ISSN (O) : 2582-3271
PubMed-National Library of Medicine - ID: 101766917

International Journal of Dental Science and Clinical Research (IJDSCR)

Dr. Angel Vaidic Publication

Available Online at: http://www.ijdscr.org

Volume - 8, Issue – 4, July - 2026, Page No. : 57 – 67

CBCT-Guided Implant Surgery: Improving Placement Accuracy and Reducing Anatomical Complications

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Citation of this Article: Dr. Amaninder Singh, Dr. Armaan Goel, Dr. Akanksha Zutshi, Dr. Arshdeep Singh, Dr. Ajay Kumar, Dr. Arshiya Garg, "CBCT-Guided Implant Surgery: Improving Placement Accuracy and Reducing Anatomical Complications'' IJDSCR – July – 2026, Vol. – 8, Issue - 4, Page No. 57-67.

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Type of Publication: Original Research Article

Conflicts of Interest: Nil

ABSTRACT

Aim:

To evaluate the role of cone-beam computed tomography (CBCT)-based surgical guides in achieving accurate dental implant placement and preventing anatomical complications by enhancing three-dimensional treatment planning and guided implant surgery.

Materials and Methods:

This article presents three clinical cases of CBCT guided implant placement together with the narrative review of the literature regarding the accuracy of CBCT based surgical guides and prevention of anatomical complications . Relevant studies evaluating implant placement accuracy, deviation from planned implant position, surgical precision, and the incidence of anatomical complications were reviewed. Articles focusing on static CBCT-guided implant surgery, digital workflow, and comparison with conventional freehand implant placement were included. The findings were analyzed to determine the impact of CBCT-guided surgical templates on implant accuracy and patient safety.

Results:

Three patients underwent flapless implant placement using CBCT-based static surgical guides. In all cases,

the surgical guides demonstrated satisfactory adaptation and stability during the surgical procedure, allowing accurate transfer of the planned implant position. No intraoperative complications, including inferior alveolar nerve injury, maxillary sinus or nasal floor perforation, cortical plate perforation, or injury to adjacent structures, were encountered.

Postoperative CBCT evaluation demonstrated that the implants were positioned within the planned prosthetic envelope while maintaining adequate safety distances from the nearest anatomical landmarks. Measurements of the distance between the implant and the surrounding buccal and lingual cortical plates at the crestal level also confirmed favourable implant positioning with preservation of the cortical bone. Although minor differences between the planned position and the postoperative implant location were radiographically evident, the implants remained safely positioned without compromising adjacent anatomical structures.

Conclusion:

The present clinical observations further support previous evidence that CBCT-guided implant surgery is a predictable and safe technique for implant placement. Although measurable deviations between planned and placed implants remain unavoidable, these deviations generally remain within clinically acceptable limits when an appropriate digital workflow, accurate guide fabrication, adequate guide stabilization, and meticulous surgical execution are employed.

INTRODUCTION

Dental implant therapy has become a predictable and widely accepted treatment modality for the replacement of missing teeth, offering excellent functional and aesthetic outcomes. The long-term success of implant-supported restorations depends not only on osseointegration but also on the precise three-dimensional positioning of the implant. Accurate implant placement ensures optimal prosthetic rehabilitation, favourable biomechanical load distribution, maintenance of peri-implant tissues, and improved aesthetic results. Conversely, inaccurate implant positioning may lead to prosthetic complications, compromised aesthetics, difficulty in oral hygiene maintenance, implant failure, and injury to adjacent anatomical structures.

Successful implant planning requires a comprehensive evaluation of the available bone volume and quality, prosthetic requirements, and the location of vital anatomical landmarks. Conventional two-dimensional radiographic techniques, such as periapical and panoramic radiographs, provide limited information regarding the buccolingual dimensions of the alveolar ridge and may be associated with image distortion and magnification. These limitations can increase the risk of inaccurate implant placement and inadvertent damage to critical anatomical structures, including the inferior alveolar nerve, mental foramen, maxillary sinus, nasal cavity, and adjacent tooth roots.

The introduction of cone-beam computed tomography (CBCT) has revolutionized implant diagnosis and treatment planning by providing high-resolution three-dimensional images with relatively low radiation exposure compared with conventional computed tomography. CBCT enables accurate assessment of bone height, width, density, and morphology while allowing precise localization of vital anatomical structures. The Digital Imaging and Communications in Medicine (DICOM) data obtained from CBCT can be integrated with intraoral or laboratory scans to create a virtual three-dimensional model of the patient's dentition and supporting tissues, facilitating prosthetically driven implant planning.

Advances in digital dentistry have further enhanced implant accuracy through the development of CBCT-based surgical guides. These guides are designed using specialized implant planning software and manufactured using computer-aided design and computer-aided manufacturing (CAD/CAM) technologies or three-dimensional (3D) printing. Surgical guides transfer the virtual implant plan accurately to the clinical setting by controlling the position, angulation, and depth of implant osteotomy preparation. Depending on the clinical scenario, guides may be tooth-supported, mucosa-supported, or bone-supported, each offering specific advantages for partially or completely edentulous patients.

Numerous clinical studies have demonstrated that CBCT-based guided implant surgery significantly reduces deviations between planned and actual implant positions when compared with conventional freehand placement. Improved surgical precision minimizes the risk of injury to vital anatomical structures such as the inferior alveolar nerve, mental foramen, maxillary sinus, incisive canal, and adjacent teeth. In addition to enhanced safety, guided implant surgery contributes to minimally invasive flapless procedures, reduced surgical time, improved patient comfort, decreased postoperative morbidity, and greater predictability of restorative outcomes.

Despite these advantages, the accuracy of CBCT-based surgical guides depends on multiple factors, including image acquisition quality, digital planning accuracy, software integration, guide fabrication, proper seating and stabilization of the surgical guide, and the clinician's experience. Errors introduced at any stage of the digital workflow may compromise implant positioning and clinical outcomes. Therefore, understanding the indications, benefits, limitations, and potential sources of error associated with CBCT-guided implant surgery is essential for successful clinical implementation.

In view of the growing adoption of digital workflows in implant dentistry, this review aims to evaluate the role of CBCT-based surgical guides in achieving accurate implant placement and preventing anatomical complications. It also discusses the principles of digital implant planning, clinical applications, advantages, limitations, and current evidence supporting the use of CBCT-guided implant surgery in contemporary dental practice.

MATERIAL AND METHOD

Study Protocol

Patients requiring dental implant placement in edentulous sites were included in this prospective clinical study. Preoperative cone-beam computed tomography (CBCT) scans and Standard Tessellation Language (STL) files obtained from digital intraoral impressions were acquired. The Digital Imaging and Communications in Medicine (DICOM) data from the CBCT scans and the STL files were merged using 3Shape Implant Studio software (3Shape A/S, Copenhagen, Denmark) to facilitate prosthetically driven virtual implant planning and the design of a patient-specific CBCT-based surgical guide.

The surgical guide was fabricated using three-dimensional (3D) printing technology and used during implant placement to ensure accurate transfer of the virtual treatment plan to the clinical setting. Implant osteotomy preparation and implant placement were performed using the Zenex Implant System (IZEN Implant Co., Ltd., South Korea) together with its guided surgical kit, following the manufacturer's recommended drilling protocol.

Following implant placement, a postoperative CBCT scan was obtained to evaluate the final implant position. The distance between the implant and the nearest anatomical landmark (such as the inferior alveolar nerve, maxillary sinus, or nasal floor, depending on the implant site) was measured. In addition, the remaining buccal and lingual cortical bone thickness at the crestal level surrounding the implant was assessed on postoperative CBCT images to evaluate the accuracy of implant positioning and the preservation of surrounding anatomical structures.

SURGICAL PROCEDURE

The surgical procedure was performed under local anaesthesia using a flapless, static computer-guided implant placement protocol. In all three cases the patient was positioned, and the surgical guide was inserted and verified for accurate seating and stability before implant osteotomy preparation. No mucoperiosteal flap was elevated. A soft tissue punch was performed at the planned implant site when required, followed by sequential osteotomy preparation through the guide sleeves according to the manufacturer’s recommended drilling protocol under copious sterile saline irrigation.

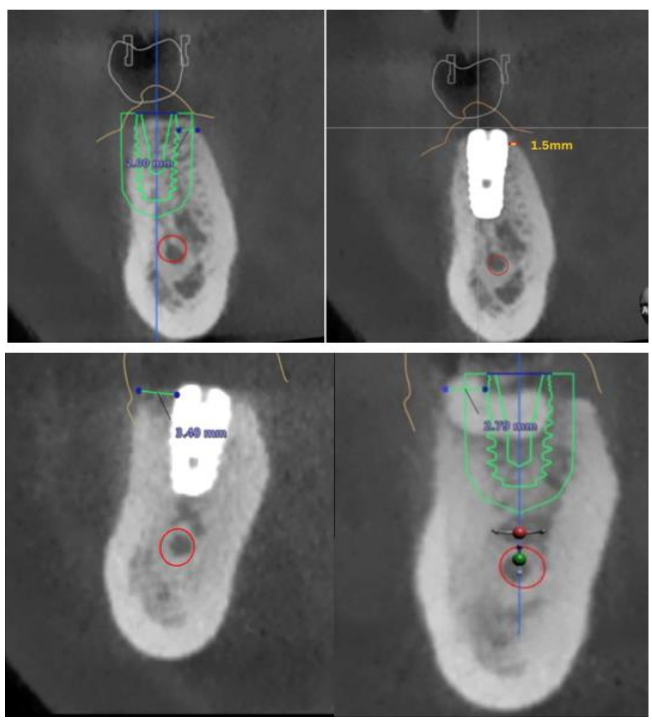
The implant was inserted through the surgical guide into the virtually planned position with the predetermined depth and angulation. After removal of the surgical guide, the implant position and primary stability were evaluated clinically. A healing abutment was placed when indicated. Intraoperative findings were recorded, with specific attention to anatomical complications, including maxillary sinus or nasal floor perforation, cortical bone plate fracture, and injury to adjacent neurovascular structures. Postoperative instructions and follow-up care were provided according to the clinical protocol.

Surgical Guide

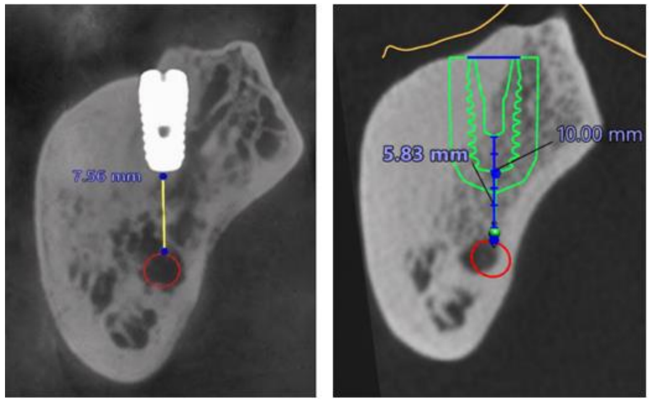
Implant Placement Using Surgical Guide

RESULTS

The patients undergoing flapless, static computer-guided implant placement were successfully treated according to the virtual treatment plan generated from the merged CBCT and STL datasets. The patient-specific 3D-printed surgical guide demonstrated adequate adaptation and stability during the surgical procedure, allowing near accurate transfer of the virtually planned implant position to the clinical setting.Implant placement was completed without elevation of a mucoperiosteal flap, and no intraope rative complications were observed. In particular, no cortical bone plate fracture, or injury to adjacent neurovascular structures occurred during the procedure. Primary implant stability was achieved, and the implant was positioned according to the planned prosthetically driven position.



Variation In the Planned Distance and Postoperative Outcome at Crest of Buccal and Lingual Cortical Plate



Variation At Apical Region in Relation to Inferior Alveolar Nerve

Postoperative CBCT evaluation and superimposition with the preoperative virtual planning dataset demonstrated a close correspondence between the planned and actual implant positions. The deviation between the virtual plan and postoperative implant position remained within the accuracy range commonly reported for static computer-guided implant surgery. Minimal linear discrepancies were observed at the crestal and apical levels, indicating precise transfer of the digital implant planning protocol to the surgical environment.

The findings of this case demonstrate that a CBCT-based, digitally planned, patient-specific surgical guide combined with a flapless approach can facilitate accurate and minimally invasive implant placement while reducing the risk of anatomical complications.

DISCUSSION

The present article combines clinical observation from three patients treated using CBCT guided static implant surgery with evidence from published literature. In all the patients, post operative CBCT evaluation demonstrated that the implants maintained adequate distances from adjacent vital anatomical structures and preserved the surrounding buccal and lingual cortical plates at the crestal region. Although slight positional differences from the preoperative virtual plan were radiographically evident, no anatomical complications were observed. These findings support previous reports of the CBCT guided implant surgery provides a predictable and safe method for implant placement, even though minor positional discrepancies may occur during the transfer of virtual plan to clinical setting.

The deviations observed in guided implant surgery are multifactorial and arise from cumulative errors occurring throughout the digital workflow.

Chrabieh et al. (2024) identified multiple reasons for deviation as follows:

CBCT-Related Factors

- Patient movement during scanning
- Metal artifacts
- Limited image resolution

Image Registration Errors

- Inaccurate merging of DICOM and STL datasets

- Registration inaccuracies between preoperative and postoperative images

Guide Fabrication Errors

- Deformation during stereolithographic printing
- Resin shrinkage or modification of the guide
- Incorrect sleeve positioning

Guide Stability

- Improper seating
- Tilting of the guide
- Inadequate fixation
- Bilateral free-end guides are more prone to movement

Mechanical Tolerance

- Clearance between drill and sleeve
- Clearance between implant carrier and sleeve
- Instrument play within the guiding system

Surgical Factors

- Limited mouth opening
- Drill deflection
- Operator experience and learning curve
- Incomplete guide seating during drilling

In the present clinical cases, postoperative assessment was performed using linear measurements rather than image superimposition. The distance between each implant and the nearest anatomical landmark, together with the remaining buccal and lingual cortical bone at the crestal level, was measured on postoperative CBCT images. These parameters confirmed that all implants were positioned within safe anatomical limits while preserving the surrounding cortical bone. Although this method does not directly quantify coronal, apical, or angular deviations, it provides clinically relevant information regarding implant safety and its relationship to adjacent anatomical structures.

The findings of the present cases are consistent with previous reports demonstrating that static computer-guided implant surgery provides predictable implant placement with clinically acceptable accuracy. Jung et al. (2009), in a systematic review and meta-analysis, concluded that although guided implant surgery significantly improves placement accuracy compared with conventional techniques, minor deviations between the planned and actual implant positions remain unavoidable because of cumulative errors during the digital workflow. Similarly, Van Assche et al. (2012) emphasized that inaccuracies may originate at multiple stages, including image acquisition, digital planning, guide fabrication, and surgical execution.

Among the various sources of error, mechanical factors related to the surgical guide play an important role in determining the final implant position. The inherent tolerance between the drill and guiding sleeve permits a small degree of lateral movement during osteotomy preparation, while inaccuracies associated with guide fabrication, polymer shrinkage, incomplete seating, or deformation may further influence implant positioning. Cassetta et al. (2013) demonstrated that sleeve height, sleeve diameter, and drill-sleeve tolerance significantly affect the accuracy of guided implant surgery. Likewise, Arisan et al. (2010) reported that discrepancies between the virtual treatment plan and the manufactured surgical guide may contribute to positional deviations, highlighting the importance of precise guide fabrication and verification before surgery.

Angular deviation represents one of the most clinically significant aspects of implant accuracy because even a small angular discrepancy at the crestal level may result in a considerably greater positional error at the implant apex. Widmann and Bale (2006) demonstrated that errors in image registration and guide positioning become amplified as the distance from the reference point increases, thereby influencing the final osteotomy trajectory.

In addition to guide-related factors, anatomical characteristics and surgical handling also contribute to deviations. Variations in cortical thickness, bone density, and local anatomical morphology influence drill behavior during osteotomy preparation. Dense cortical bone may deflect the drill because of increased resistance, whereas softer cancellous bone may permit greater lateral movement during drilling. Ozan et al. (2009) and Nickenig et al. (2010) similarly reported that the final implant position is influenced not only by the accuracy of digital planning but also by intraoperative surgical handling and clinical conditions. Scherer et al. (2015) further emphasized that bone quality and anatomical morphology should be considered when evaluating implant placement accuracy because they directly affect drilling dynamics and implant insertion.

The flapless surgical approach employed in the present cases offers several clinical advantages, including reduced postoperative pain and swelling, preservation of the peri-implant soft tissue architecture, decreased surgical morbidity, and faster patient recovery. However, because the alveolar ridge is not directly visualized, successful flapless implant placement depends heavily on accurate CBCT-based planning, appropriate case selection, and stable seating of the surgical guide. Campelo and Camara (2002) demonstrated favorable outcomes with flapless implant surgery in carefully selected cases, while Beretta et al. (2014) reported that accurate virtual planning combined with well-adapted surgical guides enables reliable implant placement using a flapless approach.

Although minor discrepancies between the planned and achieved implant positions were observed in the present cases, the implants remained within safe anatomical limits and no complications involving adjacent vital structures were encountered. Schneider et al. (2009) similarly reported that small coronal, apical, and angular deviations are inherent to static computer-guided implant surgery and should be considered clinically acceptable when adequate safety margins are maintained during virtual treatment planning.

Therefore, accurate CBCT acquisition, precise DICOM-STL registration, meticulous virtual planning, stable guide fixation, appropriate sleeve design, and careful surgical execution remain essential for minimizing positional deviations. The present clinical findings further support the use of CBCT-guided flapless implant surgery as a safe and predictable technique for implant placement, provided that the clinician understands the mechanical and anatomical factors responsible for deviations and incorporates appropriate safety margins during treatment planning.

Dynamic Navigation in Implant Surgery

In addition to static computer-guided implant surgery, dynamic navigation systems have emerged as an alternative computer-assisted approach that provides real-time guidance during implant placement. Unlike static surgical guides, dynamic navigation eliminates the need for a prefabricated template and allows continuous monitoring and correction of the drilling trajectory during osteotomy preparation. The system integrates CBCT-based virtual planning with optical tracking technology to display the real-time position, angulation, and depth of surgical instruments relative to the planned implant position. This flexibility may be advantageous in anatomically complex cases where intraoperative modifications are required.

However, the accuracy of dynamic navigation depends on several factors, including CBCT image quality, registration accuracy, stability of the reference marker, instrument calibration, and operator experience. **Widmann and Bale (2006)** emphasized that registration errors are among the most important contributors to inaccuracies in computer-assisted implant surgery. Similarly, **block et al. (2017)** reported that dynamic navigation provides clinically acceptable accuracy for implant placement, although minor deviations between the virtual plan and the final implant position are unavoidable due to technical and anatomical variables.

The angular discrepancies observed with dynamic navigation may result from mechanical and biological factors, including tracking errors, calibration inaccuracies, drill deflection, mechanical tolerance within the navigation system, bone density variations, and cortical resistance during osteotomy preparation. Compared with static guides, dynamic navigation provides greater intraoperative flexibility and allows real-time correction of deviations; however, it requires adequate operator training and precise workflow calibration. Both static and dynamic navigation techniques demonstrate high predictability when supported by accurate CBCT-based planning, although cumulative errors from digital data acquisition, registration, surgical execution, and anatomical variations may influence the final implant position.

Although dynamic navigation offers the advantage of real-time visualization and intraoperative modification of implant positioning, its clinical application is associated with several practical limitations. The system requires sophisticated tracking equipment, meticulous calibration, additional registration procedures, and a substantial learning curve for the operator. Furthermore, the high initial investment and maintenance costs may limit its routine use in many clinical settings. In contrast, CBCT-based static guided implant surgery provides a relatively simple, cost-effective, and highly predictable workflow. Once the surgical guide is fabricated from accurate CBCT data and prosthetically driven planning, implant placement can be performed with minimal dependence on intraoperative navigation, thereby reducing surgical complexity and chairside time. Consequently, static guided surgery remains the preferred approach in routine implant practice because it combines high accuracy, ease of use, reduced operative time, and lower overall treatment costs while maintaining excellent clinical outcomes.

CONCLUSION

Although minor deviations between the planned and the final implant position cannot be completely eliminated in CBCT-guided static implant surgery, these discrepancies are generally within clinically acceptable limits when appropriate planning and surgical protocols are followed. More importantly, the use of CBCT-based surgical guides enables prosthetically driven implant placement while maintaining a safe distance from critical anatomical structures. This significantly reduces the risk of buccal and lingual cortical plate breach**,** inferior alveolar nerve injury**,** and maxillary sinus membrane penetration, thereby enhancing surgical safety and minimizing postoperative complications. Therefore, despite the presence of small positional deviations, CBCT-guided static implant surgery remains a reliable and predictable technique for achieving accurate implant placement while preserving vital anatomical structures and improving overall treatment outcomes.

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