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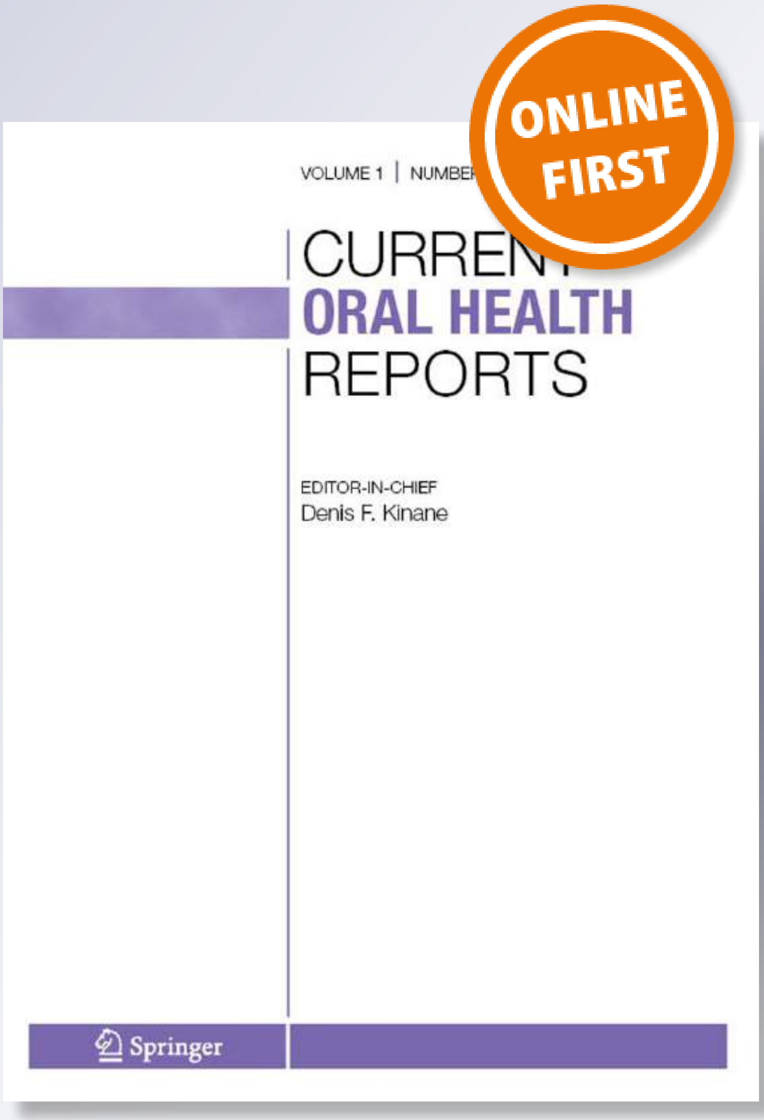

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Current Workflows for Computer-Aided Implant Surgery: a Review Article

Mariam Margvelashvili-Malament[1] **· Andre' Barbisan De-Souza**[1] **· Wael Att**[1]

Abstract

Purpose of Review Implant dentistry is a fast-evolving field and the computer-aided implant placement is becoming an inseparable part of it. There is a vast variety of techniques, workflows, and software making it hard for the dental practitioner to know which technique to apply to which clinical scenario. Therefore, the purpose of this review is to classify and describe current techniques and compare advantages and disadvantages of different methods. Workflows for various clinical scenarios are also presented to guide a clinician in decision-making.

Recent Findings Static computer-aided implant surgery offers safe and prosthetically driven implant placement and gives the possibility for flapless surgery to reduce postoperative healing time and the number of appointments. However, appropriate training is mandatory even if fully computer-aided implant placement is being done.

Summary Based on current trends, it is obvious that further digitization and automatization are inevitable for the academic and the private dental environments. However, one should realize that major safety screenings are yet to be conducted for newly introduced methods.

Keywords Implant dentistry · Guided surgery · Computer-aided implant placement · Static guidance · Dynamic guidance · Workflow for computer-aided implant surgery

Introduction

Since the introduction of implant supported restorations in the mid-1960s, it has become the standard of care for treating partial and complete edentulism. However, it took around 40 years until Verstreken et al. highlighted the difficulty and importance of converting information from two-dimensional (2D) slices to three-dimensional (3D) tangible structures during surgery. The article discussed 3D implant planning and how to transfer the planned data to the surgical field [1]. The development of the cone beam computed tomography (CBCT) helped popularize implant planning and computer-aided surgery, offering improved 3D visualization at reduced radiation dosage [2].

Computer-aided implant surgery has gained popularity since then and may offer advantages such as reduced time of surgery, reduced postoperative healing and discomfort (in the event of flapless technique), anatomically safer placement, and predictable prosthodontic outcomes. Additionally, it was hypothesized that computer-aided implant surgery provides an opportunity to less experienced practitioners (general practitioners and newly graduated specialists) to place implants predictably and safely [3].

Initially, radiographic imaging was done with radiopaque guides to obtain information regarding the future restoration (e.g., incisal edge position, cervical margin) in relation to the existing alveolar bone. These imaging guides were then converted into surgical guides to help visualize future restoration in relation to implant positioning during surgery. Currently, with the advancements in digital dentistry, Computer-Aided Design (CAD) software are incorporated with a CBCT scan produced Digital Imaging and Communications in Medicine

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(DICOM) data. This can be fused with optical scan Standard Tessellation Language (STL) files allowing 3D planning in both virtual and 3D bony environment. This approach relates the virtual data to the surgical field using fully guided procedure and has been categorized as "Static" method [4].

Another method for transferring 3D data to surgical field is the "Dynamic" navigation [4], which uses visual imaging tools on the monitor. A surgical template is not needed, instead osteotomy and implant placement are tracked on the screen in real time. The DICOM data is integrated into the navigation software to plan 3D implant position. The surgeon then uses the monitor to guide the implant placement with minimal direct visualization of the handpiece in the patient's mouth [5, 6, 7•]. Apart from the human-controlled dynamic guidance, a relatively new system is the robot-assisted implant surgery incorporating haptic guidance with dynamic computer-assisted implant surgery. It physically guides and controls the surgeon's hand to replicate planned implant angulation and positioning. Robot-guided implant placement has the capability to track patient motion and adjust the parameters in real time (real-time patient tracking). A surgeon can visually confirm the implant position on the monitor.

The flow chart of the classification of computer-aided implant surgery is presented in Fig. 1.

The body of evidence available in the literature is still related to the use of static computer-aided implant surgery, which has been applied by clinicians globally. Therefore, this article focused on most widely spread method of static computer-aided implant surgery and described workflows for various clinical scenarios, current trends, and limitations and future directions. It also summarized workflows for dynamic computer-aided and robot-assisted implant surgeries to discuss advantages and limitations of the methods. This review used electronic literature search of PubMed database to obtain recent and the most relevant scientific information from previous systematic reviews and clinical trials.

Surgical Guides for Static Computer-Aided Implant Placement

The static computer-aided implant placement was defined as "the use of a static surgical template that reproduces virtual implant position directly from computerized tomographic data and does not allow intraoperative modification of implant position" [8]. Static computer-aided implant placement has an advantage to allow multiple clinicians to work and plan together at their own time of availability.

Static guides are produced in the lab on the cast or through CAD/CAM via additive (i.e., printing) or subtractive (i.e., milling) methods. The variety of the static guides exists. While some guides allow guided osteotomy followed by free-hand implant placement, others offer guided osteotomy as well as implant placement, described as fully guided surgery [9]. The fully guided surgery could use several guides with sequence of increasing drill diameter or a single guide with adjustable drill handles and appropriate sleeve diameter [8].

The surgical guides may also be different in terms of the support and can be classified as follows [9]:

- Tooth supported, when a guide is supported solely by the remaining teeth in partially edentulous cases.
- Mucosa supported, when a guide is positioned on the mucosa in fully edentulous cases.
- Tooth and mucosa supported, when a guide is positioned on remaining teeth and mucosa. The combination of support is used when remaining teeth do not provide enough stability to the guide. Mostly primary stress bearing areas

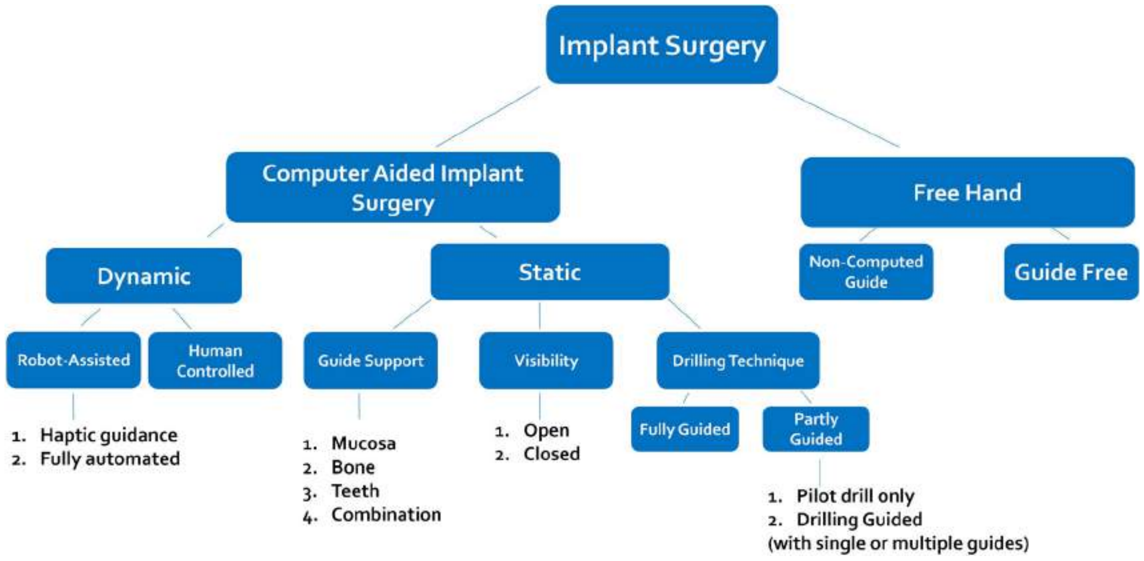

Fig. 1 Classification of computer-aided implant surgery

like retromolar pads, maxillary tuberosities, and horizontal palate are chosen to minimize tissue resilience.

- Mucosa supported with anchor (trans-mucosal) pins, when a guide is positioned on mucosa, but additional anchor pins are used to stabilize its position.
- Bone supported, when mucoperiostal flap is open and a guide is placed on the bone in patients with more extensive osteoplasties.
- Mini-implant supported, when a guide is placed on the mini-implants installed in the bone prior or during the surgery.

Depending on the clinical scenario, the workflow for virtual implant treatment planning and fabrication of static computer-aided implant guides may differ. The workflows and predictability for partial or complete edentulism present significant differences; therefore, they are discussed separately below.

Partial Edentulism (Single and Multiple Missing Teeth)—Static Computer-Aided Implant Placement

In order to implement guided implant surgery, a thorough examination and diagnosis is required like in any dental intervention. Regardless of which workflow is implemented, data fusion of the tomographic image (i.e., DICOM file) with optical scan of virtual cast (i.e., STL file) is needed.

There are several ways for obtaining patient's digital cast. It can be done through conventional impressions, fabrication of casts, and desktop scanning, or fully digitally using Intraoral Scanners (IOS). The next step is to visualize the future restoration. This can be achieved digitally using CAD software and a virtual set-up, or via digital impression of the patient with provisional restorations. Finally, an alternative method is conventional lab-based set-up and its further scanning with desktop scanner [10]. The workflow for partial edentulism is summarized in Fig. 2.

The bone 3D imaging is obtained through CBCT with or without an imaging guide, depending on the selected protocol of data acquisition. Data fusion of a CBCT and optical scans is then followed to facilitate virtual planning for ideal 3D implant positioning and fabrication of a surgical guide.

Surgical guides for single missing tooth and most of multiple missing teeth are tooth supported. However, teeth- and mucosa-supported guides can be fabricated in some distal extension cases. Figure 3 shows clinical case of mandibular distal extension edentulous space. The guide was extended up to the retromolar pad to provide distal support and stability.

Clinical examples of implants placed in single and multiple missing edentulous spaces using non-computed and static computer-aided implant placement are presented as Figs. 3, 4, 5, and 6.

Complete Edentulism—Static Computer-Aided Implant Placement

Computer-aided implant placement for completely edentulous patients rely on the same basic principles of completing comprehensive examination and obtaining 3D data of bone and prosthesis.

The data acquisition can be accomplished through conventional or digital methods or by the combination of the two. First step in the digital workflow is to obtain optical data of edentulous jaws. It can be done by making conventional impressions, fabricating casts, and scanning via desktop scanners, or fully digitally using IOS. Next step is to visualize

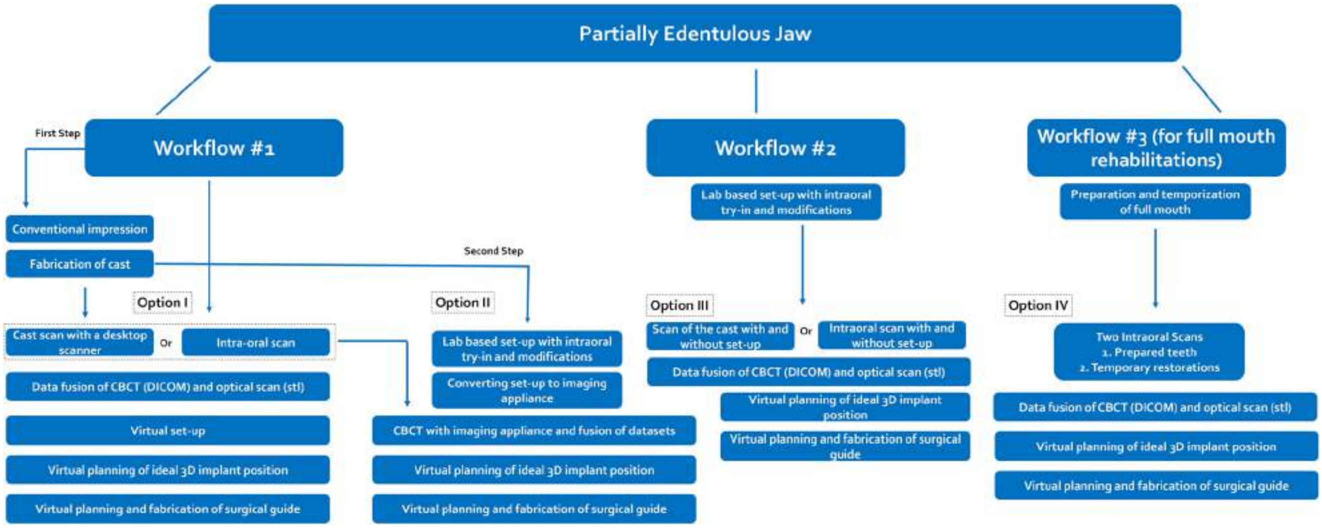

Fig. 2 Workflow for static computer-aided implant placement in partial edentulism cases

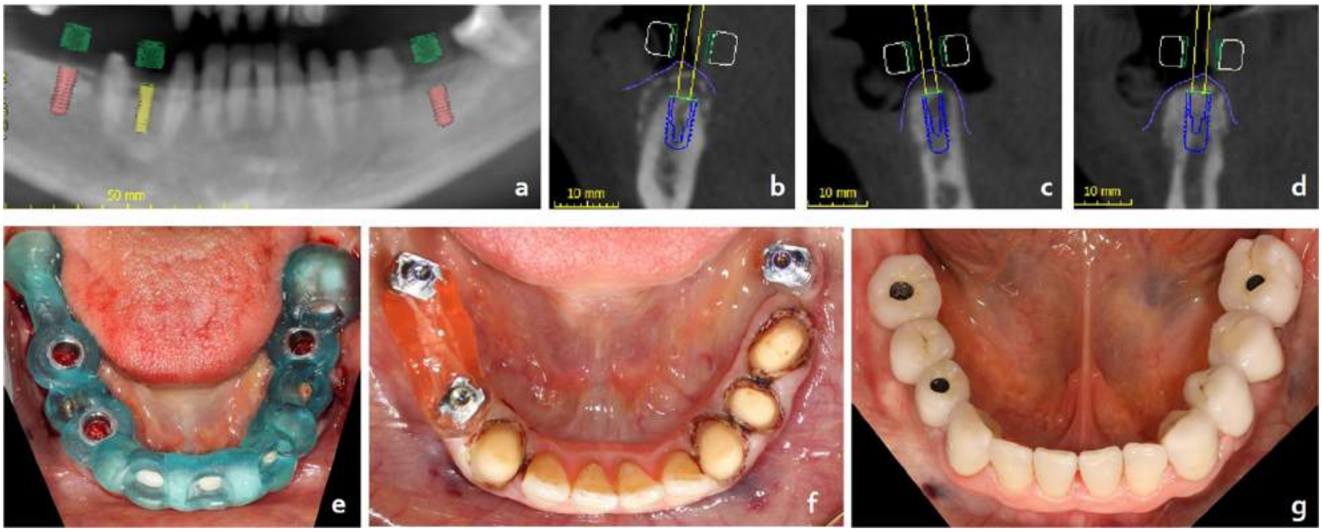

Fig. 3 Static computer-aided implant placement in multiple missing edentulous spaces. **a** Panoramic view of 3D planned implant position. **b** Cross-sectional view of planned implant position of implant #19*. **c** Cross-sectional view of planned implant position of implant #28. **d** Cross-sectional view of planned implant position of implant #30. **e** Surgical guide supported by teeth and the retromolar pad. **f** Impression posts in place ready for conventional final impression. **g** Final restorations in place showing ideal implant positioning. *Universal Numbering System

the future restoration. This can be achieved by duplicating existing conventional dentures or a lab-based teeth set-up. In the event of lab-based teeth set-up, intraoral confirmation and appropriate adjustments are required based on classic denture prosthodontic principles. The similar density of resin-based denture and the surrounding soft tissues make it impossible to differentiate these two during segmentation [3]. For this reason, an imaging appliance is fabricated based on the denture replica or teeth set-up using a radio-opaque material. The CBCT is taken with the imaging appliance. Ideal implant positioning, based on bone volume and future prosthesis, is then planned to produce the surgical guide.

Alternative option is to apply radio-opaque markers to the existing prosthesis eliminating the step of duplication. A

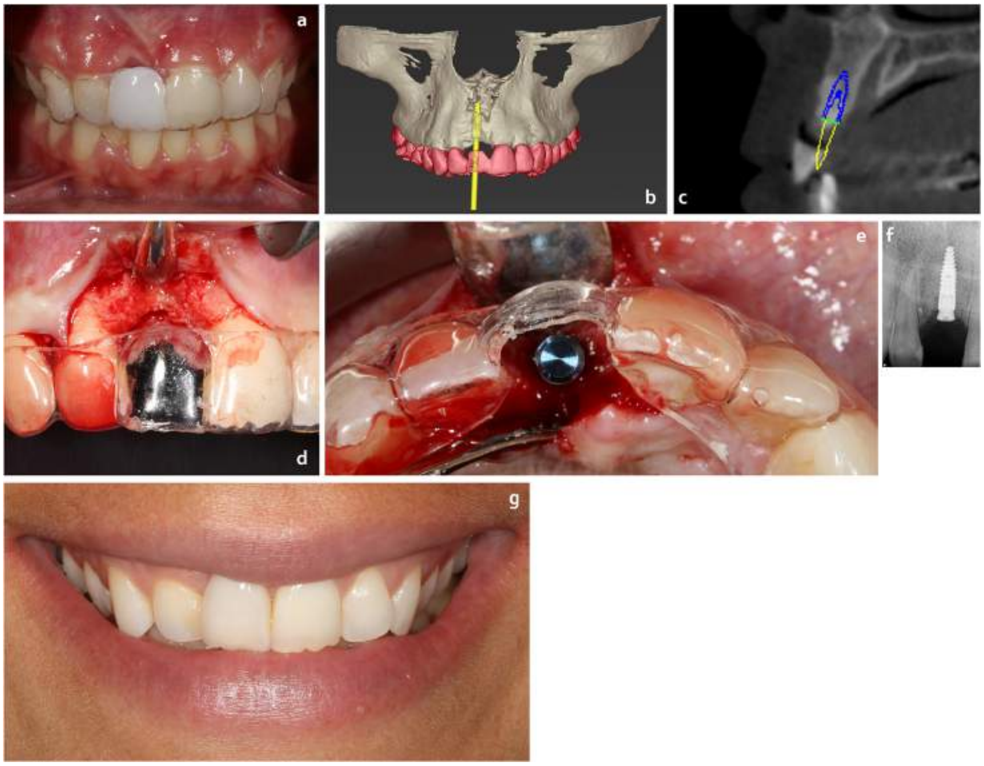

Fig. 4 Implant placement in anterior maxilla using non-computed guide. **a** Radio-opaque guide in place. **b** Ideal 3D implant positioning using radio-opaque guide as reference. **c** Cross-sectional view of planned implant position of implant #8. **d** Frontal view of the non-computed guide in place during the implant placement. **e** Occlusal view of the non-computed guide and implant. **f** Peri-apical radiograph of implant placed. **g** Implant restored with screw-retained crown

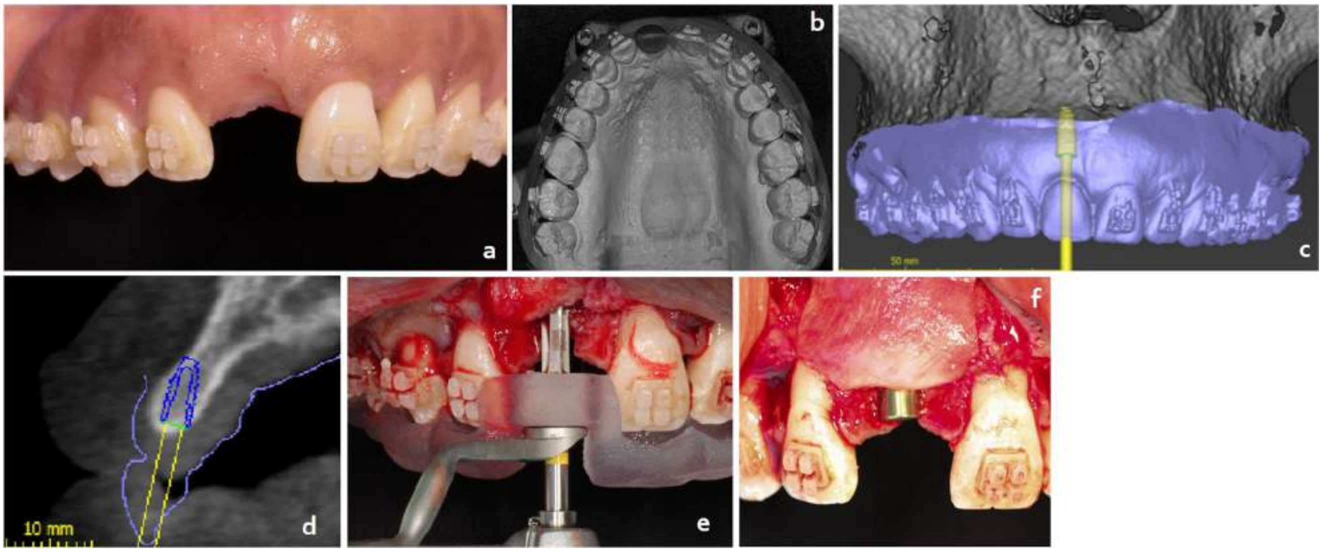

Fig. 5 Static computer-aided implant placement in anterior maxilla. **a** Preoperative view of missing #8. **b** STL file of the stone cast and conventional wax-up. **c** 3D implant positioning in the planning software using data fusion of STL and DICOM files. **d** Cross-sectional view of planned implant position of implant #8. **e** Implant placement using tooth-supported static guide. **f** Implant placed and the bone grafting material

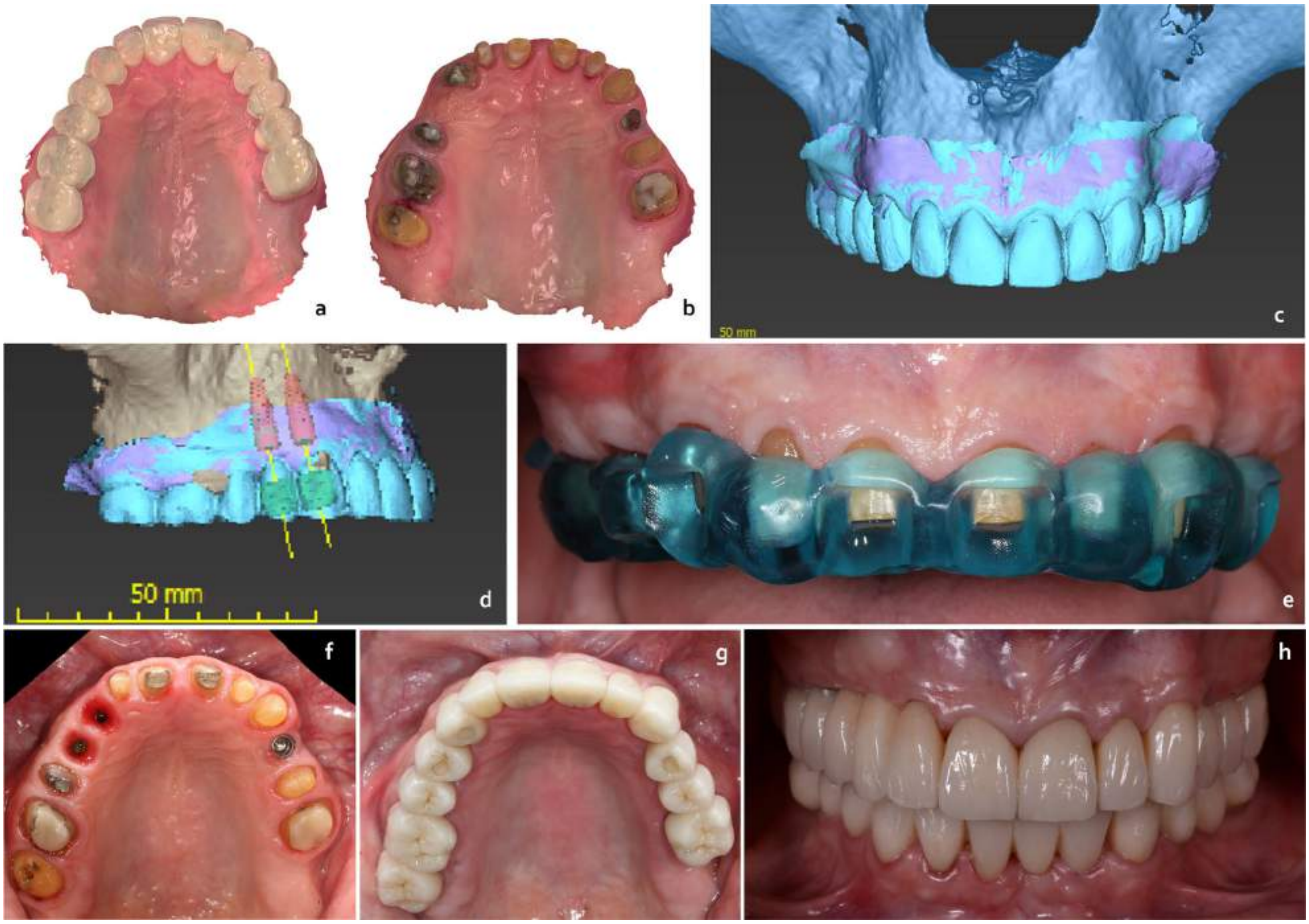

Fig. 6 Static computer-aided implant placement in multiple missing edentulous spaces. **a** STL file of scanned maxillary full-arch provisional restorations. **b** STL file of scanned maxillary prepared teeth. **c** Data fusion of 2 STL and DICOM files. **d** Ideal 3D implant positioning. **e** Tooth-supported guide in place. **f** Occlusal view of maxilla after the implant placement. **g** Occlusal view of full-arch restorations, implants are in ideal position. **h** Frontal view of final restorations

CBCT is taken with an existing denture followed by the second scan of the denture only, with altered exposure parameters. The markers are seen in both scans that allows accurate superimposition of two scans for further implant planning and design of the guide. This was described as the dual-scan technique. The duplication of preexisting denture often requires an intraoral reline of the duplicate to ensure adequate fit.

When a mucosa supported imaging appliance (duplicate or denture with markers) is used, it includes information of teeth set-up as well as the tissue surface. Thus, it is crucial to verify proper adaptation of the template. When implementing implant planning, the space between the denture and soft tissues indicates inadequate fit of the denture that will introduce errors and inaccuracies [11]. The workflow for complete edentulism is summarized in Fig. 7.

Support for surgical guides of completely edentulous jaws can be mucosa, bone, mucosa with anchor pins, and mini-implants. Bone-supported guides showed highest inaccuracy and are only used in major surgeries [7•].

Clinical cases of implants placed in completely edentulous jaws using computer-aided implant placement is presented in Figs. 8 and 9.

Dynamic Computer-Aided Implant Placement Workflow

After thorough examination and diagnosis, a CBCT is taken with the clip containing fiducial markers. A clip is typically positioned on the side of the arch that will not undergo surgery. Ideal 3D implant position is virtually planned. On the day of implant placement, an array is attached to the clip with fiducial markers. The array of the clip, which is like the array on the handpiece is registered to the navigation system. The surgeon should ensure direct alignment of the patient and the arrays with the overhead cameras. The surgeon then uses monitor to guide the implant placement. The assistant is strictly focused on the irrigation and suctioning. The implant placement can be fully or partially guided [5].

The workflow is summarized in Fig. 10.

Robot-Assisted (Haptic Guidance) Implant Placement Workflow

Yomi is the first robotic dental surgery system to receive FDA approval in 2017; it is a system that provides planning software and dynamic guidance. Yomi planning software accepts DICOM and STL files. After thorough examination and diagnosis, an intraoral splint is positioned on the contralateral side of the arch. Fiducial array is magnetically attached to the intraoral splint. CBCT is then taken with the intraoral splint and fiducial array. The DICOM file is integrated into the Yomi software to plan ideal 3D implant positioning. During the surgery, the patient tracking arm is connecting to the intraoral splint to monitor patient's movement in real time. Haptic guidance is achieved via the robotic arm that stabilizes handpiece. The robotic arm permits the motion so that the surgeon could move the handpiece towards the drilling site. It only allows motion within the planned position (location, angulation, and depth) of the implant. The arm gets locked if there is deviation from the planned location thus preventing inaccuracy in

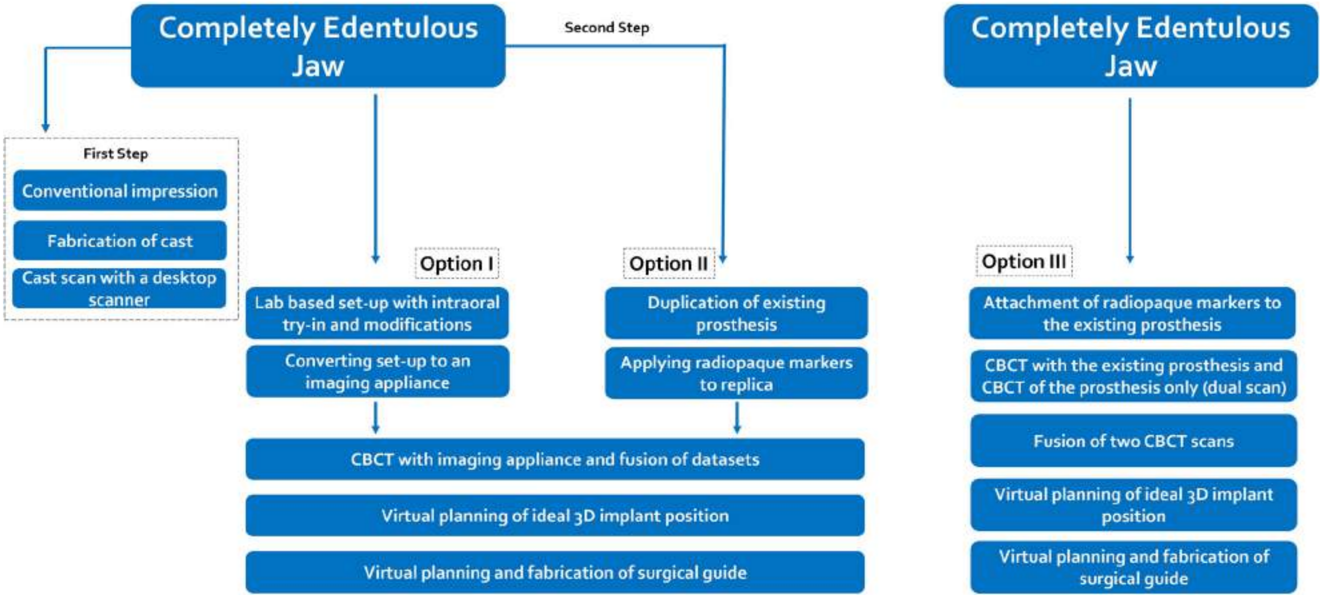

Fig. 7 Workflow for static computer-aided implant placement in completely edentulous cases

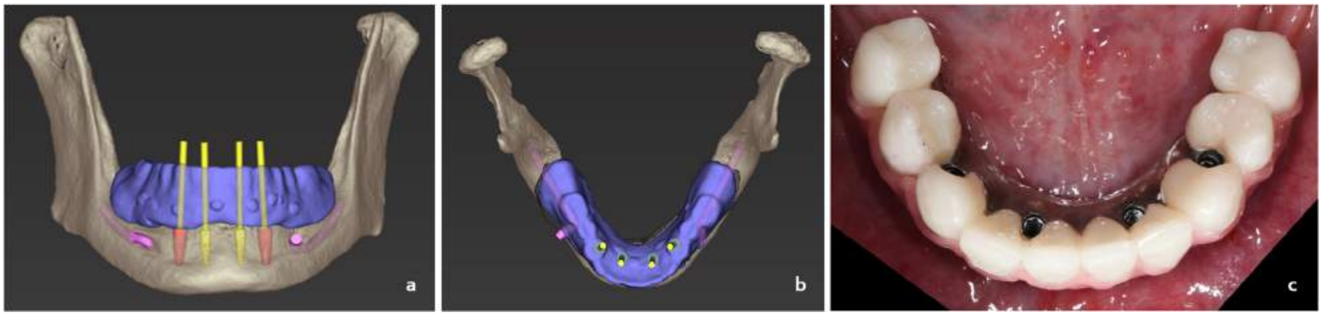

Fig. 8 Static computer-aided implant placement in completely edentulous jaw using dual-scan technique. **a** Frontal view of ideal 3D implant positioning. **b** Occlusal view of ideal 3D implant positioning. **c** Final full-arch restoration

placement. Additionally, real-time tracking like dynamic navigation is available on the monitor to add visual confirmation [12]. The workflow is summarized in Fig. 11**.**

Discussion

Digital revolution is in uprise; hence, the analogue technique is being replaced by digital. Computers and digital devices are becoming inseparable parts of dentistry and implant dentistry is not an exception. This is dramatically changing not only the way we treat the patients but also patients' expectations towards treatment. However, one should realize that guided surgery involves additional steps in treatment planning, increased time of planning, and additional cost. It requires knowledge of CAD software and high maintenance technology but does not replace required skills and experience, nor guarantees perfect accuracy and or outcome. In fact, studies show that having a guide does not necessarily compensate for an inexperienced clinician [13•].

In order to achieve accurate implant positioning, the data acquisition should be meticulous. Errors can be caused and are not limited by the quality of the CBCT and possible artifacts caused by radio-opaque restorations of the patient or the

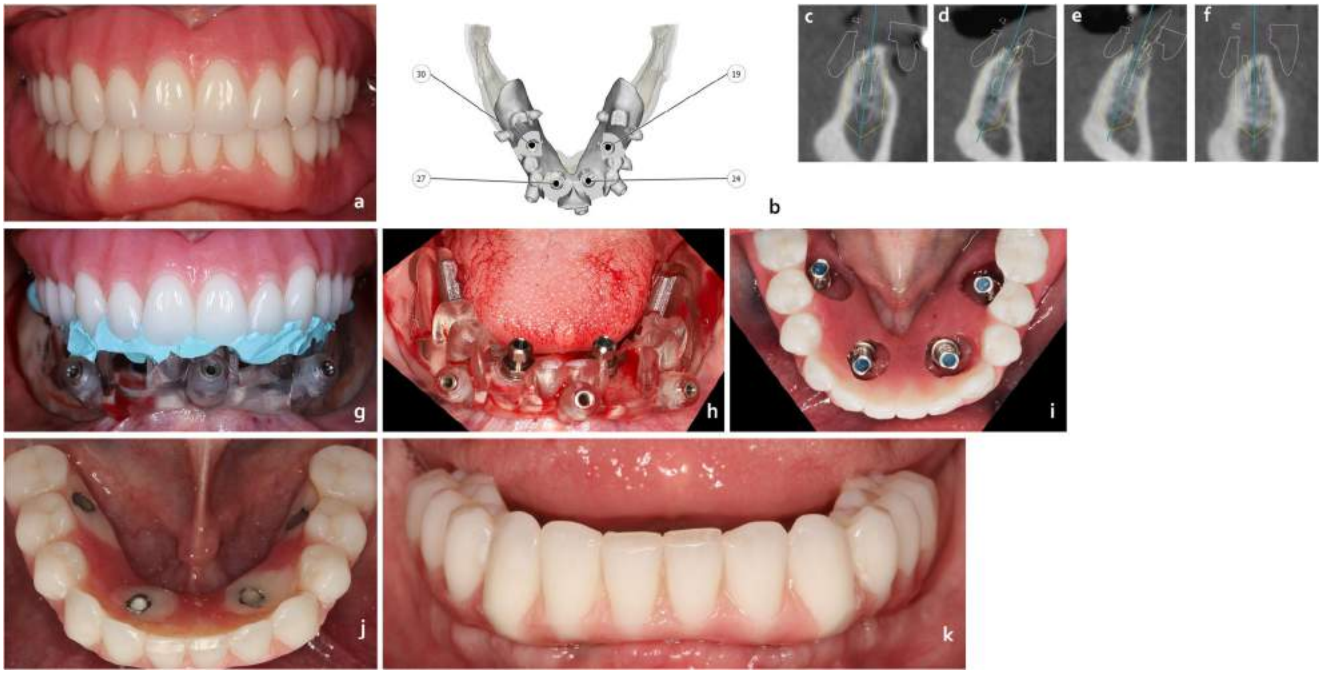

Fig. 9 Static computer-aided implant placement in completely edentulous jaw using dual-scan technique. **a** Frontal view of conventional complete dentures. **b** Occlusal view of surgical guide in an implant planning software. **c** Cross-sectional view of planned implant position of implant #19. **d** Cross-sectional view of planned implant position of implant #24. **e** Cross-sectional view of planned implant position of implant #27. **f** Cross-sectional view of planned implant position of implant #30. **g** Stabilization of the surgical guide using centric relation record. **h** Implant placement with the surgical guide in place. **i** Conversion of the conventional denture to implant supported screw-retained provisional prosthesis. **j** Occlusal view of the converted implant supported screw-retained provisional prosthesis. **k** Frontal view of the implant supported screw-retained provisional prosthesis

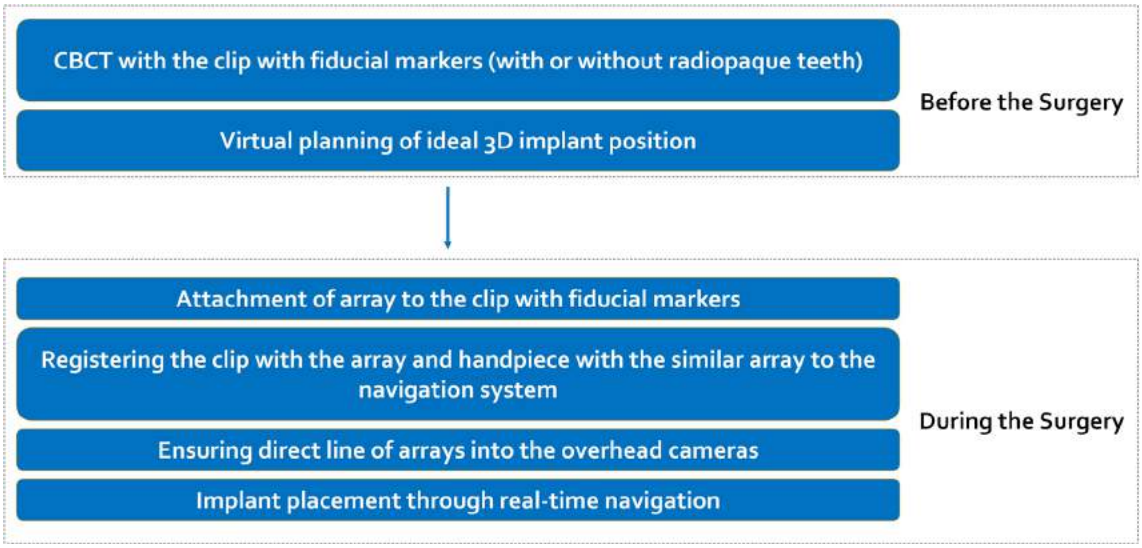

Fig. 10 Workflow for dynamic computer-aided implant placement

movement of the patient during data collection, accuracy of IOS or conventional impressions and casts, adaptation of the imaging appliance, quality of imaging appliance, superimposition of the optical and CBCT data, fabrication method of surgical guide, and the adaptation of the surgical template [14, 15]. Additional training and surgical skills are necessary for the clinicians using computer-aided implant placement compared to those providing conventional implant surgeries [16–18].

In order to evaluate how accurately implants have been placed, deviation between 3D planning and actual 3D positioning is quantified. It is often referred as the implant placement accuracy, which is evaluated using pre- and post-operative CBCTs. After the two images are superimposed, deviation between the shoulder and the apex of the implant is measured in mm and variance in implant axis in degrees. They have nine measurement points to express this 3D variance accounting for apico-coronal and mesio-distal deviations [19, 20••].

A recent systematic review by Tahmaseb et al. reported mean average error of 1.2 mm and 3.3 degrees of deviation [20••]. The authors recommend a 2 mm safety zone to be taken in consideration with anatomic landmarks, particularly with completely edentulous patients as there seem to be

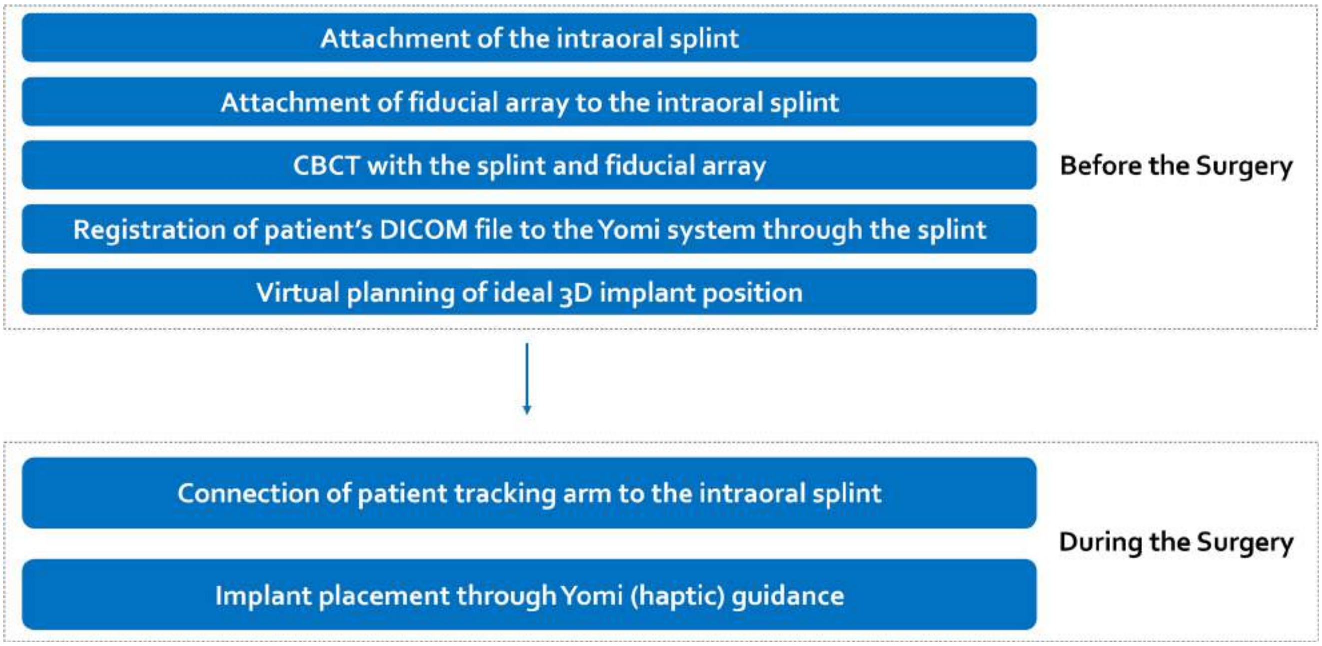

Fig. 11 Workflow for robot-assisted (haptic guidance) implant placement

statistically significant difference in deviation between partially and fully edentulous cases [20••]. Therefore, understanding the different workflows for data acquisitions for computer-aided implant placement not only increases the predictability but also gives flexibility to the clinician.

As previously stated, lower accuracy has been reported for completely edentulous cases. When partially edentulous jaws are scanned, it is easy to merge the CBCT with the surface scans due to the presence of the teeth. However, in the event of fully edentulous jaws, soft tissues should be merged with surface scans which are not always clearly seen in the CBCT. Researchers have tried to merge Magnetic Resonance Imaging (MRI) with the surface scans instead [21]. This method seems to be promising but further research is needed for the validation of the method in the clinical setting.

Apart from the accuracy, the success of implant placement has often been related to the primary stability. Lower primary stability was seen when implants were placed via computer-aided method as measured by Resonance Frequency Analysis (RFA) and insertion torque [19]. One could speculate that the operator has less tactile perception of implant stability through the surgical guide. Once the implant is inserted to its planned depth, the guide is removed regardless of the stability achieved, which is not the case in the freehand placement or dynamic guidance where the depth is often determined in consideration of tactile perception of primary stability.

Despite the listed limitations, possibility of errors, and need of advanced skills, number of reported clinical complications related to computer-aided implant surgery seems to be scarce [22]. Survival rate of implants placed freehand and those with guided implant approach are comparable and vary between 95 and 100% [23]. Additionally, computer-aided implant surgery offers multiple advantages that are not necessarily reflected when studying implant survival. Because prosthetic component is included in the planning, the most optimal implant positioning can be achieved, allowing not only functional but also esthetic restoration with adequate soft tissue appearance [13•, 23–25].

Static computer-assisted implant surgery sometimes allows flapless implant placement. This is particularly beneficial when working in anterior esthetic zones. Pink esthetics has been pointed out to be equally important in achieving pleasing outcomes [26, 27]. Soft tissue appearance around implants varies from that of the teeth due to mucoperiosteal flap elevation resulting in disorientation of vessels, scar formation, and subepithelial fibrosis [28–30]. Therefore, avoiding extra step of flap elevation, when applicable, would result in healthier looking soft tissues. In fact, study by Furhauser et al. demonstrated that accurate implant positioning via computer-aided method resulted in predictable and favorable soft tissue esthetics in the anterior maxilla, while higher inaccuracy and deviation resulted in worse esthetic scores [24, 25].

CAD software allows predesigned customized healing abutments, provisional restorations, and temporary (provisional) or definitive abutments prior to implant placement. With customized healing abutments, proper soft tissue healing and conditioning can be achieved while the implant is being osseointegrated. In some posterior cases, this could eliminate need for temporization (provisionalization). Predesigned provisional restorations are an ideal solution for immediate loading. In certain scenarios, the need of final impression can be eliminated after the implant is osseointegrated; definitive restoration can be delivered using 3D data obtained with a scan of the implant scan body on the day of implant placement. Therefore, computer-aided implant surgery can reduce not only time of the surgery but also number of visits needed for the definitive restoration.

Dynamic computer-assisted implant surgery is also becoming popular both in the academic and private dental practices. Clinical study has compared the accuracy of implant placement via static vs dynamic computer-assisted implant surgeries. Although static method slightly outperformed dynamic guidance, the difference was not statistically significant, and the authors suggested the dynamic guidance to be equally reliable method [31, 32].

Table 1 Comparison of static, dynamic, and robot-assisted computer-aided implant placement ("+" represents advantage and "–" represents disadvantage). Accuracy assessment for robot-assisted computer-aided implant placement was left blank as the research is still scarce on the topic

	Static computer-aided implant surgery	Human-controlled dynamic computer-aided implant surgery	Robot-assisted computer-aided implant surgery
Learning curve	–	–	–
Specific kit	–	+	+
Additional equipment cost	+	–	–
Intervention during placement	–	+	+
Tactile perception	–	+	–
Mouth opening	–	+	+
Accuracy	+	+	
Irrigation	–	+	+
Time	–	–	–

Dynamic guidance offers possibility to intervene during the surgery and alter the planning, which is not the case for static method. Another clear advantage is the ease of access in the posterior sites in cases of the limited mouth opening [5]. However, it is a limitation that the surgeon should move the head from the operative field to the screen. There are already attempts to overcome this limitation and an experimental study combined the static method with the dynamic using a head mounted display. They have described the technique as Augmented Reality (AR)–guided implant placement [33] showing high accuracy in a clinical report [34].

One should keep in mind that the dynamic computer-aided implant surgery also requires a learning curve, change in the clinical working habits, and more importantly substantial investment in technology [7•].

For the comparison, advantages and disadvantages of static and dynamic and robot-assisted computer-aided implant surgery are summarized in Table 1**.**

Future Directions

As the digital dentistry evolves, improvements and simplifications are yet to follow for the current workflows and methodologies. We should also expect new technologies and breakthroughs that will further digitize and computerize implant surgery.

The research is directed towards automating the implant surgery even more through autonomous robotics. In fact, the first autonomous dental implant placement system was already introduced, and the world's first fully automated implant surgery was also performed in China with an accuracy of 0.2–0.3 mm [35].

We are entering the era where fiction becomes nonfiction. Certainly, the two branches of computer-aided implant placement, namely, static and dynamic, will intersect more in future. Integration of the Artificial Intelligence (AI) in implant planning software will simplify diagnosis and implant planning process. Augmented Reality (AR), Virtual Reality (VR), and online dental platforms will change our way of communication with the patients, other specialists, and the lab technicians. Haptic guidance holds promise not only for the implant placement but also for the other fields of dentistry. Interestingly, haptics can be beneficial also for the elderly professionals to account for age-related dexterity limitations. Further digitization and automatization are inevitable for the academic and the private dental environments. However, one should realize that major safety screenings are yet to be conducted. Besides, there are certain links in the chain of diagnosis and treatment that still can only be achieved conventionally.

Conclusions

Computer-aided implant surgery offers safe and prosthetically driven implant placement and gives the possibility for flapless surgery to reduce postoperative healing time. It allows better communication between a restorative dentist and a surgeon. Additionally, the prosthetic components can be fabricated prior to the surgery, shortening not only the time for the surgery but the number of appointments as well. With advancing field of digital dentistry, computer-aided implant surgery will become an inseparable part of standard of care. However, one should be cautious of possible errors and consider maximum inaccuracies reported to guarantee safe placement. Most importantly, computer-aided implant surgery should not serve as a green light to inexperienced surgeons for implant installation. Appropriate training and learning curve are mandatory even if fully computer-aided implant placement is being done. Skills and knowledge that will detect errors throughout the data acquisition and implant planning will result in predictable, functionally adequate, and esthetically pleasing outcomes.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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- • Of importance
- •• Of major importance

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