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Static computer-guided dental implant surgery: accuracy, clinical outcomes and digital workflows in contemporary practice: a narrative literature review

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Abstract

This narrative review analyzes current evidence regarding static computer-guided implant surgery in comparison with traditional freehand placement, with consideration of dynamic navigation and robotic assistance as emerging alternatives. Multiple studies consistently demonstrate that static guides significantly decrease coronal, apical, and angular deviations relative to freehand techniques, often reducing linear error by approximately half and achieving mean deviations near or below 1 mm. The accuracy levels are generally comparable to those attained with dynamic navigation and early robotic systems, with all computer-assisted approaches clearly outperforming freehand methods. Despite these improvements in precision, long-term implant survival rates and peri-implant bone level changes remain similar between guided and freehand protocols in most reports. This suggests that once a fundamental accuracy threshold is achieved, biological and prosthetic factors predominantly influence long-term outcomes. Static guidance exhibits particular strength when integrated within a comprehensive digital workflow that links cone-beam imaging, virtual planning, intraoral scanning or photogrammetry, and CAD/CAM prosthetics. Such integration facilitates flapless or minimally invasive surgical procedures, promotes smoother early recovery, and ensures predictable same-day or next-day immediate loading in full-arch rehabilitations. Patients report comparable long-term satisfaction levels between guided and freehand surgeries, whereas clinicians value increased confidence, standardization, and risk mitigation—especially in anatomically complex or prosthetically demanding cases—though these benefits are balanced by additional costs, complexity, and potential over-reliance. Overall, static computer-guided implant surgery is best regarded as a valuable adjunct that enhances safety and predictability in selected applications, rather than as a universal replacement for meticulously executed freehand techniques.

Keywords: Dental Implants; Computer-Assisted Surgery; Image-Guided Surgery; Cone-Beam Computed Tomography; Robotics.

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Introduction

Dental implants represent a well-established method for the replacement of missing teeth, with long-term success being closely associated with precise three-dimensional positioning. The location and angulation of the implant directly influence prosthetic fit, functionality, and aesthetics [1]. Historically, implant placement was carried out freehand utilizing two-dimensional imaging and, occasionally, traditional surgical stents. These techniques often necessitate flap elevation and are highly dependent on the surgeon's expertise, which may introduce variability in implant positioning, particularly in cases involving resorbed ridges or proximity to vital anatomical structures [2-3]. Even when executed by experienced clinicians, freehand placement may result in deviations that compromise the prosthetic ideal positioning or elevate the risk of encroachment upon the mandibular canal or sinus floor [2].

Computer-assisted implantology (CAI) was developed to address these limitations by enhancing the precision and safety of implant surgery. Early work with stereolithographic surgical templates demonstrated the feasibility of flapless, prosthetically driven implant placement and immediate loading in edentulous patients [4-5]. In static computer-guided surgery, implant positions are virtually planned on three-dimensional imaging, usually cone-beam computed tomography (CBCT), and transferred to the patient through a prefabricated guide that constrains drill angulation, depth, and position [6-7-8]. This approach often enables flapless or minimally invasive surgery with reduced operative trauma and facilitates pre-fabrication of provisional restorations for immediate loading in full-arch cases [9-10-11-12].

Concurrently, the advent of "guide-free" digital techniques, such as dynamic navigation and robotic assistance, has become increasingly apparent. Dynamic systems employ optical or electromagnetic tracking to deliver real-time guidance and have demonstrated accuracy comparable to static guides in numerous studies [13-14]. Robotic implant surgery utilizes a robot-controlled handpiece to execute the digitally planned trajectory with a high degree of precision. Nevertheless, both modalities require substantial financial investment, involve intricate workflows, and are less widely adopted [15-16-17]. In this context, static computer-guided implant surgery presently constitutes the most established CAI modality in routine clinical practice.

This narrative review synthesizes contemporary evidence on static guided implant surgery in comparison with traditional freehand placement, with a particular emphasis on its accuracy, clinical performance, integration within digital workflows, and implications for both patients and clinicians.

Implant placement modalities and accuracy metrics

Dental implants can be installed either freehand or with computer-assisted guidance. In freehand implant placement, the osteotomy and implant insertion are conducted without a guiding device; the precision largely depends on the clinician's experience and intraoperative visualization [18]. Computer-aided implant placement (CAIP) employs digital imaging and planning to facilitate or govern the drill trajectory [19]. Static CAIP utilizes a prefabricated surgical guide that fits over teeth, mucosa, or bone and may be secured with fixation pins in edentulous arches [6-20]. Fully guided protocols employ the guide throughout all drilling steps and implant placement, whereas partially guided techniques (pilot-drill or drill-guided) only restrict part of the procedure and subsequently revert to freehand placement [18-19]. Conventional analogue templates, based on diagnostic wax-ups, are occasionally categorized under partial guidance but do not incorporate a digital planning component [21].

The Dynamic CAIP discontinues the utilization of a physical template, instead employing optical or electromagnetic tracking systems to correlate the handpiece with the patient's three-dimensional imaging in real time [13-22]. The surgeon performs procedures along a virtual pathway displayed on a monitor, thereby enabling intraoperative adjustments while preserving the benefits of computer guidance. Meta-analyses consistently demonstrate that fully guided static and dynamic systems achieve higher precision relative to freehand techniques, with partially guided protocols offering intermediate levels of accuracy [14-18-19-23]. Guided workflows further facilitate flapless surgical procedures, which are associated with reduced postoperative pain and swelling in appropriate cases [9-10-24]. Nevertheless, freehand surgery remains prevalent in routine practice due to its cost-effectiveness, flexibility, and familiarity among many clinicians [19-25].

Robotic computer-aided implant surgery (r-CAIS) represents an emerging modality wherein a semi-active or task-autonomous robotic arm directs the drill in accordance with the digital plan. This methodology seeks to combine the stability characteristic of static guides with the real-time flexibility provided by navigation technologies [15-26]. Preliminary data, primarily derived from in vitro or phantom studies, suggest that robotic systems can achieve accuracy comparable to, or surpassing, that of static and dynamic computer-aided implant placement (CAIP). Nonetheless, their application remains limited due to substantial costs and a lack of comprehensive clinical evidence [27-28].

Accuracy in implant placement is typically assessed by quantifying the discrepancy between the preoperative plan and the actual implant positions observed on postoperative CBCT or surface scans. Global deviation refers to the three-dimensional

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linear distance between the designated and the actual implant locations, generally reported at both the entry point and the apex [23-24]. Vertical (depth) deviation concerns the occluso-apical difference in implant level, while horizontal deviations pertain to mesio-distal and bucco-lingual offsets. Angular deviation, measured in degrees, indicates the divergence between the planned and actual implant axes, with particular importance attributed to minor angular errors that can induce significant apical offsets, especially in the case of longer implants [21-29]. These metrics underpin comparative analyses of freehand, static, dynamic, and robotic techniques within the literature. A query of the Scopus database covering dental literature from 2001 to 2025 (refer to Figure 1) identified 636 publications related to guided implant surgery, with annual publication output increasing from only a few papers in the early 2000s to over 80 annually by 2025.

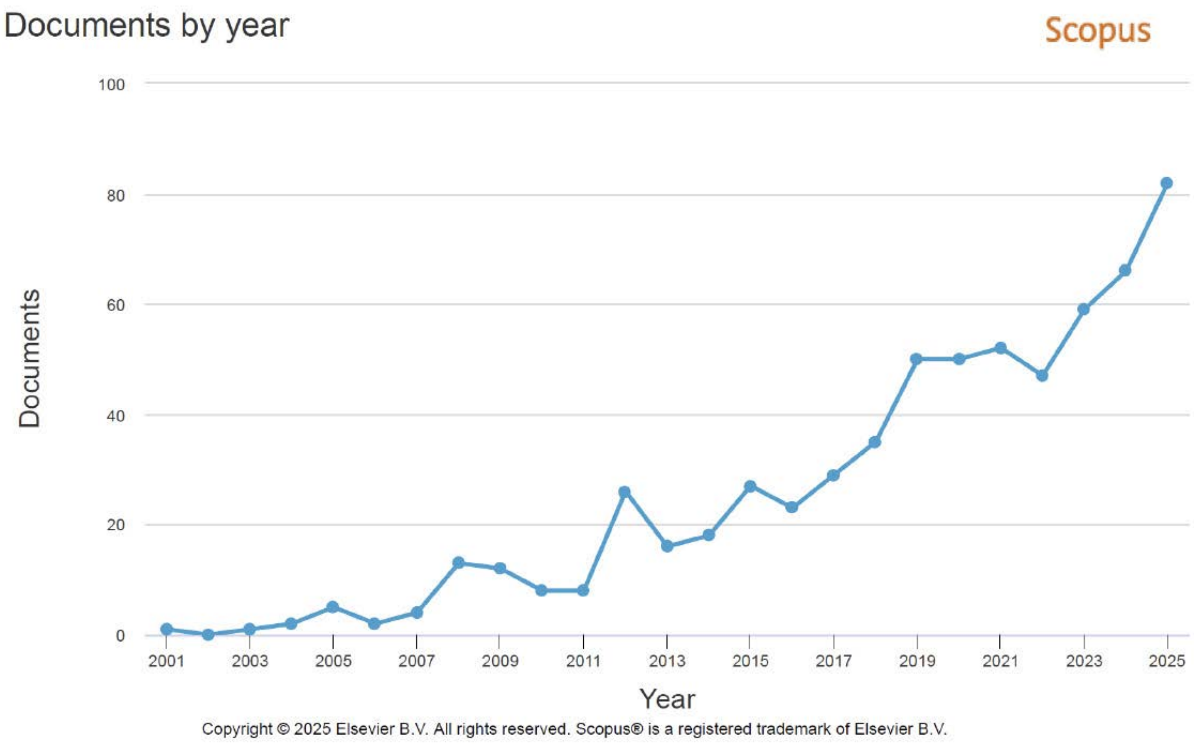

Figure 1. depicts the annual volume of scholarly publications concerning guided implant surgery indexed in Scopus from 2001 to 2025. A Scopus analytics query executed on 12 September 2025 (search string: TITLE-ABS-KEY(guided-implant*) AND LIMIT-TO(SUBJAREA, “DENT”)) identified a total of 636 documents related to guided implant surgery. The graph illustrates a significant increase in scholarly output, evolving from a limited number of publications per year in the early 2000s to approximately 50 publications annually by 2019-2021, and surpassing 80 publications in 2025.

Accuracy of implant placement

One of the most evident advantages of static computer-guided surgery in comparison to freehand techniques is the enhanced transfer of the virtual plan to the patient. Numerous scientific studies indicate that static guides considerably diminish coronal, apical, and angular deviations when contrasted with traditional freehand placement [6-30-31]. Generally, fully guided protocols attain average linear errors of approximately or below 1 mm and angular deviations of about 2-4°, whereas freehand placement under comparable conditions more frequently exhibits discrepancies of 1.5-2 mm in linear measurement and angular errors ranging from 5-10° [1]. Randomized and controlled clinical trials involving partially edentulous patients affirm this trend: fully guided protocols consistently outperform pilot-drill-only or drill-guided workflows and manual procedures, delivering smaller deviations at the entry and apex levels, as well as more consistent angulation [2-32]. A recent meta-analysis similarly concluded that fully guided surgery results in markedly lower coronal, apical, and angular deviations compared to pilot-only guided approaches, underscoring that constraining all drilling steps confers the greatest benefit in accuracy [33].

Current evidence further indicates that static guides and dynamic navigation systems exhibit comparable performance in terms of accuracy, and both clearly surpass freehand placement. Meta-analytical comparisons report mean entry-point deviations of approximately 0.7 mm for static guidance, around 1.0 mm for dynamic navigation, and about 1.5 mm for freehand surgery [34]. Other reviews describe minor trade-offs between static and dynamic modalities—such as slightly improved angular precision with dynamic systems and marginally enhanced depth control with static guides—though these differences

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are negligible and seldom hold clinical significance [14-35]. Importantly, even advanced guided surgical techniques do not entirely eliminate errors. Residual deviations originate from CBCT resolution limitations, guide-design and manufacturing tolerances, and minor intraoperative movements [36]. Early benchmarking studies commonly reported mean deviations close to 1 mm and 3°, whereas more recent high-precision studies in ideal, tooth-supported cases have reduced these figures to approximately 0.5 mm and 2°. Nonetheless, a safety margin of roughly 2 mm from vital structures such as the inferior alveolar nerve or sinus floor remains advisable, even when employing a guide [37]. Overall, static guidance diminishes linear errors by approximately 50-70% compared with freehand drilling, significantly enhancing the predictability of implant positioning and providing the groundwork for prosthetically driven, minimally invasive workflows.

Clinical outcomes and complications

Despite the clear improvements in accuracy associated with static guidance, most comparative studies demonstrate that the principal clinical outcomes are comparable to those achieved through meticulously performed freehand surgical procedures. Both methods have shown high implant survival rates in patients with partial or complete edentulism, with no conclusive evidence indicating the superiority of guided surgery in routine cases [25-38]. The limited number of meta-analyses that have performed direct comparisons generally conclude that, provided implants are strategically positioned within a prosthetically acceptable envelope and sufficient alveolar bone tissue is accessible, the survival rate is primarily influenced by biological and prosthetic factors rather than the use of a guiding system.

Peri-implant marginal bone level fluctuations are largely comparable across different protocols. Multiple cohort and randomized studies demonstrate that the average bone loss within one year remains below 1 mm for both guided and freehand procedures, with no statistically or clinically significant differences observed between the groups [9-10-18]. Variations in bone remodelling are more strongly correlated with factors such as the implant-abutment connection, loading protocol, soft tissue thickness, and patient-related factors including smoking and periodontal health, rather than the utilization of a static guide [12-38].

Concerning early failures and surgical complications, static guides may offer a modest safety advantage in anatomically challenging situations by mitigating the risk of severe malposition or encroachment on critical structures. Nonetheless, extensive clinical series generally report low and comparable rates of early failure, neurosensory disturbances, sinus perforation, or hemorrhagic events associated with both guided and freehand surgical techniques [25-30-31]. The majority of complications within guided workflows are procedural or technical, including diminished access in posterior regions, guide fracture, restricted irrigation which may lead to overheating, or the necessity to forego the guide when it does not fit adequately.

Digital workflow innovations and immediate loading

Beyond accuracy, a significant advantage of static guided implantology lies in its integration within a comprehensive digital workflow. Guided surgery correlates CBCT-based planning with digital impression methods and CAD/CAM prosthetic fabrication. Contemporary high-precision intraoral scanners and implant photogrammetry enable clinicians to record implant positions immediately following guided placement with exceptional accuracy, thereby obviating the necessity for traditional open-tray impressions in numerous full-arch cases [39]. Once implants are positioned utilizing a static guide, the coordinates can be swiftly captured and subsequently utilized to design or finalize an interim fixed prosthesis.

The integration of precise static guidance with immediate digital capture underpins the feasibility of predictable same-day or next-day immediate loading procedures. In full-arch protocols, the provisional bridge may be milled or 3D-printed in advance based on the virtual plan, requiring only minor adjustments upon delivery due to the close correspondence between implant positions and the planned trajectories [12-30-31]. This approach contrasts with freehand workflows, where positional discrepancies could necessitate extensive chairside modifications or even remaking the provisional. Such “backward planning,’ which begins with the desired prosthetic outcome and subsequently plans the surgical procedure accordingly, exemplifies the shift toward continuous digital workflows in implant dentistry [7].

Static guided surgery has also catalyzed other digital innovations. Digital smile design and facial scanners can be incorporated during planning so that implant position reflects facial aesthetics and lip dynamics, not only intraoral anatomy [15]. Virtual articulators and jaw-motion simulations allow occlusal considerations to be integrated into the plan from the outset. While dynamic navigation and robotic systems can also be integrated with digital planning, static guides currently offer the most straightforward transition from virtual design to prefabricated prostheses, particularly in All-on-4-type immediate full-arch cases, where high one-year survival rates (>95%) and reliable prosthesis fit have been documented [40-12]. Overall, the integration of static guides with digital prosthetic workflows reduces laboratory and chairside time, enhances predictability, and enables many patients to depart from surgery with fixed teeth in place.

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Patient outcomes and clinician perceptions

From the patient's perspective, static guided and freehand implant surgery generally yield similarly high satisfaction once healing is complete. Studies comparing patient-reported outcome measures such as pain, swelling, oral health-related quality of life, and perceived improvement usually find no significant long-term differences between techniques, provided the implants integrate and the prosthetic result meets expectations [40]. In other words, patients tend to judge success by function and aesthetics rather than by how the implants were placed.

The primary advantages of static guidance for patients are observed during the early postoperative period. Guided workflows often facilitate flapless or minimally invasive surgical procedures, which have been correlated with reduced operative times, diminished postoperative pain and swelling, and decreased analgesic consumption in the initial days, when compared to open-flap freehand techniques [11-30-31]. Several studies also indicate milder effects on heart rate, blood pressure, and anxiety, particularly when the surgical procedure is shorter and less invasive [11]. However, these benefits tend to diminish after the initial healing phase; within a few weeks post-surgery, patient-reported outcomes generally align between guided and freehand protocols [40].

For clinicians, static guided implant surgery presents evident advantages in planning and implementation. Numerous practitioners observe that guides enhance confidence, especially in complex anatomical cases characterized by limited bone availability, proximity to vital structures, or challenging angulations required for immediate full-arch restorations [6-41]. Furthermore, guides assist less experienced implantologists in achieving more consistent outcomes, thereby reducing the performance gap between novices and seasoned professionals. Surveys reveal that users value the capacity to visualize and rehearse cases digitally, subsequently reproducing the plan with high fidelity during procedures [17-25].

Conversely, clinicians acknowledge certain limitations that hinder widespread implementation. Static guidance entails additional expenses related to imaging, software, and guide fabrication, while also introducing supplementary procedural steps that may extend the overall treatment duration if workflows are not optimized [11-25]. Access may be limited in posterior regions; irrigation could be hindered if sleeves and drills are excessively bulky; and mechanical complications or poor fit occasionally necessitate the abandonment of the guide during surgery [6-41]. Furthermore, there are concerns pertaining to human factors: some experienced surgeons maintain that freehand placement continues to be more efficient in straightforward cases, and educators have cautioned that excessive dependence on guides may diminish fundamental surgical skills if residents are not concurrently trained to execute procedures safely without them [37].

Dynamic navigation and robotic implant surgery

While this review predominantly emphasizes static guided surgery, it is crucial to acknowledge the significant role of dynamic navigation and robotic assistance as essential contextual elements in computer-assisted implant placement. Dynamic navigation (dynamic CAIS) utilizes optical or electromagnetic tracking technologies to correlate the drill and handpiece with the patient's anatomy in real time, thereby eliminating the necessity for a physical guide stent [13-22]. The surgeon observes a virtual drill path on a monitor, while the system continuously updates the instrument's position. These dynamic systems negate the need for guide fabrication and allow for intraoperative modifications to the treatment plan. Comparative analyses typically demonstrate that the accuracy of dynamic systems is comparable to that of fully guided static surgery, with both modalities clearly outperforming freehand placement [14-34]. Some studies suggest marginally lower angular deviations when employing dynamic systems; however, such differences are minor and do not appear to impact short-term implant success [14-35]. Limitations inherent to dynamic navigation include the costs associated with tracking hardware and software, the necessity for precise calibration and registration, and a learning curve related to coordinating manual hand movements with visual feedback. Furthermore, dynamic navigation lacks the mechanical stability provided by a guide tube, rendering the accuracy ultimately dependent on the operator's manual control [16-17-27].

Robotic computer-assisted implant surgery (r-CAIS) represents the latest advancement in guided workflow technology. Within these systems, a robotic arm either constrains or executes osteotomy and implant placement in accordance with the virtual plan, aiming to integrate the stability of static guides with the flexibility of dynamic navigation [15-26]. Bench and phantom investigations report mean deviations of less than one millimeter and less than one degree, with some meta-analyses indicating that robot-assisted placement may attain the lowest error among CAIS modalities [16-28]. Nonetheless, in clinical practice, robotic implantology remains in its nascent stages. Adoption has been limited to a few centers, primarily due to substantial capital investment, extended setup and calibration durations, and the necessity for specialized training and technical support [26-27]. Moreover, comprehensive long-term clinical data are limited, and it is still uncertain whether the incremental improvements in accuracy justify the additional complexity in routine practice.

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Discussion

The evidence reviewed indicates that static computer-guided implant surgery offers distinct procedural advantages over freehand techniques, particularly in terms of placement accuracy and early postoperative experience. Static guides effectively transfer the digital plan to the operative field, with mean deviations frequently below 1 mm, whereas freehand placement demonstrates greater variability [1-33]. This level of precision holds clinical significance, especially when operating near vital structures, in narrow ridges, or when precise angulation is necessary for immediate full-arch loading. Guided workflows also support minimally invasive, flapless surgical procedures, which can diminish early pain and swelling by preserving soft tissue and blood supply [30-31]. The capacity to pre-plan implants and prostheses further streamlines immediate temporization and enhances the predictability of complex surgeries, thereby reducing stress for clinicians [12-25].

Simultaneously, a central paradox arises: these evident process improvements have not consistently resulted in superior long-term clinical outcomes. When appropriately planned and executed, both guided and freehand approaches demonstrate high implant survival rates and healthy peri-implant tissues over a period of 1-5 years [40-36]. Once a fundamental accuracy threshold is achieved—placing the implant within available bone, avoiding critical structures, and ensuring a prosthetically acceptable position—additional refinements of a few tenths of a millimeter appear not to significantly enhance osseointegration or bone stability. Biological responses are predominantly influenced by implant design, loading conditions, and patient factors rather than submillimetric positional differences. In skilled hands, freehand surgery supported by meticulous planning can thus be considered.

This matter holds significant implications concerning cost-benefit considerations. Guided surgery incurs additional expenses related to imaging, software, and guide fabrication, as well as supplementary planning procedures, thereby necessitating justification based on clinical necessity. For straightforward single implants placed in ample bone, the incremental advantage of employing a fully guided protocol may be marginal, rendering freehand surgery often more expeditious and cost-effective. Conversely, static guidance demonstrates distinct value in high-risk or technically complex cases, such as atrophic posterior mandibles in proximity to the inferior alveolar nerve or full-arch immediate loading where the precise alignment of multiple implants is imperative. In such scenarios, the guide serves as a risk mitigation instrument that can avert serious malposition and costly complications. Nonetheless, a guide can only carry out the digital plan; meticulous planning and the willingness to deviate from the guide when fit or primary stability are suboptimal remain fundamental clinical obligations.

From the patient's perspective, the long-term functional and aesthetic outcomes of guided and freehand approaches appear comparable. Patients predominantly observe that the implant feels natural and the restoration functions effectively, independent of the implant placement method [19-42]. The primary advantages of static guidance for patients are transient: reduced invasiveness of surgery, accelerated early recovery, and, in certain cases, the opportunity to leave with immediate fixed teeth [12-30-31]. These initial benefits tend to diminish as healing progresses, and by several weeks postoperatively, most studies report convergence in comfort and function between guided and freehand groups [40]. In essence, guided surgery can enhance the overall experience; however, both techniques can ultimately achieve the same goal of a well-integrated implant and a satisfied patient.

The broader technological landscape is also evolving in the manner in which static guidance is positioned. Boundaries between static and dynamic systems are becoming increasingly indistinct, as emerging solutions incorporate augmented reality, trace-based registration, and more efficient 3D printing workflows that diminish costs and chairside time. Artificial intelligence is beginning to support treatment planning by suggesting implant positions or identifying potential collisions, which may standardize and expedite the planning process [43]. As intraoral scanners, CBCT, and in-house CAD/CAM systems become routine components of dental practices, the additional step of printing a guide is more easily integrated and potentially more cost-effective, given that much of the digital infrastructure is already established.

Several limitations of this review and of the underlying literature must be acknowledged. This was a narrative rather than systematic review, with a focused search strategy and no formal meta-analysis or risk-of-bias assessment. The conclusions are therefore qualitative and may be influenced by study selection. Follow-up in most guided versus freehand comparisons is relatively short, often 1 year and only occasionally 3-5 years, so long-term differences in prosthetic maintenance or bone stability beyond a decade cannot be ruled out. In addition, many data originate from academic or specialist centres, where operator experience and case selection may not fully reflect general practice. Longer follow-up, broader practice settings, and standardised outcome reporting are needed to clarify whether specific patient groups or clinical scenarios derive distinct long-term advantages from static guidance.

Research on static computer-guided implant surgery must now expand its scope beyond short-term accuracy and survival rates to include long-term outcomes, pragmatic clinical application settings, and patient-centered results. Large multicenter trials and meticulously designed prospective cohort studies are crucial for comparing guided and freehand procedures

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across diverse levels of operator experience, with standardized reporting of complications, prosthetic maintenance, and quality of life over periods of at least 5 to 10 years [23-19]. Particular emphasis should be placed on high-risk indications such as severely resorbed jaws, full-arch immediate loading, and anatomically critical regions, where static guidance is most likely to provide clinically significant advantages [6-33]. Moreover, there exists a notable deficiency in health-economic evaluations; future studies should aim to quantify the comprehensive cost-benefit ratio of static guidance by incorporating equipment costs, software expenses, guide fabrication, chairside time, complication management, and prosthetic remakes into formal cost-effectiveness analyses. Concurrently, research should explore how emerging technologies—including hybrid static-dynamic workflows, augmented reality, artificial intelligence-assisted planning, and robotic assistance—can be seamlessly integrated into straightforward, reproducible protocols, rather than introducing unnecessary complexity with marginal benefits. Lastly, educational research is essential to delineate optimal training strategies for new implantologists, ensuring they can effectively utilize guided workflows without compromising their ability to perform safe and precise freehand surgeries when guides are unavailable or must be discarded intraoperatively.

Conclusion

Static computer-guided implant surgery has evolved into a dependable and widely accessible form of computer-assisted implantology that significantly enhances the planning and placement of implants. It consistently improves positional accuracy, supports flapless and minimally invasive techniques, and seamlessly integrates with digital workflows that facilitate predictable immediate loading in intricate rehabilitations. When cases are meticulously planned and executed, long-term survival rates and peri-implant bone stability are broadly comparable to those achieved through carefully performed freehand surgery. Therefore, the primary benefit of static guidance lies in making favorable outcomes more predictable and less operator-dependent, rather than in elevating an already high standard of success. Its application is most appropriate in anatomically challenging or prosthetically complex scenarios where precision and risk mitigation are essential, while maintaining freehand skills as a fundamental component of safe implant procedures.

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