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ISNI: 0000 0004 8495 2390

Dolna 17, Warsaw,
Poland 00-773
+48 226 0 227 03
editorial_office@rsglobal.pl

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# ACCURACY OF 3D-PRINTED SURGICAL GUIDES IN DENTAL IMPLANTOLOGY: A NARRATIVE REVIEW OF STATIC, DYNAMIC, AND ROBOTIC TECHNIQUES

***Paweł Buć*** *(Corresponding Author, Email: pawelbuc19@gmail.com)*
*Pomeranian Medical University, Szczecin, Poland*
*ORCID ID: 0009-0001-1533-6610*

***Jagoda Józefczyk***
*Pomeranian Medical University, Szczecin, Poland*
*ORCID ID: 0009-0007-5235-2074*

***Karolina Buć***
*Pomeranian Medical University, Szczecin, Poland*
*ORCID ID: 0009-0000-8491-7200*

***Łukasz Krzystek***
*Pomeranian Medical University, Szczecin, Poland*
*ORCID ID: 0009-0001-1988-0402*

***Konrad Zieliński***
*Pomeranian Medical University, Szczecin, Poland*
*ORCID ID: 0009-0005-3652-592X*

***Karolina Ganczar***
*University Teaching Hospital named after F. Chopin, Rzeszów, Poland*
*ORCID ID: 0009-0003-8152-8076*

***Michał Mazurek***
*University Teaching Hospital named after F. Chopin, Rzeszów, Poland*
*ORCID ID: 0009-0005-7111-2397*

***Marianna Rudzińska***
*Pomeranian Medical University, Szczecin, Poland*
*ORCID ID: 0009-0002-9622-7439*

***Mikołaj Zalewski***
*Pomeranian Medical University, Szczecin, Poland*
*ORCID ID: 0009-0002-7803-6145*

***Stanisław Jurkowski***
*Pomeranian Medical University, Szczecin, Poland*
*ORCID ID: 0009-0005-9715-8385*

**ABSTRACT**

**Background:** Digital technologies and 3D printing have transformed implant dentistry, enabling improved precision in implant placement through static and dynamic computer-assisted approaches. Ensuring accurate implant positioning is essential for long-term success, particularly in anatomically demanding or esthetic regions.
**Objective:** To evaluate the accuracy of 3D-printed surgical guides and compare their performance with dynamic navigation, robotic systems, and freehand implant placement techniques.
**Materials and Methods:** A structured narrative review was conducted using the PubMed database (up to November 2025). A total of 44 records were identified, of which 19 studies met the inclusion criteria. These comprised randomized clinical trials, prospective and retrospective studies, in vitro investigations, and systematic or narrative reviews. Data extraction focused on linear and angular deviations, clinical outcomes, guide design, printing technology, and planning protocols.
**Results:** Across included studies, 3D-printed guides consistently demonstrated high accuracy, with mean platform deviations of approximately 0.2–1 mm, apical deviations of 0.5–1.6 mm, and angular deviations of 1–3°. Clinical findings mirrored in vitro results. Dynamic navigation achieved comparable accuracy, while robotic systems showed even lower angular deviations (<1.6°). Guide stability, printing technology, and imaging protocol significantly influenced outcomes.
**Conclusion:** 3D-printed surgical guides provide predictable, clinically acceptable precision and enhance the safety and efficiency of implant placement. Dynamic and robotic systems offer promising complementary technologies. Further long-term clinical trials are needed to establish their definitive clinical impact.

**KEYWORDS**

Dental Implants, Implant Surgery, 3D-Printed Surgical Guides, Computer-Guided Surgery, Accuracy, Clinical Outcomes

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## 1. Introduction

Implant dentistry has undergone dynamic development in recent years, largely due to the introduction of digital technologies and 3D printing. Accurate implant positioning is critical for long-term success, whereas traditional freehand methods remain susceptible to errors in angulation, depth, and drilling trajectory. In response to these limitations, computer-assisted implant surgery has become increasingly widespread—both in its static form, involving the use of 3D-printed surgical guides, and in its dynamic form, supported by real-time navigation systems.

Numerous studies have confirmed the high precision of guided techniques. Herstell et al. demonstrated that 3D-printed guides provide consistent and reproducible accuracy, while Fang and colleagues emphasized the clinical importance of this precision particularly in the anterior region (4,5). Clinical investigations conducted by Chrabieh et al., as well as the randomized controlled trial by Nomiyama and co-workers, showed that guided implant placement results in significantly lower deviations compared with conventional surgery, often improving patient comfort as well (8,13). At the same time, the accuracy of the procedure is significantly influenced by the 3D-printing technology used and the structural design of the surgical templates (9,14,16).

Dynamic and robotic navigation techniques represent an alternative to static guides. As demonstrated by Pellegrino et al., Mai and colleagues, and Neugarten, these technologies can achieve precision comparable to or even exceeding that of static guidance, paving the way for further digitalization of implant procedures (2,3,10).

Despite the extensive body of literature, understanding the technological and procedural factors that determine the effectiveness of guided implant surgery remains essential. The aim of this study is to present the current state of knowledge regarding the accuracy of implant placement using 3D-printed surgical guides and to discuss key determinants influencing the success of digitally guided implant procedures.

## 2. Material and Methods

### 2.1 Search strategy

This review was conducted in accordance with the principles of a structured narrative review. A comprehensive literature search was performed in the PubMed database up to November 2025. The following search strategy was applied:

("Dental implants"[Title/Abstract] OR "Implant surgery"[Title/Abstract])
AND ("3D-printed surgical guides"[Title/Abstract] OR "Computer-guided surgery"[Title/Abstract])
AND ("Accuracy"[Title/Abstract] OR "Clinical outcomes"[Title/Abstract])

The search yielded a total of 44 records. Additionally, reference lists of the included articles were screened to identify potentially relevant studies that may not have been captured during the initial search.

After removing duplicates and conducting a preliminary screening of titles and abstracts, full-text articles meeting the predefined inclusion criteria were assessed. Ultimately, 19 studies were included in this review, comprising clinical trials, in vitro studies, and review articles.

### 2.2 Eligibility criteria

Inclusion criteria

Articles were included if they met the following criteria:

**Population**

- Adult patients with partial or complete edentulism undergoing or scheduled for dental implant placement;
- In vitro models (jaw models, phantoms) used to assess the accuracy of surgical guides or navigated systems.

**Intervention**

- Static computer-assisted implant surgery using surgical guides, particularly those manufactured using 3D printing technologies;
- Dynamic computer-assisted navigation or robotic systems used in implantology (included as reference technologies in the discussion of guided surgery accuracy).

**Comparison (when applicable)**

- Freehand implant placement;
- Comparisons between different types of guides (e.g., fully guided vs. partially guided, various support types, different 3D printing technologies);
- Static versus dynamic navigation;
- Different imaging and planning protocols (e.g., DICOM–DICOM vs. DICOM–STL).

**Outcomes**

- Quantitative assessment of implant placement accuracy, including linear and angular deviations;
- Clinical outcomes such as implant survival, surgical complications, patient comfort, and procedural time (when reported).

**Study design**

- Randomized controlled trials (RCTs);
- Prospective and retrospective clinical studies;
- In vitro accuracy assessments;
- Systematic and narrative reviews addressing accuracy or navigation in implant dentistry.

**Language and availability**

- Articles published in English;
- Full text available.

Exclusion criteria

Studies meeting any of the following criteria were excluded:

- Animal studies;
- Case reports and small case series lacking quantitative accuracy assessment;
- Studies where dental implants were not the primary focus (e.g., other maxillofacial procedures without an implant component);
- Articles without numerical accuracy data or without clinical outcomes related to guided or navigated surgery;
- Letters to the editor, commentaries, and expert opinions without complete research methodology.

### 2.3 PICOS framework

The structure of this review was defined using the PICOS framework:

**P (Population)**

Adult patients with partial or complete edentulism undergoing implant treatment, as well as in vitro models used to evaluate the accuracy of guides or navigated systems.

**I (Intervention)**

Computer-assisted implant surgery using:

- Static surgical guides manufactured with 3D-printing technologies,
- Dynamic navigation systems,
- Robotic systems—evaluated for accuracy and potential clinical benefits.

**C (Comparison)**

- Freehand implant placement;
- Different types of guides (static vs. dynamic, support type, 3D-printing modality);
- Different planning protocols (DICOM–DICOM vs. DICOM–STL);
- Different implant locations (anterior vs. posterior, maxilla vs. mandible).

**O (Outcomes)**

Primary outcomes:

- Linear deviation at the implant platform (mm);
- Linear deviation at the implant apex (mm);
- Angular deviation between planned and actual implant axis (°).

Secondary outcomes (when reported):

- Implant survival rates;
- Marginal bone loss;
- Surgical and prosthetic complications;
- Procedure duration;
- Patient-reported and clinician-assessed comfort metrics.

**S (Study design)**

Randomized clinical trials, prospective and retrospective studies, in vitro research, systematic and narrative reviews.

### 2.4 Data extraction

Data extraction from each included article was performed using a structured template. To ensure reliability, extraction was conducted independently by two reviewers (PB, KB), with disagreements resolved through discussion.

The following data were collected:

- General study information: first author, year of publication, country;
- Study design (RCT, prospective, retrospective, in vitro, review);
- Population characteristics (number of patients/models, age, type of edentulism, implant location);
- Intervention details:
- type of guide (static, partially guided, stackable, in-office printed),
- guide support type (tooth-supported, mucosa-supported, bone-supported),
- 3D-printing technology and material used;
- Comparator (freehand, alternative guide type, static vs. dynamic/robotic surgery);
- Imaging and planning protocols (CT/CBCT, DICOM–DICOM, DICOM–STL);
- Accuracy assessment methodology (reference points, superimposition techniques, measurement software);
- Main outcomes: linear and angular deviations, reported clinical results, complications.

### 2.5 Outcome measures

The primary outcome of this review was the accuracy of implant positioning in computer-assisted surgery, defined as:

- Linear deviation (mm) at the implant platform;
- Linear deviation (mm) at the implant apex;
- Angular deviation (°) between the planned and actual implant axis.

Secondary outcomes included:

- Implant survival during follow-up;
- Surgical complications (e.g., cortical perforation, injury to adjacent structures);
- Prosthetic parameters (need for adjustment of prosthetic restoration, fit of immediate prostheses);
- Objective and subjective indicators of procedure duration and patient comfort, when reported.

### 2.6 Data synthesis

Due to the heterogeneity of the included studies—different guide systems, 3D-printing technologies, planning protocols, patient groups, and measurement methodologies—a statistical meta-analysis was not performed.

Instead, a narrative synthesis was conducted. Studies were grouped according to intervention type:

- Static guided surgery using 3D-printed templates,
- Dynamic navigation systems,
- Robotic implant-placement systems.

Within each category, the following aspects were compared:

- Ranges and mean values of linear and angular deviations;
- Key factors influencing accuracy (guide type, support type, implant location, printing technology, imaging protocol);
- Reported clinical outcomes.

Clinical findings were interpreted alongside evidence from in vitro studies and systematic or narrative reviews to provide a comprehensive overview of the impact of 3D-printed guides and computer-assisted technologies on the accuracy and predictability of implant placement.

## 3. Results

A total of 19 studies published between 2019 and 2025 were included in the analysis, comprising systematic reviews, clinical studies, randomized controlled trials, in vitro investigations, and research on dynamic and robotic implant surgery. Across the included literature, the findings consistently demonstrated high accuracy of implant placement performed with 3D-printed surgical guides.

In vitro studies reported mean implant deviations within ranges characteristic of precise static methods (4,11,14). Linear deviations at the implant platform typically ranged from 0.2 to 1 mm, whereas apical deviations ranged from 0.5 to 1.6 mm. Angular deviations most commonly fell within 1–3°, depending on guide support type, printing technology, and sleeve configuration used (4,11,14). Surgical templates manufactured from biopolymers using the FDM technique demonstrated an accuracy comparable to that of SLA-produced guides; however, further research on cytotoxicity is required to confirm their intraoral biocompatibility (14).

Clinical investigations revealed similarly favorable outcomes. In the prospective study by Chrabieh, the mean platform deviation was 0.71 mm, the apical deviation was 0.52 mm, and angular deviations ranged between 3.3° and 3.4° (8). Fang's work confirmed that even in the anterior region—an area of high esthetic sensitivity—guides maintained reliable precision, with deviations below 1.2 mm and approximately 2.5° (5).

Randomized clinical trials, including those by Nomiyama and Husain, demonstrated a significant advantage of guided surgery over freehand techniques (13,16). Additionally, guided procedures were associated with shorter operative times and improved patient comfort, while implant survival rates remained comparable between groups.

Studies evaluating dynamic navigation reported accuracy levels similar to or occasionally exceeding those of static guides, with platform deviations between 0.7 and 1.1 mm, apical deviations between 0.9 and 1.3 mm, and angular deviations ranging from 3.8° to 3.96° (2,3). Robotic systems, as examined in the study by Neugarten, achieved exceptionally high precision, with angular deviations of the drilling axis frequently remaining below 1.6° (10). This suggests that robotic assistance may represent a promising, highly stable future modality in implantology, surpassing the accuracy of many current static systems.

A substantial influence of imaging and planning protocols was also observed across studies. D'Addazio demonstrated that the DICOM–STL protocol provided more accurate anatomical representation compared with DICOM–DICOM, reducing deviations by approximately 0.4–1.2 mm. Although both protocols yielded clinically acceptable results, statistically significant differences were observed between maxillary and mandibular implant placement. Procedures performed in the mandible showed noticeably higher accuracy, attributable to superior guide stability on denser cortical bone (18).

Overall, the findings consistently indicate that 3D-printed surgical guides provide very high accuracy, typically maintaining deviations around 1 mm and 3–4°, values considered safe and clinically acceptable for most implant procedures.

The results of the study by Du further emphasized the capabilities of hybrid CAIS systems, demonstrating that this approach can achieve excellent accuracy despite the anatomical complexity of zygomatic implant placement. Angular deviation was 1.99 ± 0.17°, while mean coronal deviation measured 1.21 ± 0.45 mm. Apical deviation, reported as a median, was 1.67 mm (IQR: 1.11–1.93 mm). Importantly, no differences were observed based on ZAGA classification, implant length, or laterality. All implants remained stable over a mean follow-up period of 14.5 months, confirming the safety and predictability of the hybrid method. The combined static–dynamic system notably improved control over angulation and drilling trajectory, which is critical in cases of high anatomical complexity where standard static guides may be limited (19).

## 4. Discussion

The findings of the present review confirm that 3D-printed surgical guides significantly improve the accuracy of dental implant placement compared with freehand techniques (1, 4, 5, 8, 11, 13, 16). Evidence from clinical trials, in vitro studies, and review articles demonstrates that both linear and angular deviations achieved with guided surgery consistently fall within clinically acceptable limits, making this method one of the most predictable approaches in contemporary implantology (2, 3, 7, 12).

The study by Pieralli showed that the choice of 3D-printing technology substantially affects the stability and dimensional fidelity of surgical guides, which in turn influences implant placement accuracy (14). Similarly, the findings by Husain indicated that guides manufactured using 3D-printing technology provide greater precision and lower deviation values compared with thermoplastic templates (16).

Clinical studies such as the investigation conducted by Fang reaffirm the effectiveness of surgical guides, particularly in esthetically demanding regions, where even minimal deviation may compromise treatment outcomes (5). The ability to accurately predict implant trajectory is crucial for preserving thin cortical plates and achieving esthetic harmony, and 3D-printed guides play a key role in this process (5, 8). Importantly, these studies demonstrate that clinical accuracy aligns closely with in vitro results, highlighting the stability and reproducibility of digital guided workflows (4, 14, 11).

Comparisons between guided and freehand implantation consistently favor digitally assisted approaches. The randomized clinical trial by Nomiyama demonstrated significantly lower deviations in the guided group, accompanied by improved patient comfort and reduced operative time (13). These benefits are further supported by narrative reviews such as that by Naeini, which emphasizes that minimally invasive, guided surgery not only enhances accuracy but also reduces surgical trauma (7).

Another important aspect highlighted in the literature is the central role of digital planning. D'Addazio demonstrated that even subtle differences in data superimposition protocols (DICOM–DICOM vs. DICOM–STL) may significantly influence implant placement accuracy. This underscores the necessity of strict control over the entire digital workflow—from imaging and planning to guide fabrication—to ensure optimal surgical outcomes (18).

Further insights come from studies assessing dynamic navigation and robotic systems. Investigations by Pellegrino and Mai indicate that dynamic navigation can achieve very high accuracy, with the added advantage of real-time correction of drilling trajectory (2,3). Neugarten's study on robotic assistance demonstrated exceptionally low angular deviations, suggesting that robotic systems may offer superior control compared with many static systems (10). Although these technologies are more complex and costly, they represent an important direction in the digital evolution of implant dentistry. Complementary to this, the hybrid approach described by Du suggests that combining static and dynamic systems may enhance safety and precision in anatomically challenging scenarios, such as zygomatic implant placement (19).

Despite the advantages of 3D-printed guides and dynamic systems, the reviewed studies also reveal several limitations. The number and distribution of teeth supporting the guide significantly affect the stability and thus the accuracy of implantation, as noted by El Kholy and colleagues (17). Additionally, heterogeneity among study protocols—differences in measurement methods, guide design, printing technologies, and planning procedures—complicates the ability to fully standardize results (6, 12).

Overall, the evidence clearly demonstrates that 3D-printed surgical guides constitute a valuable tool in modern implant dentistry, substantially enhancing placement accuracy (1, 4, 5, 8, 11). At the same time, current data suggest that the technology will continue to evolve, with dynamic navigation and robotic systems likely to complement or, in some cases, surpass static guides in terms of precision (2, 3, 10).

## 5. Limitations

This review has several important limitations that should be considered when interpreting the findings. First, the included studies exhibited substantial methodological heterogeneity. This variability encompassed differences in guide design (fully guided, partially guided, stackable systems), manufacturing technologies (SLA, DLP, FDM), and materials used. Such discrepancies may have influenced the reported deviation values, complicating direct comparisons between studies.

A second limitation is the lack of standardization in accuracy assessment methods. The studies employed different data superimposition protocols (DICOM–DICOM, DICOM–STL, STL–STL), various reference points, and diverse software platforms for comparative analysis. These inconsistencies may introduce measurement errors and limit the comparability of results.

Another limitation is the predominance of in vitro studies over clinical investigations. Although laboratory studies offer high levels of control and allow precise evaluation of deviations, they do not fully replicate clinical conditions, particularly due to the absence of soft tissues, their compressibility, and the anatomical variability of patients.

Furthermore, the limited number of randomized clinical trials and the relatively short follow-up periods restrict the ability to assess long-term outcomes associated with the use of 3D-printed guides, such as implant survival, marginal bone loss, and prosthetic stability.

It should also be noted that this review relied primarily on a single database (PubMed), which may introduce publication bias and increase the likelihood of missing relevant studies indexed elsewhere. Although supplementary manual searching (snowballing) was performed, it remains possible that some important publications were not captured.

Finally, a statistical meta-analysis was not conducted due to the heterogeneity of the data. As a result, the conclusions are based on narrative synthesis, which may affect the overall strength of the evidence.

## 6. Conclusions

The analysis of the available literature indicates that 3D-printed surgical guides represent an effective and predictable tool for achieving precise dental implant placement. The integration of digital technologies allows for a substantial reduction in linear and angular deviations, thereby enhancing surgical safety and improving clinical outcomes, particularly in procedures that demand high accuracy, such as implant placement in the esthetic zone.

However, the precision of surgical guides is influenced by numerous technical factors, including the type of support, printing technology, material properties, and imaging protocol used. The reviewed studies emphasize the necessity of maintaining strict control throughout all stages of the workflow—from planning and digital design to guide fabrication and intraoral stabilization. Dynamic navigation and robotic systems have demonstrated comparable, and in some cases superior, accuracy, representing promising complementary modalities to static guidance.

Despite the growing body of evidence, further well-designed clinical studies with long-term follow-up are required to definitively assess the impact of 3D-printed guides on long-term treatment outcomes. Nevertheless, based on current data, the use of 3D-printed surgical guides in implant dentistry can be considered a safe, effective, and digitally aligned approach consistent with contemporary trends in dental technology.

**Disclosure**

Author's contributions

Conceptualization: Karolina Buć, Paweł Buć

Methodology: Łukasz Krzystek, Jagoda, Józefczyk

Software: Łukasz Krzystek, Konrad Zielinski

Check: Marianna Rudzińska, Mikołaj Zalewski

Formal Analysis: Michał Mazurek, Stanisław Jurkowski

Investigation: Jagoda Józefczyk, Karolina Ganczar, Paweł Buć

Resources: Łukasz Krzystek, Karolina Ganczar, Stanisław Jurkowski

Data curation: Michał Mazurek, Konrad Zieliński,

Writing - Original draft: Paweł Buć, Marianna Rudzińska

Writing - Review & editing: Karolina Buć, Mikołaj Zalewski

Visualization: Łukasz Krzystek, Jagoda Józefczyk

Supervision: Michał Mazurek, Mikołaj Zalewski

Project administration: Karolina Buć, Paweł Buć

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In preparing this work, the authors used ChatGPT for the purpose of improving language and readability. After using this tool, the authors have reviewed and edited the content as needed.

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