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Evaluation of the Accuracy of Dental Implant Placement on Different Cast Models

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ABSTRACT

Introduction: To compare the accuracy of implant placement on mandibular models fabricated from different materials using a single digitally designed surgical guide, and to identify which model provided the highest precision and cost-effectiveness for research and training applications.

Materials and Methods: Nine identical mandibular models were fabricated with missing teeth at the right lateral incisor, right first molar, and left first premolar. Three cast models were used: porous polyethylene (MedPor), photopolymer resin (SprintRay), and photopolymer resin (MAZIC® D MODEL). A single CAD/CAM surgical guide was designed in REALGuide 5.3 and printed with SprintRay technology. Using standardized protocols, 27 demo implants (three per model) were placed. Postoperative CBCT scans were digitally superimposed with planned positions to assess angular and linear deviations (coronal, apical, mesial, distal, and labial). The data were analyzed via descriptive statistics, one-way ANOVA, and Tukey's HSD tests.

Results: Analysis revealed a statistically significant deviation at the lateral apical position (ANOVA, $p = 0.0011$). Porous polyethylene (MedPor) demonstrated greater error than did photopolymer resin (SprintRay) ($p = 0.0107$) or photopolymer resin (MAZIC® D MODEL) ($p = 0.0009$), whereas no significant difference was detected between the two resin-based models ($p = 0.0775$). Although the photopolymer resin (SprintRay) resulted in greater mean deviations at premolar sites, these differences were not statistically significant. Intragroup analysis indicated site-dependent variation within photopolymer resin (MAZIC® D MODEL) ($p = 0.0313$), whereas porous polyethylene (MedPor) and photopolymer resin (SprintRay) exhibited more consistent error distributions across sites.

Conclusion: Photopolymer resin models presented the highest apical accuracy at lateral incisor sites, outperforming porous polyethylene. Resin-based models (SprintRay and MAZIC® D MODEL) proved accurate and cost-effective, whereas porous polyethylene produced larger deviations despite being more than ten times more costly. The two photopolymers also differ in their mechanical properties.

Keywords: Apical deviation; Dental implant; Digital implantology; Mandibular model; Surgical guide.

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Introduction

Dental implants have advanced conventional dentistry by offering a long-lasting and dependable alternative to the replacement of lost teeth. These have become the gold standard for restoring the beauty and functional status of completely or partially edentulous patients [1,2,3]. Dental implants offer the best and longest-lasting remedy for the issue of tooth loss. With a ten-year success rate of more than 95%, dental implants constitute a valuable and indispensable part of prosthodontics and oral surgery, as laid down by Brånemark et al. (1969). This treatment consists of implanting a fixture made of titanium or zirconia into the alveolar ridge [4]. The fixture then osseointegrates with the surrounding bone to permit the secure placement of a prosthetic tooth [5]. Although implant technology has progressed tremendously, surgical perfection, meticulous planning, and operator skill still constitute key determinants of the effectiveness of implant therapy. Thus, competent planning in implantology is necessary to avoid pitfalls and complications. This necessitates further research and refinement of the teaching of the subject [6,7].

Specialist practitioners and general practitioners conduct dental implant placement operations throughout various regions of the world. However, it is a highly technical procedure that necessitates cautious planning and procedure execution. As claimed by Sadowski [8], aesthetic complications, peri-implantitis, and biomechanical complications can be produced by unsuitable implant placement. Hence, initiating robust training programs and practice on a hands-on level is crucial to enhancing clinical outcomes. The practice of dental implantation can be conducted efficiently with simulation-based practice and the use of in vitro specimens, which allows practitioners to practice on a more realistic level ahead of procedure execution for patients. Drilling, angulation, and accuracy of implant placement could be practiced safely and efficiently with the use of dental models [9]. The dental models used for in vitro research and teaching include various materials, all of which have unique mechanical and physical properties. As Papaspyridakos et al. [10] reported, resin-based models have often been used for preoperative planning and surgical guidance because of their remarkable precision and hardness [11]. As an alternative, biocompatible porous polyethylene (Medpor), which has bone-like structural mimicry, has been studied [12,13]. The current study aimed to evaluate the effectiveness of three dental models used for implant training and in vitro research. Two of the dental models are made by respected producers and are of the resin type; the remaining model is made of porous polyethylene material. Using the techniques of rapid-prototype medical modeling and stereolithography, individually customized surgical guides can be generated that have their foundation on a preprogrammed surgical plan with critical prosthetic information. These steps allow significantly greater precision and predictability [14,15,16]. To optimize implant training protocols and improve clinical results, it is indispensable to be acquainted with the advantages and disadvantages of each model material. The purpose of this study is to provide valuable information on the optimum dental implant simulation materials by considering parameters such as dimensional accuracy and implant linear and angular position accuracy. Patients and practitioners will benefit from the study, which will optimize preclinical research protocols and implantology teaching.

Materials and Methods

Study design

This in vitro comparative study was designed to evaluate the accuracy of implant placement via digitally fabricated surgical guides on mandibular models fabricated from different materials. The objective was to assess deviations between planned and actual implant positions, to determine whether the material type influences placement accuracy, and to consider implications for cost-effectiveness in training and research. Nine identical mandibular models, each missing the right lateral incisor, right first molar, and left first premolar, were constructed using three different materials: photopolymer resin models (Mazic® D Model, Vericom Co., Ltd., Gangwon-do, South Korea), photopolymer resin models (SprintRay Die and Model 2 Resin, SprintRay Inc., Los Angeles, CA, USA), and porous polyethylene models (MedPor, Stryker CMF, Kalamazoo, MI, USA). Three models from each material were included.

A single surgical guide was designed using REALGuide 5.3 software (3DIEMME, Cantù, Italy) and fabricated with a SprintRay Pro 95 s printer (SprintRay Inc., Los Angeles, CA, USA) at a 0.1 mm layer thickness, employing the SprintRay Surgical Guide Resin. This guide was applied uniformly across all the models for the placement of 27 demo implants (3.5 × 11.5 mm, OXY Implant, South Korea), three per model. Implant placement was performed by the same surgeon under standardized protocols via a Woodpecker surgical engine (Guilin Woodpecker Medical Instrument Co., Guangxi, China) with a drilling speed of 1500 rpm, torque of 50 Ncm, and intermittent irrigation.

Data collection

Each model was scanned pre and postoperatively with a Medit i700 intraoral scanner (Medit Corp., Seoul, South Korea), and postoperative CBCT images were obtained via a Carestream CS9600 unit (Carestream Dental LLC, Atlanta, GA, USA) under standardized exposure settings (0.7 mm Cu, 120 kV, 6.3 mA, 60 ms, 2.02 mGy·cm^2, FOV 10 × 5 cm). The planned and actual implant positions were digitally superimposed with REALGuide 5.3 software, and deviations were measured in terms of angular differences, linear deviations at the coronal and apical positions, mesial and distal shifts, and labial displacement, relative to anatomical reference points such as the alveolar crest and labial surface.

Statistical Analysis

All the measurements were analyzed with SPSS version 26.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics (means ± standard deviations) were calculated, and normality was tested via the Shapiro–Wilk test. One-way ANOVA was used to compare differences among the three groups, and Tukey's HSD post hoc test identified intergroup differences. Intragroup analysis was performed with pairwise t tests, while Z scores were applied for standardization and outlier detection. A p value of less than 0.05 was considered statistically significant. This study was approved by the Ethics Committee of the University of Sulaimani, College of Dentistry (Approval No. 24/288), and conducted in accordance with the principles of the Declaration of Helsinki.

Results

Models, implant placements, and distribution

A total of nine mandibular models were investigated, each receiving three implants, resulting in twenty-seven placements. The models were fabricated from porous polyethylene and two different brands of photopolymer resins. A single CAD/CAM surgical guide was applied uniformly across all the models to ensure consistency of implant placement. Postoperative CBCT scans were obtained, and deviation analyses were conducted via REALGuide 5.3 software to compare planned and actual implant positions (Figure 1). The measurements included angular, coronal, apical, mesial, distal, and labial deviations (Tables 1–3).

Intergroup comparisons

At the lateral apical site, a statistically significant difference was observed among the three model types (ANOVA, $p = 0.0011$). Porous polyethylene exhibited greater deviation than photopolymer resin (SprintRay) did ($p = 0.0107$) and photopolymer resin (MAZIC® D MODEL) did ($p = 0.0009$), whereas no significant difference was noted between the two resin-based models ($p = 0.0775$). At the premolar ($p = 0.729$) and molar ($p = 0.121$) sites, apical deviations did not differ significantly among the three models. Labial deviations were comparable across groups (all $p > 0.05$), although photopolymer resin (SprintRay) tended toward higher mean values at premolars (0.967 ± 0.306 mm) than did porous polyethylene (0.700 ± 0.300 mm) and photopolymer resin (MAZIC® D MODEL) (0.800 ± 0.500 mm). Mesial and distal deviations at both the coronal and apical levels also did not show significant intergroup differences (all $p > 0.05$), despite slightly higher values being observed for photopolymer resin (SprintRay) at premolars. Angular deviations followed a similar pattern, with photopolymer resin (SprintRay) premolars showing the largest mean angle (5.367 ± 2.61°) compared with porous polyethylene (2.0 ± 1.229°) and photopolymer resin (MAZIC® D MODEL) (3.567 ± 3.301°), although these differences were not statistically significant (ANOVA, $p = 0.333$).

Intragroup analysis

Within-model comparisons revealed a significant variation in apical deviation across tooth positions for photopolymer resin (MAZIC® D MODEL) ($p = 0.0313$). The greatest differences were observed between the molar and premolar sites and between the lateral and molar sites, although not all the comparisons reached strong significance. In contrast, the porous polyethylene ($p = 0.0769$) and photopolymer resin (SprintRay) ($p = 0.7023$) models did not demonstrate significant site-to-site variability, indicating a more uniform error distribution. For labial, mesial, distal, and angular deviations, intragroup differences were not significant for any model ($p > 0.28$).

Characteristics of deviations

Photopolymer resin models (MAZIC® D MODEL) demonstrated superior apical accuracy in lateral incisor regions, which is clinically relevant in areas with limited bone availability and where precise angulation control is critical. Porous polyethylene models exhibited greater variability and higher mean deviations despite higher material costs. Photopolymer resin-based models (SprintRay and MAZIC® D MODEL) provided consistent accuracy and were more cost-effective. The trends observed in the photopolymer resin (SprintRay),

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particularly at premolar sites, may be clinically because they identify regions where deviations are more likely to occur, even if the differences do not reach statistical significance.

Summary of findings

Overall, these results suggest that resin-based models, especially the MAZIC® D MODEL, offer reliable apical placement accuracy for implant training and research applications. Porous polyethylene, although more expensive, demonstrated greater variability and lower precision, highlighting the importance of material selection in in vitro implant studies.

Table 1. Summarizes the means and standard deviations of implants used in MedPor models.

Measurement	no.42 Mean	no.42 SD	no.44 Mean	no.44 SD	no.36 Mean	no.36 SD
Apical deviation	0.9	0.173	0.367	0.208	1.067	0.473
Labial deviation	0.8	0.1	0.7	0.3	0.633	0.058
Mesial at crest	0.233	0.231	0.2	0.265	0.367	0.115
Distal at crest	0.233	0.231	0.167	0.208	0.267	0.208
Mesial at apical	0.6	0.361	0.333	0.153	0.467	0.115
Distal at apical	0.433	0.252	0.567	0.404	0.4	0.529
Angular deviation	3.767	2.434	2	1.229	3.6	1.179

Table 2. Summarizes the means and standard deviations of implants used in SprintRay models.

Measurement	no.42 Mean	no.42 SD	no.44 Mean	no.44 SD	no.36 Mean	no.36 SD
Apical deviation	0.467	0.058	0.367	0.153	0.367	0.231
Labial deviation	0.667	0.306	0.967	0.306	1	0.1
Mesial at crest	0.267	0.462	0.4	0.2	0.467	0.404
Distal at crest	0.433	0.208	0.6	0.1	0.533	0.153
Mesial at apical	0.6	0.173	0.6	0.721	0.467	0.379
Distal at apical	0.6	0.265	0.867	0.551	0.4	0.173
Angular deviation	2.467	1.665	5.0367	2.61	3.8	2.666

Table 3. Summarizes the means and standard deviations of implants used in MAZIC® D Models.

Measurement	no.42 Mean	no.42 SD	no.44 Mean	no.44 SD	no.36 Mean	no.36 SD
Apical deviation	0.2	0.1	0.267	0.153	0.733	0.289
Labial deviation	0.767	0.252	0.8	0.5	0.767	0.289
Mesial at crest	0.133	0.153	0.133	0.155	0.467	0.289
Distal at crest	0.167	0.153	0.3	0.3	0.4	0.1
Mesial at apical	0.4	0.173	0.167	0.289	0.167	0.115
Distal at apical	0.233	0.115	0.4	0.1	0.767	0.404
Angular deviation	2.733	1.582	3.567	3.301	2.967	1.914

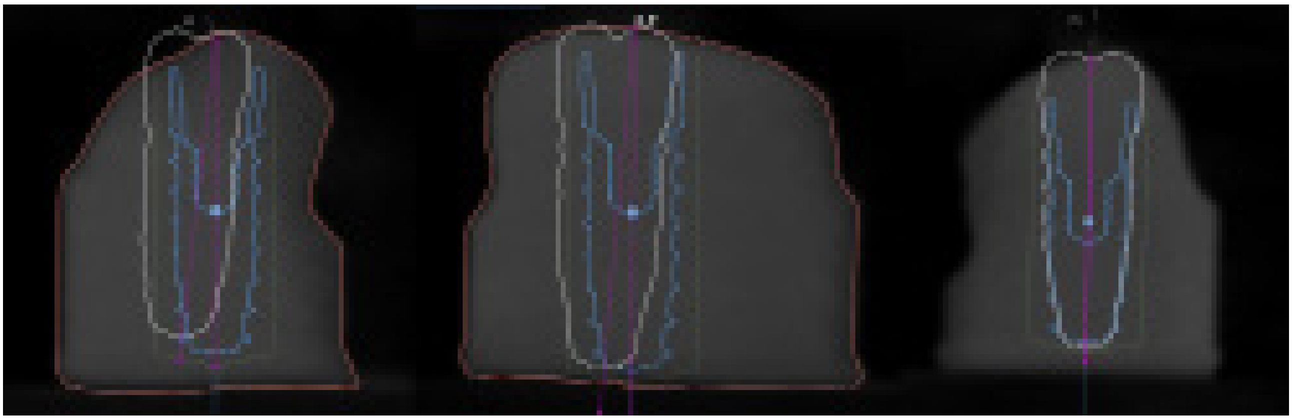

Figure 1. Cone-beam computed tomography superimposition showing apical deviations in mandibular models fabricated from three different materials: (A) Porous polyethylene (MedPor), (B) Photopolymer resin (SprintRay), and (C) Photopolymer resin (MAZIC® D MODEL).

Discussion

The integration of virtual implant planning with the fabrication of surgical guides through additive manufacturing offers to reduce the learning curve of dental implantology, particularly for novice practitioners, while simultaneously lowering the risk of treatment failure. Beyond its value in training, digital planning enhances precision, minimizes complications, and improves overall predictability, even in the hands of experienced clinicians [17,18,19]. This study evaluated the accuracy of implant placement across three different training and research models: porous polyethylene (MedPor), photopolymer resin (SprintRay), and photopolymer resin (MAZIC® D MODEL). Deviations were assessed at multiple sites and in multiple directions, with particular focus on apical positioning, which is critical for implant stability, esthetics, and long-term success. The superior performance of photopolymer resin (MAZIC® D MODEL) at the lateral apical site supports earlier findings that fully guided models enhance control of apical positioning [20].

Although both MAZIC® D MODEL and SprintRay resins are photopolymer materials, they exhibit measurable differences in mechanical and physical properties that may influence guide stability and implant accuracy. For example, the MAZIC® D MODEL has a flexural strength ≥ 80 MPa, a flexural modulus ≥ 1,700 MPa, and a shore hardness D80–90 with low shrinkage. In contrast, the SprintRay Die & Model 2 resin has a flexural strength of ~91.5 MPa and a flexural modulus of ~2,650 MPa. Differences in stiffness, strength, hardness, and dimensional stability may contribute to minor variations in how each resin responds under drill torque and guides seating, thereby affecting implant deviation outcomes.

Previous studies have reported that guided systems reduce both apical and angular deviations compared with semiguided or freehand models [21,22,23]. The present results align with these observations, particularly in the lateral incisor region, which is often considered clinically demanding because of limited bone availability and restricted visibility. In contrast, the lack of significant differences in labial, mesial, distal, and angular deviations is consistent with recent meta-analyses, which suggest that while guided models improve reproducibility, the clinical impact of such improvements may be limited [22,24]. The relatively small sample size of this study likely contributed to the absence of statistical significance in several comparisons. From a cost perspective, the differences among the models were substantial. Porous polyethylene (MedPor) was the most expensive and nearly ten times more expensive than the photopolymer resins (SprintRay and MAZIC® D MODEL) model. Despite this high cost, MedPor produced the largest apical deviations, indicating reduced accuracy. Conversely, the more economical 3D-printed and CAD/CAM-milled models not only offered significant cost savings but also demonstrated superior or comparable precision. This combination of affordability and accuracy underscores their clear advantages for both research applications and clinical training, where cost-effectiveness and reliability are equally important.

Conclusion

This study demonstrated that the choice of model material significantly affects the accuracy of digitally guided implant placement. Photopolymer resin (MAZIC® D MODEL) offered the best apical control at lateral incisor sites, whereas porous polyethylene (MedPor) produced the greatest deviations despite be-

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ing the costliest. The photopolymer resin (SprintRay) resulted in slightly greater deviations at premolars but performed comparably overall. Importantly, although both SprintRay and MAZIC® D MODEL are photopolymer-based, differences in their mechanical and physical properties may partly explain the variation in performance. Taken together, resin-based models such as SprintRay and MAZIC® D MODEL represent practical, cost-effective options for both research and training, balancing affordability with reliable accuracy.

Conflict of Interest

There is no conflict of interest to declare.

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