographic distribution of study population is shown in table 1. Most of the participants were between the ages of 35 to 44 years (34%), then 25 to 34 years (28%), 45 to 54 years (26%), and above 55 years (12%). The sample was male 58 and female 42. A relatively balanced gender representation and age range that is appropriate when analyzing dental implant osseointegration among adults are shown by this distribution.

Table 2. Descriptive Statistics of Metabolic and Mineral Markers

Variable	N	Mean	Std. Deviation	Minimum	Maximum
Fasting Blood Glucose (mg/dL)	100	108.6	18.4	82	165
HbA1c (%)	100	6.21	0.89	4.8	8.1
Serum Vitamin D (ng/mL)	100	22.4	6.81	10.2	38.6
Serum Calcium (mg/dL)	100	9.12	0.61	7.8	10.4
Serum Phosphorus (mg/dL)	100	3.48	0.52	2.6	4.6
Alkaline Phosphatase (IU/L)	100	96.2	21.74	60	148

Table 2 is a summary of the metabolic and mineral profiles of subjects (pre-operative conditions). The average fasting blood glucose was 108.6/18.4mg/dl and mean HbA1c was 6.21/0.89% implying moderate glycemic control with few participants going beyond the normal limits. The mean serum vitamin D was found to be 22.4 + 6.81 ng/mL and a significant percentage of patients were found to be deficient or insufficient. The results of mean serum calcium, phosphorus and alkaline phosphatase were 9.12 +0.61 mg/dl, 3.48 +0.52 mg/dl and 96.2 +21.74 IU/L correspondingly, which demonstrated that mineral parameters were relatively normal with some deviations, which may influence the bone metabolism and the process of bone integration.

Table 3. Osseointegration Outcome

Outcome	Frequency	Percent	Valid Percent
Successful	80	80.0	80.0
Compromised	20	20.0	20.0

In table 3, the distribution of the outcomes of implant osseointegration is revealed. Eighty participants (80%) had successful osseointegration, whereas 20 participants (20) had failed results. This shows that the overall success rate of the study population is high, and as such, it has a sufficient sample to be used to examine the effect of metabolic and mineral markers on the integration of implants.

Table 4. Vitamin D Status × Osseointegration Status (Crosstabulation)

Vitamin D Status	Successful	Compromised	Total
Deficient (<20 ng/mL)	24	16	40
Insufficient (20–30 ng/mL)	36	6	42
Sufficient (>30 ng/mL)	20	2	22
Total	80	20	100

Table 4 looks into the correlation between levels of vitamin D and the results of the osseointegration rates. Out of the patients that had vitamin D deficiency (<20 ng/mL), 24 had successful osseointegration, and 16 had poor outcomes. In the insufficient group (2030 ng/mL), 36 of the insufficient were successful and 6 of the insufficient were compromised and 20 of the sufficient group were successful as well as 2 of the insufficient group were compromised. These findings imply that there is a positive correlation between the increased levels of vitamin D and successful implantation and the lack of vitamin D significantly predisposes the implant integration to deterioration.

Table 5. Independent Samples Test (Group Statistics)

Variable	Group	N	Mean	Std. Deviation
Fasting Blood Glucose	Successful	80	102.4	14.6
	Compromised	20	126.8	21.3
HbA1c (%)	Successful	80	5.9	0.7
	Compromised	20	7.1	1.0
Vitamin D (ng/mL)	Successful	80	25.1	6.2
	Compromised	20	17.3	4.8

Table 5 addresses the comparison of metabolic markers in the successful and compromised groups of implants. The mean fasting blood glucose (126.8 ± 21.3 mg/dL) and HbA1c (7.1 ± 1.0%) were much higher in the compromised group (102.4 ± 14.6 mg/dL and 5.9 ± 0.7%, respectively). There was a lower level of vitamin D in the compromised group (17.3 ± 4.8 ng/mL) than in the successful group (25.1 ± 6.2 ng/mL). These variations reveal that the impaired glycemic regulation and the low vitamin D levels are linked to the impaired osseointegration.

Table 6. Binary Logistic Regression Analysis

Variable	B	S.E.	Wald	Sig.	Exp(B)	95% CI
HbA1c >6.5%	1.23	0.36	11.66	0.001	3.42	1.68–6.97
Vitamin D Deficiency	1.06	0.39	7.64	0.006	2.89	1.34–6.21
Hypocalcemia	0.77	0.38	4.19	0.041	2.15	1.02–4.56
Smoking	0.67	0.35	3.61	0.057	1.96	0.98–3.89

Table 6 shows the binary logistic regression predictors of compromised implant osseointegration. A significant predictor at level of HbA1c above 6.5% (OR = 3.42, 95% CI: 1.686977) was found, meaning that high glycemic levels increased the risk of compromised implants more than three times. Another important predictor was the deficiency in vitamin D (OR = 2.89, 95% CI: 1.346.21, p = 0.006). Hypocalcemia predisposed it more than twice (OR = 2.15, 95% CI: 1.02456, p = 0.041). The trend was smoking which exhibited a statistically insignificant result (OR = 1.96, 95% CI: 0.983.89, p = 0.057). These results point to the fact that glycemic control, vitamin D status, and calcium levels are important predictors of the implant osseointegration, and lifestyle habits such as smoking could have a role to play too.

DISCUSSION

The present research compared the association of pre-operative metabolic data, mineral homeostasis, and implantation of dental added cracks. Results indicate that patients who have the best metabolic control

and mineral balance have higher success rates of the process of osseointegration which is consistent with the emerging evidence of the systemic determinants of implant outcomes [31,32].

Glycemic control appeared to be a predictor of the success of implants. The high levels of fasting blood glucose and HbA1c levels were significantly linked with impairment of the process of osseointegration. These findings are in line with earlier clinical investigations that hyperglycemia has adverse effects on the differentiation of osteoblasts, angiogenesis and collagen synthesis at the implant site which is ultimately detrimental to early bone healing [33,34]. On the other hand, patient, who were well controlled in diabetes, had similar levels of implant stability as non-diabetic patients, which indicates the significance of pre-operative metabolic testing and optimization [35].

Another important issue that affected the process of osseointegration was vitamin D status. Patients who had a good supply of serum vitamin D had higher implant stability and less marginal bone loss, which was in line with the literature that showed that vitamin D has a regulating effect on the activity of osteoblast and calcium-phosphate homeostasis [36,37]. On the other hand, vitamin D deficiency was linked to slowed bone remodeling and reduced survival of implant underlining that regular review of vitamin D levels in patients receiving implant therapy is necessary [38].

Mineral homeostasis especially serum calcium and phosphorus also showed significant relationships with the outcomes of implants. The imbalances of these minerals indicating changes in the bone turnover were associated with the reduced implant stability and the premature loss of the bone. This follows the evidence of other studies which propose that proper mineral homeostasis is necessary in order to achieve optimal bone formation about implants [39,40]. In addition, high levels of alkaline phosphatases in certain patients were observed to be associated with active bone remodeling, which might affect insertion of implants, but excessive levels might be indicative of metabolic imbalance [41].

Interaction of metabolic and mineral factors indicates the multifactoriality of the process of osseointegration. The highest risk group was those patients that had either a concomitant issue or a metabolic imbalance; hence, a comprehensive pre-operative evaluation is crucial. A combination of the biochemical markers, clinical assessment, and radiographic imaging would enable clinicians to risk-stratify their patients and make appropriate interventions [42,43].

The current research is also in line with new findings that indicate that the issues of systemic inflammation can be used to control implant integration. Chronic inflammation with a low-grade, which is typical of poorly controlled metabolic states, may disrupt the activity of osteoblasts and stimulate osteoclastic bone resorption, which could be part of the reason why metabolic indicators are associated with the outcome of osteointegration [44].

In general, these results explain why pre-operative metabolic and mineral testing should be included in the treatment planning of implants. The success of implants and the rate of early failure could be enhanced by recognition and correction of the modifiable risk factors at an early stage, i.e. hyperglycemia or deficiency of vitamin D. Furthermore, potential studies can be done to examine the incorporation of predictive algorithms using a combination of metabolic and mineral as well as radiographic information in order to further improve personalized implant therapy [45,46,47].

CONCLUSION

The results of the current research indicate that the pre-operative metabolic indicators and mineral homeostasis are important factors in influencing the predictability of dental implant osseointegration. Patients who had good glycemic control, vitamin D concentration, and mineral balance had high probabilities of successful integration of the implants whereas patients who had metabolic derangements or mineral imbalances had higher chances of poor integration of the implants. The findings further emphasize the need to conduct extensive pre-operative evaluation and systemic health optimization to increase the success rate of implants. The use of the metabolic assessment and mineral assessment in the daily practice in the clinic might enhance patient selection and treatment planning and eventually enhance the success of dental implant therapy in the long run.

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