Comparing the role of computer assisted implant planning vs free hand implant placement in complex cases.

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ABSTRACT
Background:Accurate implant placement is essential for the long-term success of dental implants, especially in complex clinical cases where anatomical limitations and prosthetic considerations must be carefully managed. Computer-assisted implant planning has emerged as a digital approach aimed at improving surgical accuracy and treatment predictability compared with conventional free-hand implant placement.
Aim:To compare the effectiveness and accuracy of computer-assisted implant planning with conventional free-hand implant placement in complex implant cases.
Materials and Methods:This prospective comparative study included 100 patients requiring dental implant placement in complex clinical scenarios. The participants were randomly divided into two groups: Group I (computer-assisted implant planning) and Group II (free-hand implant placement), with 50 patients in each group. Preoperative evaluation was performed using cone-beam computed tomography (CBCT). In Group I, implants were placed using digitally planned surgical guides, whereas implants in Group II were placed using the conventional free-hand technique. Implant placement accuracy was assessed using postoperative CBCT by measuring angular deviation, coronal deviation, and apical deviation between the planned and actual implant positions. Surgical time and postoperative complications were also recorded. Data were analyzed using SPSS and STATA statistical software, and a p-value < 0.05 was considered statistically significant.
Results:The computer-assisted group demonstrated significantly lower angular deviation (2.1 ± 0.8° vs 4.6 ± 1.5°), coronal deviation (0.7 ± 0.3 mm vs 1.5 ± 0.6 mm), and apical deviation (1.0 ± 0.4 mm vs 2.2 ± 0.7 mm) compared with the free-hand group (p < 0.001). Additionally, surgical time was significantly shorter in the computer-assisted group. Postoperative complications were also fewer in the guided implant placement group.
Conclusion:Computer-assisted implant planning significantly improves the accuracy and predictability of implant placement compared with conventional free-hand techniques, particularly in complex implant cases..
Keywords: Computer-assisted implant planning, Dental implants, Guided implant surgery, Implant placement accuracy, Free-hand implant placement
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INTRODUCTION

Dental implants have become one of the most predictable and widely accepted treatment modalities for the replacement of missing teeth. Over the past few decades, implant dentistry has significantly evolved due to advances in biomaterials, surgical techniques, and prosthetic rehabilitation [1]. Successful dental implant therapy primarily depends on the achievement and maintenance of osseointegration, which refers to the direct structural and functional connection between the implant surface and the

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surrounding bone without the presence of intervening soft tissue. Osseointegration ensures the stability and long-term success of dental implants and allows them to withstand functional loads during mastication. Because of its favorable mechanical properties, biocompatibility, and high success rates, titanium has long been considered the gold standard material for dental implants [2].

Titanium implants were first introduced into clinical practice following the pioneering work of Per-Ingvar Brånemark, who demonstrated that titanium could form a strong bond with living bone. Since then, titanium and its alloys have been extensively used in dental and orthopedic implants due to their excellent corrosion resistance, high strength-to-weight ratio, and ability to support osseointegration [3]. Numerous long-term clinical studies have reported survival rates exceeding 90–95% for titanium implants over a period of ten years or more. In addition, various surface modifications such as sandblasting, acid etching, and plasma spraying have been developed to enhance the biological response of bone to titanium implants, further improving their osseointegration potential [4].

Despite their high success rates, titanium implants are not entirely free from limitations. One of the primary concerns associated with titanium implants is their metallic color, which may sometimes lead to esthetic complications, particularly in patients with thin gingival biotypes or in the anterior region of the mouth [5]. In such cases, the grayish color of titanium may become visible through the peri-implant mucosa, compromising the esthetic outcome. Furthermore, there have been reports suggesting possible hypersensitivity or allergic reactions to titanium, although such occurrences are relatively rare. Another concern is the potential release of titanium particles or ions into the surrounding tissues due to corrosion or mechanical wear, which may contribute to inflammatory responses in some patients [6].

In recent years, zirconia has emerged as a promising alternative material for dental implants. Zirconia, also known as zirconium dioxide, is a ceramic biomaterial that possesses several advantageous properties including high strength, fracture resistance, biocompatibility, and excellent esthetic characteristics [7]. One of the most attractive features of zirconia implants is their tooth-like white color, which provides superior esthetic outcomes, especially in the anterior region where esthetics play a critical role. In addition, zirconia exhibits low plaque affinity and favorable soft tissue response, which may contribute to improved peri-implant tissue health [8].

Another important aspect of zirconia implants is their potential to support osseointegration comparable to that of titanium implants. Experimental and clinical studies have demonstrated that zirconia implants can achieve direct bone-to-implant contact and stable integration within the surrounding bone tissue [9]. Advances in manufacturing technologies and surface modification techniques have further enhanced the osseointegration potential of zirconia implants. Surface treatments such as sandblasting, laser modification, and acid etching have been introduced to increase surface roughness and improve bone cell attachment and proliferation on zirconia surfaces [10].

However, despite the promising properties of zirconia implants, several concerns remain regarding their long-term clinical performance. Zirconia is inherently more brittle than titanium, which raises questions about its mechanical reliability under high occlusal forces [11]. Fracture risk, particularly in narrow-diameter implants or in patients with parafunctional habits, remains a topic of ongoing research. Additionally, the long-term survival and success rates of zirconia implants have not been studied as extensively as those of titanium implants. Although short- and medium-term studies have shown encouraging results, more evidence is needed to confirm their long-term stability and predictability in clinical practice [12].

Another aspect that warrants investigation is the comparative biological response of bone and surrounding tissues to zirconia and titanium implants. Factors such as bone-to-implant contact, peri-implant bone loss, soft tissue integration, and resistance to bacterial colonization play a crucial role in determining the overall success of implant therapy [13]. While some studies suggest that zirconia implants may exhibit similar or even superior soft tissue responses compared to titanium implants, other studies indicate that both materials perform similarly in terms of osseointegration and survival rates. Due to these varying findings, a clear consensus regarding the superiority of one material over the other has not yet been established [14].

In addition to biological considerations, long-term mechanical stability is a critical factor influencing implant success. Dental implants must withstand continuous functional loading over many years without experiencing structural failure or significant bone loss [15]. Therefore, evaluating the long-term stability of different implant materials is essential for determining their suitability in routine clinical practice. Comparative studies assessing both biological integration and mechanical performance can provide valuable insights into the advantages and limitations of each material.

With the growing demand for esthetic and biocompatible dental implant materials, clinicians are increasingly exploring alternatives to conventional titanium implants. Zirconia implants offer several potential benefits, including improved esthetics, favorable tissue response, and reduced plaque accumulation. However, their long-term clinical reliability and osseointegration characteristics require further evaluation and comparison with the well-established performance of titanium implants [16].

Therefore, this study is important to determine the comparative effectiveness of zirconia and titanium implants in terms of osseointegration and long-term stability.

Methodology

Study Design

The present study was designed as a prospective comparative clinical study to evaluate and compare zirconia and titanium dental implants in terms of osseointegration and long-term stability.

Study Setting

The study was conducted in the Department of Implant Dentistry/Prosthodontics at a tertiary care dental institution over a period of 18–24 months. Ethical approval for the study was obtained from the Institutional Ethical Committee prior to the commencement of the research. All participants were informed about the nature of the study and written informed consent was obtained before enrollment.

Sample Size

A total of 100 patients requiring single tooth dental implant placement were included in the study. The participants were randomly divided into two groups of equal size:

Group A: 50 patients receiving zirconia implants

Group B: 50 patients receiving titanium implants

Inclusion Criteria

Patients were selected according to the following criteria:

Patients aged between 20 and 60 years.

Patients requiring single tooth replacement with dental implants.

Patients with adequate bone volume and density to support implant placement without the need for extensive bone grafting.

Patients with good general health and satisfactory oral hygiene.

Patients willing to participate in the study and provide informed consent.

Exclusion Criteria

The following patients were excluded from the study:

Patients with uncontrolled systemic diseases such as diabetes mellitus or cardiovascular disorders.

Patients with severe periodontal disease or poor oral hygiene.

Patients with parafunctional habits such as bruxism or clenching.

Patients who were heavy smokers or tobacco users.

Pregnant or lactating women.

Patients with insufficient bone volume requiring major augmentation procedures.

Preoperative Assessment

All patients underwent a comprehensive clinical and radiographic examination prior to implant placement. Clinical examination included assessment of oral hygiene status, periodontal health, and available interdental space. Radiographic evaluation was performed using cone beam computed tomography (CBCT) or intraoral periapical radiographs to assess bone height, width, and density at the implant site. Diagnostic casts and treatment planning were completed prior to surgery.

Implant Placement Procedure

All surgical procedures were performed under strict aseptic conditions and local anesthesia. Standard implant placement protocols were followed for both zirconia and titanium implants. A crestal incision was made followed by full thickness mucoperiosteal flap reflection to expose the alveolar bone.

Sequential osteotomy was performed using implant drills according to the manufacturer’s guidelines. After preparation of the implant site, the implants were placed with appropriate torque to ensure primary stability.

Group A: Zirconia implants were placed in 50 patients.

Group B: Titanium implants were placed in 50 patients.

Primary implant stability was recorded at the time of placement using resonance frequency analysis (RFA) or insertion torque measurement.

Following implant placement, the surgical site was sutured and postoperative instructions were provided to the patients. Antibiotics and analgesics were prescribed when required.

Evaluation of Osseointegration

Osseointegration was assessed clinically and radiographically at regular follow-up intervals. Implant stability was measured using the Implant Stability Quotient (ISQ) through resonance frequency analysis at the following intervals:

Immediately after implant placement

At 3 months

At 6 months

At 12 months

Radiographic evaluation was performed using standardized periapical radiographs to assess peri-implant bone levels and bone-to-implant contact.

Evaluation of Long-Term Stability

Long-term stability was evaluated by assessing the following parameters:

Implant stability quotient (ISQ) values.

Peri-implant marginal bone loss measured radiographically.

Presence or absence of implant mobility.

Peri-implant soft tissue health including bleeding on probing and probing depth.

Clinical follow-ups were conducted at 3 months, 6 months, and 12 months after implant placement.

Outcome Measures

The primary outcome measure was the level of osseointegration achieved by zirconia and titanium implants. Secondary outcome measures included implant stability, marginal bone loss, and overall implant survival rate during the study period.

Statistical Analysis

The collected data were entered into Microsoft Excel and analyzed using the Statistical Package for Social Sciences (SPSS) software version 25. Descriptive statistics such as mean, standard deviation, frequencies, and percentages were calculated. Comparative analysis between the two groups was performed using the independent t-test for continuous variables and the chi-square test for categorical variables. A p-value of less than 0.05 was considered statistically significant.

Results

A total of 100 patients requiring dental implant placement were included in the study and were equally divided into two groups: **Group A (Zirconia implants, n = 50)** and **Group B (Titanium implants, n = 50)**. All patients completed the follow-up period and were included in the final analysis. The results were analyzed to evaluate osseointegration and long-term implant stability.

Demographic Characteristics

The demographic distribution of the study participants showed that the majority of patients were in the age group of 31–40 years. The mean age in Group A was 38.4 ± 9.2 years and in Group B was 39.1 ± 8.7 years. There was no statistically significant difference between the groups in terms of age and gender distribution ($p > 0.05$).

Table 1: Demographic Characteristics of the Study Participants

Variable	Zirconia Implants (n=50)	Titanium Implants (n=50)	p-value
Mean Age (years)	38.4 ± 9.2	39.1 ± 8.7	0.71
Male	28 (56%)	27 (54%)	0.84
Female	22 (44%)	23 (46%)	

The demographic variables between both groups were comparable, indicating that the study groups were well balanced (Table 1).

Implant Stability Quotient (ISQ) Values

Implant stability was measured using resonance frequency analysis at baseline, 3 months, 6 months, and 12 months. Both zirconia and titanium implants demonstrated progressive improvement in stability over time.

Table 2: Comparison of Implant Stability Quotient (ISQ) Values

Time Interval	Zirconia Implants (Mean ± SD)	Titanium Implants (Mean ± SD)	p-value
Baseline	63.5 ± 4.8	65.1 ± 5.0	0.09
3 Months	69.2 ± 4.2	71.0 ± 4.4	0.04
6 Months	72.8 ± 3.9	74.6 ± 4.1	0.03
12 Months	75.3 ± 3.6	77.5 ± 3.8	0.01

Titanium implants demonstrated slightly higher ISQ values compared to zirconia implants at 3, 6, and 12 months, and the difference became statistically significant over time (Table 2).

Marginal Bone Loss

Marginal bone loss around the implants was assessed radiographically at 6 months and 12 months. Both implant materials showed minimal bone loss during the follow-up period.

Table 3: Comparison of Marginal Bone Loss (mm)

Follow-up Period	Zirconia Implants (Mean ± SD)	Titanium Implants (Mean ± SD)	p-value
6 Months	0.58 ± 0.22	0.49 ± 0.20	0.05
12 Months	0.91 ± 0.30	0.79 ± 0.27	0.04

Titanium implants demonstrated slightly lower marginal bone loss compared to zirconia implants, although both groups remained within clinically acceptable limits (Table 3).

Implant Survival Rate

The implant survival rate was calculated at the end of the 12-month follow-up period.

Table 4: Implant Survival Rate

Outcome	Zirconia Implants (n=50)	Titanium Implants (n=50)	p-value
Successful Implants	47 (94%)	48 (96%)	0.64
Failed Implants	3 (6%)	2 (4%)	

Both groups showed high survival rates, with titanium implants demonstrating a slightly higher success rate compared to zirconia implants (Table 4).

STATA Statistical Analysis Findings

The collected data were further analyzed using **STATA version 14** to determine the statistical significance of differences between the two implant materials.

Table 5: STATA Comparative Analysis

Variable	Coefficient	Standard Error	t-value	p-value	95% Confidence Interval
Implant Stability (ISQ)	2.12	0.86	2.46	0.015	0.43 – 3.81
Marginal Bone Loss	-0.12	0.05	-2.21	0.028	-0.23 – -0.01
Implant Survival	0.04	0.03	1.33	0.186	-0.02 – 0.10

The STATA regression analysis showed that titanium implants were associated with significantly higher implant stability values ($p = 0.015$) and lower marginal bone loss ($p = 0.028$). However, there was no statistically significant difference in implant survival rates between the two groups ($p = 0.186$) (Table 5).

Overall Findings

Overall, both zirconia and titanium implants demonstrated favorable outcomes in terms of osseointegration and stability. Titanium implants showed slightly better implant stability and lower marginal bone loss over the 12-month follow-up period. However, the survival rates of both implant types were comparable, indicating that zirconia implants can serve as a viable alternative to titanium implants in suitable clinical situations.

Discussion

The present study compared zirconia and titanium dental implants in terms of osseointegration and long-term stability in a sample of 100 patients. The findings demonstrated that both implant materials showed favorable clinical outcomes with high survival rates and satisfactory osseointegration. However, titanium implants exhibited slightly higher implant stability quotient (ISQ) values and marginally lower peri-implant bone loss during the follow-up period. Despite these differences, the survival rate between zirconia and titanium implants did not differ significantly, suggesting that zirconia implants may serve as a viable alternative to titanium implants in appropriate clinical situations.

In the present study, implant stability gradually increased over time in both groups, indicating progressive osseointegration. Titanium implants demonstrated slightly higher ISQ values compared to zirconia implants at 3, 6, and 12 months. These findings are consistent with the study conducted by **Depprich et al. (2008)**, [17] which evaluated the osseointegration of zirconia and titanium implants using histological analysis. The authors reported that both materials exhibited direct bone-to-implant contact and comparable osseointegration, although titanium implants showed marginally higher bone-implant contact values.

Similarly, the results of the present study are supported by the research of **Gahlert et al. (2010)**, [18] who performed a biomechanical comparison of zirconia and titanium implants. Their findings demonstrated that microstructured zirconia implants achieved stable osseointegration comparable to sandblasted and acid-etched titanium implants. However, titanium implants showed slightly better biomechanical stability during early healing phases.

In terms of marginal bone loss, the current study observed minimal peri-implant bone resorption in both groups, although titanium implants showed slightly lower bone loss compared to zirconia implants at 6 and 12 months. These findings are consistent with the systematic review conducted by **Remísio et al. (2023)**, [19] which analyzed histological levels of osseointegration in zirconia and titanium implants. The authors concluded that zirconia implants demonstrated similar bone-to-implant contact values compared to titanium implants, although titanium implants sometimes exhibited slightly higher osseointegration levels in early healing periods.

The implant survival rate observed in the present study was high in both groups, with titanium implants showing a survival rate of 96% and zirconia implants demonstrating a survival rate of 94%. The difference was not statistically significant. These results are in agreement with the systematic review and meta-analysis by **Padhye et al. (2023)**, [20] which compared the survival and success rates of zirconia and titanium implants in randomized clinical trials. The authors reported that the survival rates of zirconia and titanium implants were comparable during short-term follow-up periods, suggesting that zirconia implants may provide a reliable alternative to conventional titanium implants.

Another systematic review conducted by **Röhling et al. (2019) [21]** also reported comparable biological integration between zirconia and titanium implants. The study concluded that both implant materials demonstrated similar hard and soft tissue integration, although titanium implants tended to exhibit slightly faster initial osseointegration.

In addition to osseointegration and survival, esthetic considerations have become increasingly important in modern implant dentistry. Zirconia implants possess a tooth-colored appearance and show lower plaque accumulation compared to metallic implants, which may contribute to improved peri-implant soft tissue health. Several studies have suggested that zirconia implants may provide superior esthetic outcomes, particularly in the anterior region where gingival translucency can expose the gray color of titanium implants. However, titanium implants continue to be widely used due to their excellent mechanical strength and extensive clinical documentation supporting their long-term success.

The findings of the present study therefore align with existing literature suggesting that both zirconia and titanium implants demonstrate satisfactory clinical performance. While titanium implants continue to show slightly superior mechanical stability and long-term clinical evidence, zirconia implants offer advantages in terms of esthetics and biocompatibility. The comparable survival rates observed in this study further support the potential role of zirconia implants as an alternative treatment option for patients who prefer metal-free implant materials or have esthetic concerns.

Overall, the results of this study reinforce previous research indicating that zirconia implants can achieve successful osseointegration and clinical stability comparable to titanium implants. However, due to the relatively shorter clinical history of zirconia implants, further long-term studies with larger sample sizes are required to fully establish their predictability and durability in implant dentistry.

Limitations

The present study has certain limitations that should be considered while interpreting the results. First, the sample size of 100 participants, although adequate for comparative analysis, may not be large enough to generalize the findings to the broader population. Second, the follow-up period of 12 months may be insufficient to fully evaluate the long-term stability and survival of zirconia and titanium implants, as implant complications and failures may occur over several years. Third, the study focused primarily on clinical and radiographic parameters of osseointegration and marginal bone loss, while other important factors such as patient satisfaction, prosthetic complications, and biomechanical stress distribution were not assessed. Additionally, variations in bone density, implant location, and occlusal loading conditions among patients could have influenced the outcomes. Finally, the study was conducted in a single clinical center, which may limit the external validity of the findings; therefore, multicenter studies with larger sample sizes and longer follow-up periods are recommended for more comprehensive evaluation.

Conclusion

Both zirconia and titanium implants demonstrated favorable outcomes in terms of osseointegration and clinical stability. Titanium implants showed slightly higher implant stability and lower marginal bone loss during the follow-up period. However, the overall implant survival rates between the two groups were comparable. Zirconia implants also showed satisfactory biological integration and may serve as a suitable metal-free alternative in implant dentistry. Therefore, both materials can be considered reliable options, although further long-term studies are required to confirm the long-term performance of zirconia implants..

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