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Accuracy and efficiency of digital implant planning and guided implant surgery: An update and review

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Abstract

Advances in digital technology present seamless 3D integrated workflow options to eliminate surgical and prosthetic complications in dental implant treatment. Virtual implant planning with guided implant surgery is claimed to provide predictable results. State of art technology is capable to transfer virtual implant planning from software to clinical application. However, clinicians have to be aware of the potential deviation factors and risks of the different types of guided implant surgery systems to reduce the complications. This review aims to evaluate the efficiency and accuracy of different computer-assisted dental implant surgical techniques and to discuss their potential error sources.

Keywords: accuracy, computer-assisted dental implant surgery, digital implant planning, guided dental implant surgery

1. Introduction

The latest improvements in technology have implemented digital workflow options into implant treatments and restated implantology. The term "digital implantology'' refers to a glance that covers digitally supported treatment stages. These stages include digital implant planning and guided surgery as well as the digital impression of implant position and production of the final restoration. This review aims to discuss the advantages, disadvantages, and possible limits of dynamic and static navigation techniques in dental implant surgery.

Ideal 3D positioning of an implant has a critical role in the long-term stability of peri-implant tissues. Not only for biological concepts but also for the biomechanical principles that must be considered while deciding the location of an implant in apico-coronal, mesio-distal, and oro-facial directions. Non-ideal implant position may cause damage to anatomical structures as well as aesthetic and biomechanical complications (Buser et al., 2004; Pjetursson et al., 2007; Misch et al., 2008; Sadid-Zadeh et al., 2015).

Prosthetic and surgical principles for predictable implant treatment outcomes are well defined in the literature. Ideally, a dental implant must be circumferentially surrounded by healthy bone or bony like substance. Critical anatomical structures like inferior alveolar nerve in the mandible must not be damaged during osteotomy. The implant should provide esthetic and biomechanical requirements of future implant-supported prosthesis after osseointegration (Brief et al., 2005).

In most cases, the ideal 3D position of a dental implant might be challenging because of reduced bone and soft tissue volume. Nowadays computer-assisted navigation techniques have become favorable to overcome this challenge and optimize implant positioning. The latest CBCT technology has provided the possibility to analyze the 3D anatomy of the implant sites with a reduced radiation dose. Additionally, digital implant planning softwares have been developed to simulate 3D virtual implant planning. The planning software should be able to import and export. DICOM and .STL files and merge them to perform a prosthetically driven implant placement. This integrated approach helps to minimize the risk factors to avoid biological and biomechanical complications (Bou et al., 2000; Dula et al., 2001; Kopp et al., 2003; Lund et al., 2009; Greenberg et al., 2015; Panchal et al., 2019).

The very first digital implant planning software has been presented in the early '90s. In 1991, Image-Master-101 software placed some graphic images of implants on cross-sectional images. In 1993, the first version of Simplant was introduced providing 3D planning tools. Today there are many different planning software on the market, some of which are working as closed systems. The others are capable to support various implant brands. Selecting implant diameter, platform diameter, abutment height, abutment angle, performing multiple measurements on CBCT, aligning implants are some of the capabilities of these softwares (Panchal et al., 2019) (Fig.1).

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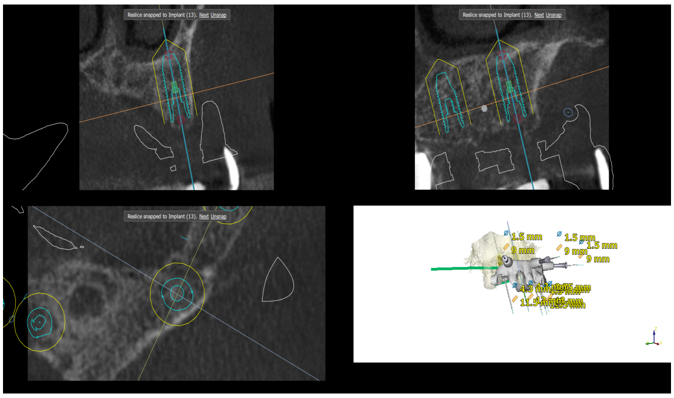

Fig. 1. Virtual implant planning (DTX Studio Implant, Nobel Biocare)

The next step after virtual implant planning is to transfer the 3D positions of implants to the surgical site. Two different techniques were defined for this purpose to make an accurate transfer of the virtual plan to the surgical area (D'haese et al., 2000; Vercruyssen et al., 2014a; Vercruyssen et al., 2015; Gallardo et al., 2017; Jung et al., 2009).

1. Dynamic Navigation
2. Static Guided Surgery

2. Dynamic navigation

This technique was first introduced for neurosurgery in 1992. In dentistry, it was first used in 2000 in the USA (Dyer et al., 1995; D'haese et al., 2000; Panchal et al., 2019). The system uses optical motion tracking technology that allows real-time guidance during surgery. Light is projected from a special source above the patient. The light is reflected off tracking arrays that are fixed to patient, surgical handpiece and drills. The software recognizes the reference markers and tracking arrays. Then it calculates the position of the jaw so a virtual reality simulation is created on screen (Fig. 2). The patient should be scanned with a special reference marker system rigidly fixed to the teeth (for a dentulous patient) or jaw (for edentulous). After virtual planning on CBCT, calibration, and registration of the system are performed. Surgery can be performed with or without a flap. There are different workflows for dentulous and edentulous patients. An edentulous patient requires screws to be placed in the bone to perform the registration in CBCT. For dentulous patients, a single-use fiducial clip is placed on teeth. Both osteotomy and implant placement are performed freehand with dynamic navigation. The freehand approach provides the operator with the freedom to be able to change the position of the implant during surgery.

Dynamic navigation ensures good visibility to the operation site and irrigation of the drilling area is predictable. There is no need for a special drill kit, reference markers can be fixed to every drill set. This technology allows guidance even when the mouth opening is limited (Stefanelli et al., 2019; Guzmán et al., 2019; Lopes et al., 2020).

Limited in vivo studies in the literature are available. Some in vitro studies show that there is a specific learning curve for this system and personal training on models is essential before performing clinical cases. Because the operator has to look at the computer screen instead of the surgical site during surgery, coordination of the operator is crucial (Block et al., 2017; Lopes et al., 2020). Sun et al. (2018) showed that gaining experience with the system reduces the operation time. Although clinician has been experienced, there is a certain level of error which is caused by the system. Stefanelli et al. (2019) found similar results in a clinical study with 231 implants.

Dynamic navigation is reliable and efficient for both experienced and novice operators. The difference between the two groups doesn't have statistically different accuracy. The only difference reported with the experienced group is the reduction of operative time but this is not at a level of changing clinical results. However, all these results are reported from in vitro studies (Jorba-García et al., 2019; Pellegrino et al., 2020). In clinical scenarios, accuracy might change as operator experience may influence the result. Deviations in dynamic navigation technology are reported in both in vivo and in vitro studies.

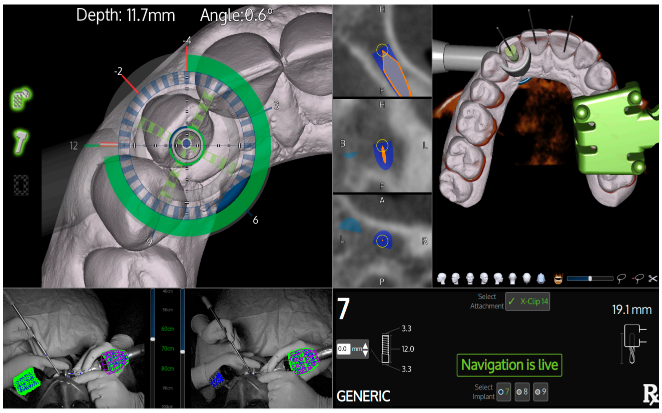

Fig. 2. Dynamic navigation operation screen (X-Guide, XNav Technologies)

The measurement for accuracy in static or dynamic navigation systems is usually performed by superimposing the preoperative planning data and post-operative data. Different studies compare different deviations but mainly there are four types of deviations:

Depth deviation: Deviation in apical-coronal direction (mm)

Lateral deviation: Mesial-distal and buccal-lingual direction (mm)

Global deviation: Overall 3D distance regarding apical and coronal deviation (mm)

Angular deviation: The angle in 3D space between center axes (degree) (Emery et al., 2016).

Some studies compared freehand surgery and dynamic navigation on study models. One study reported 4.2 ± 1.8° angular deviation for dynamic navigation and 11.2 ± 5° for freehand surgery (Hoffmann et al., 2005). Another model study found 1.6° angular deviation for dynamic and 9.7° for freehand surgery (Jorba-García et al., 2019). A clinical study of 28 edentulous, 125 dentulous patients who were treated with dynamic navigation has reported the difference between virtual plan and final implant position. This study measured 0.71 mm deviation at the entry point (lateral), 1.00 mm at apical, and 2.26° deviation (Stefanelli et al., 2019). Another clinical study including 86 implants measured 0,72 mm lateral deviation at implant shoulder, 0.69 mm at apical, and 5.33° angular deviation (Aydemir et al., 2020). Another author had reported similar results with a multicenter prospective clinical study (Block et al., 2017).Dynamic navigation ensures more accurate angular positioning and parallelism of implants when compared to freehand surgery both in clinical and in vitro studies (Hoffmann et al., 2005; Kramer et al., 2005; Block et al., 2017). But apicocoronally dynamic navigation is still not reliable enough. Some studies reported wide range values like (0 to 1,6 mm), (0 to 3.3 mm), (0,1 to 1.8 mm) in depth deviation (Hoffmann et al., 2005; Somogyi-Ganss et al., 2015; Jorba-García et al., 2019).

This is the reason why every planning software has at least a 2 mm safety zone around the virtual implant. Software are still improving to compensate for this deviation. Some possible error sources that may lead to increased deviations in dynamic navigation are voxel settings, slice thickness, patient-related motion or metal artifacts, and non-rigid fixation of fiducial marker clip or screws during CBCT scan may cause problems during STL and DICOM superimposition procedure. Errors during digital planning, limits of optical tracking, software-oriented deviations, and the difficulty of manipulation while keeping the eye on screen might also influence the accuracy.

Dynamic navigation is used daily in neurosurgery, ophthalmology, and some other medical branches. Since introduced to dentistry, this technology didn't become popular immediately because of the high investment costs and increased operative time but nowadays dynamic navigation surgery is getting more attention due to the advantages of the technique.

3. Static guided surgery

Currently, static guidance is widely used in implant dentistry. Implant placement using a static guide requires a CBCT scan with a proper field of view and impressions of the upper and lower jaws. Impressions can be obtained by either conventional or digital techniques. If a conventional technique is preferred, the cast should be digitized by an extraoral desktop scanner to be able to obtain a digital file. Direct digitization of intraoral surface geometries with an intraoral scanner is also possible. These digitization methods both present a 3D model, therefore a virtual wax-up can be designed to be merged with the CBCT scan. After the merge of data sets, virtual planning can be performed ideally using the implant planning software. Angulation, depth, diameter, and length of each implant can be specifically determined. It is possible to simulate different abutment options and multiple measurements can be performed to be able to position the critical abutment-implant shoulder connection optimally for creating a proper emergence profile. When the planning is finalized this information is used to design a surgical guide. The guide can be either milled or produced by stereolithography, the most known rapid prototyping technology (Somogyi-Ganss et al., 2015; Gallardo et al., 2017).

The static guide technique is commonly used for minimal invasive flapless surgery but the system also allows to open a flap if necessary (Fig. 3, 4).

Fig. 3. CEREC Guide, Dentsply Sirona

Fig. 4. Ideal implant positioning

For drilling through the guide, special long drilling burs are mandatory. Sleeves or drill keys are positioned on the guide which leads the drill to perform the osteotomy at the same depth and angulation as it is in planning software. There is a physical stop on the template, therefore a static guide doesn't allow to change the position of the implant during surgery. If a necessity to make a change in the implant positioning occurs, another guide must be produced (D'haese et al., 2000; Vercruyssen et al., 2015).

There are different protocols for edentulous and partially dentulous patients as it is in dynamic navigation. For partially dentulous patients, the impressions of jaws and CBCT scans are enough to produce a surgical guide. We have to use scan prosthesis when dealing with edentulous cases. The reason for producing a scan prosthesis is that the acrylic resin used in traditional removable prosthesis cannot be easily segmented on

CBCT. The soft tissue segmentation can be extremely difficult if a scan prosthesis is not used.

Two different approaches for edentulous cases are reported:

1. Single scan: A duplicate of a future prosthesis with a radiopaque material is produced and a CBCT scan is performed with this scan prosthesis. A radio-opaque scan prosthesis must be a copy of the final prosthesis and consist of 10% BaSO4 and a methylmethacrylate mixture.

2. Double scan: Radio-opaque markers are fixed on the scan prosthesis. First, the scan prosthesis has to be scanned with an increased radiation dose, secondly, the patient should be scanned with a standard radiation dose while wearing the scan prosthesis. Attention should be paid to the marker's rigid fixation. Also, the scan prosthesis should be placed in the mouth with a rigid bite index. Afterward, two scans are merged in software, and planning is performed (Verde et al., 1993; D'haese et al., 2000; Vercruyssen et al., 2014b; Witherington et al., 2017; Schubert et al., 2019).

Studies didn't define a specific learning curve for static guided surgery. Although the efficiency of the operator seems to improve with repeating applications, still a typical learning curve is not defined. Repeated use of static guides seems to improve angular and depth deviation. As it is in dynamic systems, both experienced and novice operators can achieve fewer positional deviation when compared to freehand surgery (Vasak et al., 2011; Vercruyssen et al., 2015; Cassetta et al., 2020).

Different types of static guidance depending on tissue support is defined in literature (Fortin et al., 2004; Van Assche et al., 2012; Gallardo et al., 2017).

3.1. Bone supported surgical guides

The surgical template must be placed on the bone after reflecting a full-thickness flap which usually extends 2-3 mm beyond the template. Bone supported surgical guides can be defined as the first version of surgical templates for edentulous cases. The main advantage of a bone-supported guide is the easy visualization of the operation site and control of the drilling depth. But this type of guide requires invasive surgery regarding the wide flap elevation. Postoperative discomfort is inevitable and decreased blood supply is a risk factor for postoperative healing (Rosenfeld et al., 2006; Gallardo et al., 2017).

Bone supported guides have to be screwed to the bone for stability. The absence of fixation screws and the need for replacement of different guides during surgery are considered to affect precision. Stabilization of template is difficult, guide tends to move coronally while drilling. Additionally, interference occurs between the guide and bone after the flap elevation. As a result, more pronounced deviation values are reported in the literature for bone supported guides than mucosa and tooth-supported guides (Arısan et al., 2010).

3.2. Mucosa supported surgical guides

Mucosa-supported surgical guides are commonly used for edentulous cases as they are capable of performing flapless surgery. The use of a mucosa-supported single guide to place implants without flap reflecting might help to reduce the total time of operation, postoperative pain, and some other complications (Fortin et al., 2006; Hultin et al., 2006; Divakar et al., 2020). However, another study conducted by Vercryusse with 311 implants comparing the patient outcome of conventional surgery, bone supported and mucosa supported flapless surgery didn't agree with previous findings (Vercryussen et al., 2014c). This study doesn't report a significant difference between the postoperative discomfort of guided surgery compared to conventional methods. Patients treated with conventional methods reported prolonged pain than patients treated with the flapless guided surgery. This might have occurred due to the operation time. It has been demonstrated that longer operative time caused more postoperative discomfort (Sato et al., 2009). Flapless approach with mucosa supported guides seem to reduce the operative time when compared to bone supported guides (Arısan et al., 2010).

Operators should be aware of the criteria when deciding on a flapless surgery. Flapless surgery is possible in limited cases only with adequate attached gingiva and enough bone volume. Flanagan suggested at least 5 mm bone width and 4 mm keratinized tissue, Malo and Jesch reported at least 6 mm width of bone and 6 mm keratinized tissue is needed for flapless surgery (Flanagan et al., 2007; Malo et al., 2016; Jesch et al., 2018). Another study reported a minimum width of 4 mm attached gingiva and alveolar bone thickness over 4 mm are suitable for flapless surgery (Arısan et al., 2010).

The vascular structure remains healthy and this is supposed to improve peri-implant tissue stability (Campelo et al., 2002; Becker et al., 2005). Flap reflection might have disturbed the vascular network. Nevertheless, some of the keratinized tissue is removed by a punch during flapless surgery and this also may risk peri-implant tissues (Schrott et al., 2009).

Precise positioning of the surgical guide is an important aspect and can affect accuracy. The guide should be perfectly positioned and stabilized firmly after the punching with fixation screws. Stabilization of the guide is one of the most critical clinical points during guided implant placement. Stabilization should be secured with at least 3 fixation pins. A study in 2014 reported surgical guides in edentulous patients must be fixed using at least three pins to minimize errors in the positioning of implants (Casetta et al.,2014a) (Fig. 5).

The distribution and even fixation order of pins influence the accuracy. Posterior pins are recommended to be placed into bone before anterior ones (Verde et al., 1993; Vercruyssen et al., 2014b). A properly fixed guide presented 1.66 mm deviation at coronal, 2.09 mm deviation at apical, and 4.09 degrees angular deviation. When the surgical guide is not fixed, 1.68 mm coronal deviation, 2.26 mm apical deviation, and 5.62 degrees angular deviation were recorded (Casetta et al., 2014b).

Accuracy can also be influenced by mucosal thickness, smoking habit, bone density, type of jaw (upper or lower), and implant length (Casetta et al., 2013; Vercruyssen et al., 2014b; Seo et al., 2018).

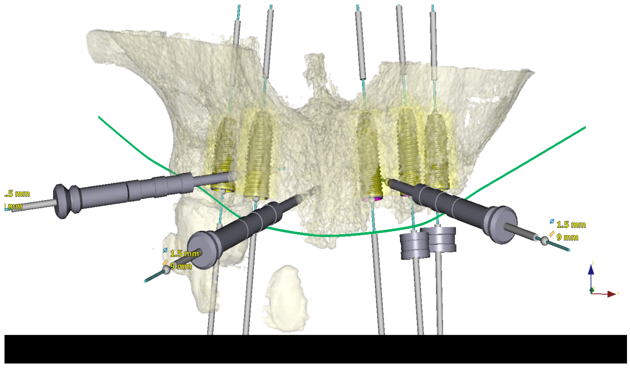

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Fig. 5. Fixation pins at planning stage

Mucosa thickness has a critical role in the accuracy of this type of guide. Overall deviation increases as the mucosa thickness increases. The apical deviation is reported to be greater than the coronal deviation in various studies (Widmann et al., 2006; Vasak et al., 2011; Gallardo et al., 2017; Seo et al., 2018). A study presented that smokers have relatively thicker mucosal tissues compared with non-smokers, which may lead to less stability of the surgical guide. The same study found that if tissue thickness is more than 3.5 mm, a flap has to be reflected (Schnutenhaus et al., 2016). The local anesthesia may also cause swelling of tissue and the fit of the guide template may be affected (D'haese et al., 2012).

Accuracy of type of jaw (upper or lower) was evaluated in some studies. When working on a mandible with a mucosa supported guide, the operator should be aware of the possibility of guide displacement since the supporting area is smaller. Tahmaseb (2014) reported no difference between maxilla and mandible in a systematic review. Another important point is the bony structure. Maxilla is supposed to have more impact on the deviations between virtual plan and realization. The reason might be the lower resistance of spongiose bone when compared to cortical bone (Marlière et al., 2018). Schelbert et al. (2019) presented in a study with partially and fully edentulous patients that maxilla has a greater deviation than the mandible. Additionally, augmented implant sites showed less depth deviation. Accomplishing template stability for mucosa supported guides is more difficult than teeth guided when dealing with edentulous patients. Therefore, no consensus yet is available about the effect on the accuracy of the type of the jaw.

D'haese et al. (2012) reported implant length also influence accuracy outcome. They found a statistically significant difference in the global apical deviation for longer implants. Vercruyssen et al. (2015) did not confirm this finding and could not find a correlation between implant height and deviation amount. Valente et al. (2009) conducted an in vivo multicenter study and reported that the type of implant did not cause a significant difference in accuracy.

3.3. Tooth supported surgical guides

The accuracy of tooth-supported surgical guides is reported to be superior to that of bone and mucosa supported guides on literature. If a patient has at least 3 or 4 periodontally healthy teeth without mobility, the rigid tooth support offers an advantage for reducing the movement of the guide (Van Assche et al., 2012; Tahmaseb et al., 2014; Pozzi et al.,2016; Gallardo et al., 2017; El Kholy et al., 2019).

Ozan (2019) found the angular deviations of final implant positions compared to virtual planning as 2.91 ± 1.3°, 4.63 ± 2.6°, and 4.51 ± 2.1° with tooth-supported, bone- supported, and mucosa-supported guides, respectively. Tooth supported guides are reported to provide more accurate results than mucosa or mucosa and pin supported guides (Ozan et al., 2009; Tahmaseb et al., 2014 and 2018; Gallardo et al., 2017).

Surgical guides can also be classified as full guidance or partial guidance. Partial guidance (pilot drill guidance or half guidance) allows us to use only a single pilot drill or to perform the complete osteotomy guided, but the implant should be placed freehand. Fully guidance allows all osteotomy and implant delivery steps through the guide. Although Wei Geng et al. (2015) compared the accuracy of these and didn't find a significant difference, Kühl et al. (2013) and Ramos et al. (2017) have reported better accuracy for fully guided systems.

Fully guided surgery showed less deviation values when compared with partial-guided surgery, but clinically both techniques are acceptable. Partially guided templates can also facilitate optimal implant placement and can simplify the surgical procedure. Fully guided systems may provide more accurate results when working with irregular bone quality, where some movements during implant placement may result in higher deviations. The only pilot drill partial guidance may have an advantage of reducing irrigation problems and when limited mouth opening exhibits (Verde et al.,1993; Kühl et al., 2013; Geng et al., 2015). Another classification is a single type or multiple type guide, describing the number of templates necessary for the surgery. A single type guide is considered to be more accurate than a multiple type for bone supported guides. Single type allows guided osteotomy and implant placement through only one template. Metal cylinder tubes called master tubes are adhesively fixed in the resin guide. The tolerance between the master tube and the internal tube and the drills may affect the accuracy of single guides (Cassetta et al., 2013).

3.4. Possible error sources

Jung et al. (2009) reported the deviation may increase due to the limited access, poor visualization, patient movements during surgery. Ramos et al. (2017) confirmed this finding in a meta-analysis comparing in vivo, ex vivo, and in vitro studies. In vitro studies have resulted better in accuracy because they don't have clinically challenge conditions.

The digital workflow steps should be carefully controlled to minimize the deviation. CBCT data acquisition, intraoral scanning, digital planning, guide production via milling or 3D printing are the steps of digital workflow where system errors may occur. Patient motion artifacts or metal artifacts may affect accuracy. During acquisition and software processing, an error of 0.5 mm deviation is reported. Additionally stereolithography material and the fit between the tubes of the guide and drills also may affect the result. Manufacturing errors can have a cumulative effect, and cause a deviation and the clinical result might be negatively affected (Reddy et al.,1994; Stumpel et al., 2012; Vercruyssen et al., 2015; Marlière et al., 2018).

4. Guide Production

Guides can be manufactured manually or using computer-assisted design and computer-assisted manufacturing (CAD/CAM) by a fully digital workflow. Computer-aided guides are usually produced by milling machines or rapid prototyping technologies (Fig. 6).

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Upper Jaw (%) 47

Restoration (%) 100

Fig. 6. Milling of a surgical guide

Rapid prototyping technique is commercially the most preferred technique in digital guide production (D'haese et al., 2000). Tahmaseb et al. (2018) recently documented in a meta-analysis of 20 clinical studies 2136 of 2135 guides were produced by this technology. Farley et al. (2013) showed in a split-mouth study that digital guides achieve better accuracy outcomes than the model-based as all steps are controlled digitally. An in vitro study reported that the intaglio surface dimension and tube deviation might be affected by the layer thickness of printing material and angulation parameter during production. If the printing layer was selected 50 µm, dimensional intaglio deviations and tube angular deviations were reduced. Faster printing was possible using a layer of printing 100 µm but thicker layers might have a negative influence on accuracy. Moreover, printing at different angulation parameters also changed the result. Printing at a 90° setting allowed more templates to be printed in a shorter time. As a result, increasing the angle and printing layer may affect the accuracy of printing (DalalN et al., 2020).

5. Clinical implications

Tahmaseb et al. (2018) reported in a meta-analysis of 20 clinical studies a total error of 1.2 mm at the coronal, 1.4 mm at the apical, and angular deviation of 3.5° for guided surgery. Partial edentulous cases presented more accurate results than full edentulous cases. The accuracy of implant surgery with computer-assisted navigation systems were shown to be superior to free-hand surgery (Tahmaseb et al., 2014). Jung et al. (2009) compared the accuracy of dynamic navigation and static guidance. Precision observed was higher in dynamic systems but the difference might be a result of the fact that most of studies were in vitro conditions. A real comparison between dynamic and static surgery is yet not possible.

Chen et al. (2018) compared horizontal deviation at the apical when using the dynamic navigation system, static guidance, and freehand implant placement. Deviations at apical point measured were (1.35 ± 0.55 mm), (1.50 ± 0.79 mm) and (2 ± 0.79 mm) respectively. The dynamic navigation system showed 4.45 ± 1.97°, static guidance showed 6.02 ± 3.71°, and free-hand surgery showed 9.26 ± 3.62° angular deviation.

6. Conclusion

Based on the literature we can conclude that both dynamic and static guided surgery is helpful for optimizing implant position when compared to freehand surgery. But each step of the digital workflow must be carefully processed to minimize errors for successful treatment outcomes. Prosthetically driven implant placement using computer software can provide predictable prosthetic outcomes and minimize biological complications. Moreover, reducing bone augmentation and sinus floor elevation procedures are possible by optimizing the implant position. Computer-assisted guided surgery options promise to add value to implantology for clinicians even in difficult cases. Despite digital workflow assures a precise implant placement, the deviation between the virtual plan and the realized position of implants is inevitable. Operators should be aware of possible errors that may occur during the workflow to be able to keep the deviation values in a clinically acceptable range.

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