Digital implant planning and guided implant surgery – workflow and reliability

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Key points

- Discusses the advantages and the reliability of digital implant planning and guided implant surgery.
- Discusses limitations and sources of error in digital implant planning and guided implant surgery.
- Describes the workflow from digital implant planning to guided implant surgery.

Modern oral implantology and implant prosthetics depend on comprehensive diagnostics and precise planning to ensure the desired outcome and meet the patient's and the dentist's expectations. In this context, digital implant planning and guided implant surgery based on three-dimensional radiographic data and the digitised intraoral surfaces can be of excellent service. They provide valuable information and permit stringent backward planning to optimise the implantological and prosthetic result, improving the safety and efficiency of the surgical procedure and rendering the restorative outcome more predictable in terms of function, biology and aesthetics. However, template-guided implant surgery carries its own specific risks in terms of manufacturing inaccuracies and application errors. These possible sources of error must be recognised and carefully considered in order to avoid adverse consequences.

Introduction

Advances in digital technologies have brought about profound changes throughout dentistry. Ever more powerful systems offer undisputed advantages, such as the economic use of resources, optimised quality management and the enhanced processability of innovative materials, resulting in computer-assisted procedures becoming firmly established.[1–3] Industrially produced blanks and standardised working processes provide excellent stability, biocompatibility and precision.[1,4,5] Even though a large percentage of dentists in the UK reported in 2016 that they had not yet actively applied computer-based technologies, the majority agreed that these technologies would play a crucial role in dentistry in the future.[6] In dentistry and in dental technology, the digital transformation now appears to be irreversible.

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To create individual and aesthetically pleasing restorations with a favourable long-term functional prognosis is the main objective of modern restorative dentistry. Patient expectations of oral implantology are high, as these procedures are typically associated with substantial cost and because any surgical intervention places great strain on the patient.

Digital implant-prosthetic planning provides a variety of interesting perspectives in terms of diagnostics, individual treatment planning and exact surgical and prosthetic implementation, if the right preconditions exist.[7,8]

The present paper intends to provide a comprehensive overview of the workflow and to discuss and critically assess the factors determining the reliability of three-dimensional implant planning and static guided implant placement using surgical templates.

Some of the advantages of digital implant planning and guided surgery are self-evident. Three-dimensional visualisation of anatomical structures and improved assessment of the available bone volume and quality facilitate a more precise diagnosis and allow potential problems to be identified early, enabling high levels of predictability in surgical planning. The courses of nerves, the delimitations of the maxillary sinus or peculiar bony features can be diagnosed more efficiently and accommodated intraoperatively. Detailed preoperative planning gives surgeons certainty, requiring fewer spontaneous intraoperative decisions or deviations from the surgical protocol.[9,10]

In most cases, three-dimensional planning includes the option to virtually anticipate the prosthetic outcome. The best possible future prosthetic corridor can then be defined, resulting in a more prosthetic driven orientation of the implant position. This backward planning allows not only to choose an implant well suited for the specific anatomic situation and prosthetic demands, but also to make informed prosthetic planning decisions, not least in terms of restorative materials or design details.

Digital implant planning requires three-dimensional radiograph data (DICOM: digital imaging and communications in medicine) as well as STL data (STL: standard tesselation language) from an intraoral scan or the scan of a plaster cast. In the past, several appointments were necessary, with a dental technician first producing a radiographic template with radiopaque markers ('dual scan'/'Lego brick'), which then had to be complicatedly converted into a surgical

template after radiological imaging. Today, all that is required for this purpose is the DICOM data and the three-dimensional data of the intraoral surfaces.[11,12] This also means in effect that the procedure can be modified at any time to accommodate a specific implant system or the corresponding software.

Less obvious but nevertheless invaluable is the improved communication within the team consisting of the patient, dentist and dental technician. A visual presentation of the anatomical situation and the planned restorative result allows the patient to substantiate his expectations, while options and limitations can be more clearly communicated within the restorative team and to the patient.

The digital workflow covers the acquisition of basic data, data processing and ultimately the production of the workpiece.[3] This also applies to digital implant planning and guided implant surgery (Table 1).

Table 1 Workflow for digital implant planning and guided implant placement. Bold text denotes steps executed in the dental surgery, while italic text indicates steps executed in the dental laboratory

Data collection	Data processing	Surgical template production	Implant surgery
Radiological data (DICOM file)	*Data fusion (DICOM+STL)*	*Additive manufacturing or subtractive manufacturing*	**Guided implant surgery**
	Prosthetic pre-planning		
Intraoral scan (STL file) *or plaster cast/impression scan (STL file)*	*Implant planning*		
	Template design (STL file)		

Data acquisition

Superimposing surface data in STL format with three-dimensional DICOM data from radiological imaging (Fig. 1) is a basic prerequisite for the digital implant planning. All the necessary data can be acquired at a single appointment. In addition to the DICOM data obtained by cone-beam computed tomography (CBCT) or standard computer tomography (CT), STL data of the intraoral clinical situation in the form of an intraoral or model scan are required.[12,13] The size and position of the field of view (FOV) of the CBCT must be appropriately chosen in order to obtain processible data (Fig. 1b). The segmentation of CBCT images, in other words the digital separation of significant structures (that is, bones from soft tissues) can be conducted automatically or manually.[13]

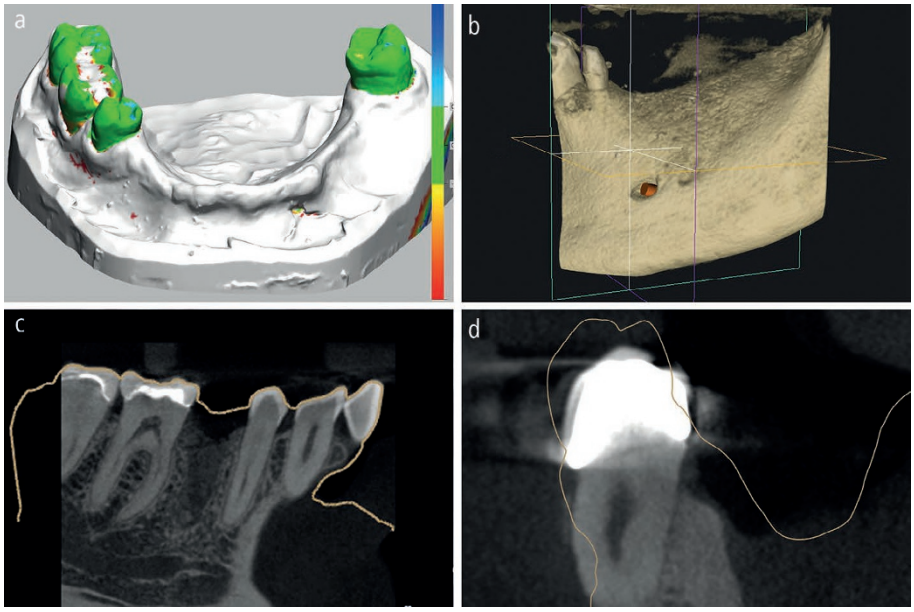

Fig. 1 a) Correlation of the DICOM data with the STL data of the clinical situation using a colour-coded distance image after registration (ImplantStudio; 3Shape). b) 3D DICOM data. Field of view not optimised for data superimposition (CS 3D Imaging Software; Carestream); c) Sectional image control of the correlation of the STL data (brown line) and DICOM data with optimised overlay; and d) inadequate alignment (ImplantStudio; 3Shape)

Data processing

Data fusion

The surgical template is generated based on the STL surface data of the clinical situation. To allow this, the two data sets (STL and DICOM data) are imported into the implant planning software and superimposed ('matching'/'registration'). Most planning software necessitates the marking of specific points, preferably on residual dental hard tissue, to perform an alignment of the recorded data.

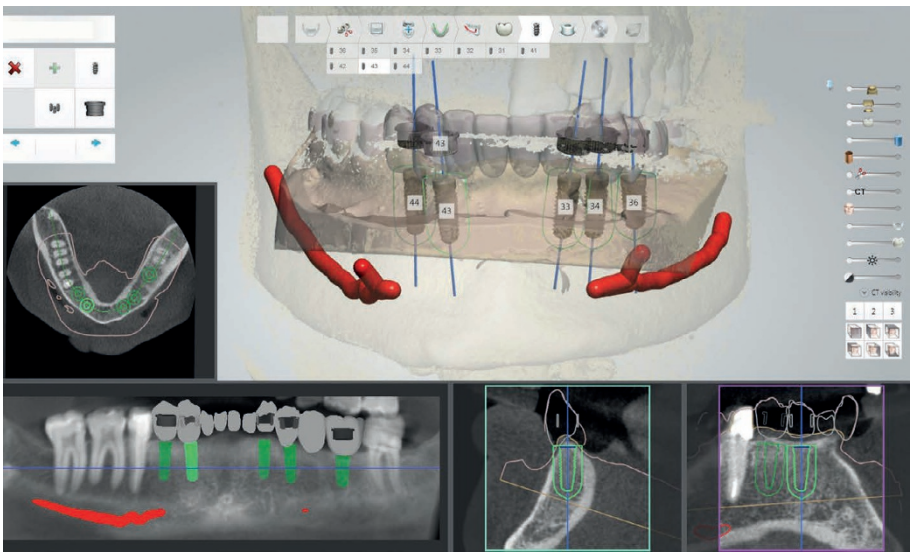

Fig. 2 Marking the inferior alveolar nerve (red) and implant placement planning, taking into account the anatomical situation and the prosthetic pre-planning (ImplantStudio; 3Shape)

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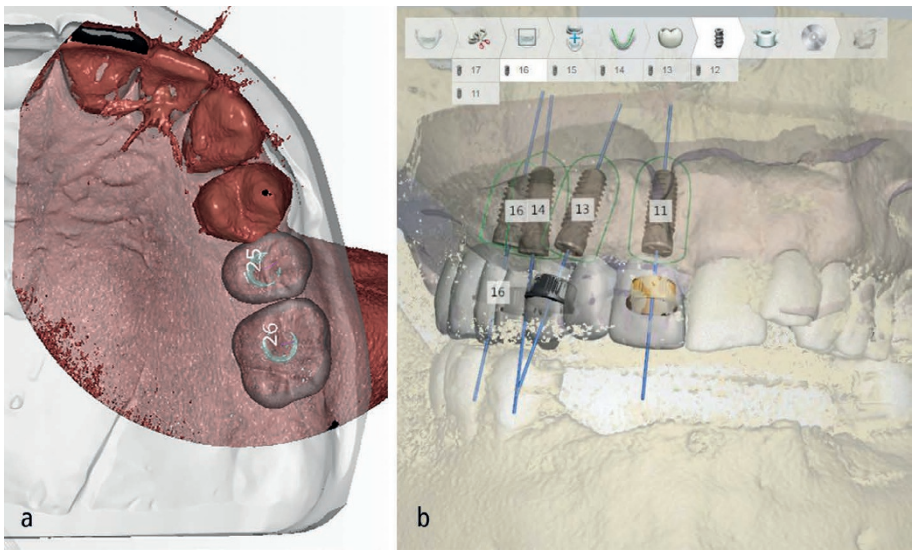

Fig. 3 a) Virtual planning of the projected dental prosthesis via backward planning allows the best possible orientation of the implant from a prosthetic point of view. DICOM data are shown in red, while STL data are shown in grey (Design CAD 6.0; Zfx); b) Virtual prosthetic restoration and implant alignment (ImplantStudio; 3Shape)

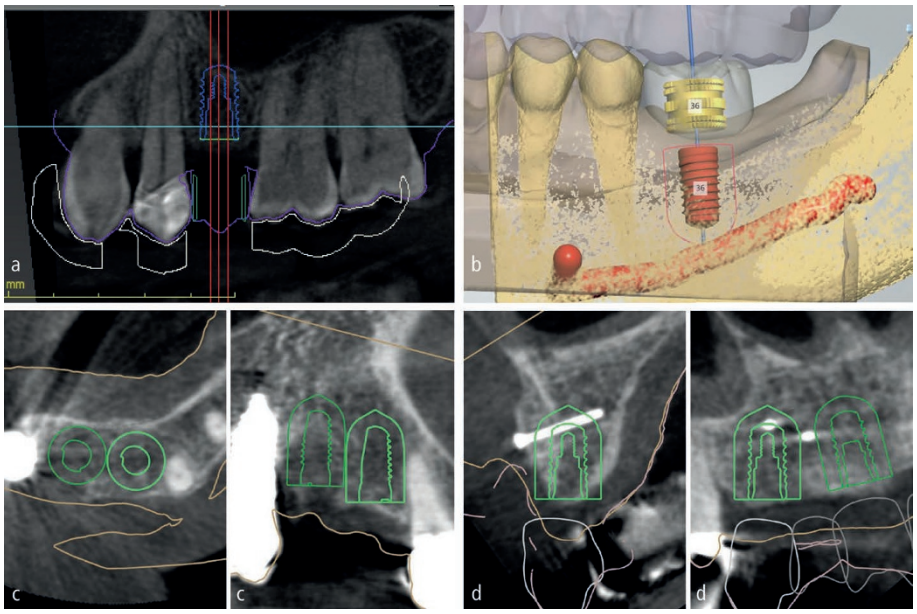

Fig. 4 a) Reduced vertical bone supply constituting an indication for internal sinus floor elevation (coDiagnostiX; Dental Wings); b) Below minimum distance from previously marked inferior alveolar nerve, where the software has marked the implant in red (ImplantStudio; 3Shape); c) Restricted horizontal space (ImplantStudio; 3Shape); d) Situation after bone augmentation (ImplantStudio; 3Shape)

The colour-coded distance image (Fig. 1a) and cross-sections of the superimposed data sets (Figs 1c and d) can be employed to assess the quality of the registration. If there are doubts about the reliability of the superimposition, error analysis and correction is indispensable to avoid adverse events. While an inadequately fitting surgical template is a considerable nuisance intraoperatively as it forces the surgeon to deviate from the planned surgical protocol, an incorrectly positioned implant can have dramatic consequences for adjacent anatomical structures.

Prosthetic pre-planning and implant planning

A scanned or directly digitally produced wax-up is imported into the planning software or generated there. This first virtual prosthetic planning covers both functional and aesthetic aspects and helps to optimally align the implant position with the prevailing anatomical conditions (Figs 2 and 3) or, in some cases, forces the prosthetic planning to be reconsidered. On successful registration, important anatomical structures such as the inferior alveolar nerve can be marked and subsequently protected (Fig. 2). The inferior alveolar nerve is the nerve most frequently injured during oral surgery procedures, therefore a safety distance of at least 1.5 mm should be provided for in the planning process.[14,15] Bony undercuts can also be easily identified which helps to avoid the complications associated with perforating the lingual compacta.

The planning software usually already features a database of common implants or allows such data to be imported. The information inherent in the existing bone situation can be used to select a suitable implant, taking into account the anatomical situation and the planned prosthetic restoration (Fig. 4) as well as the specific indications for each implant as approved by its manufacturer. In addition, a potential need for augmentation procedures can be identified at this point and prepared for as needed, after obtaining the patient's informed consent. Further aspects such as the eventual axis of the screw access channel, the vertical position of the implant shoulder in relation to the adjacent teeth or the thickness of the soft tissue can be accommodated at this planning stage.

If the implant planning was not performed by the surgeon in person, he or she must carefully check and formally approve it before the surgical template is fabricated.[16] Responsibility for the planning and its consequences for the clinical outcome rests exclusively with the surgeon.

Designing the surgical template

Once the future implant positions have been defined, they are translated into the design of the surgical template. It is possible to perform an either partially guided approach, where only the pilot drill is template-guided, or a fully guided procedure, where special guide sleeves adapted to the selected implant system are incorporated into the surgical template.

When the implant planning has been approved, the software provides a planning report specifying the type, size and position of the planned implants. The 'drilling protocol' provides the surgeon with the relevant technical information on the correct use of the system-specific surgical instruments (Fig. 5a).

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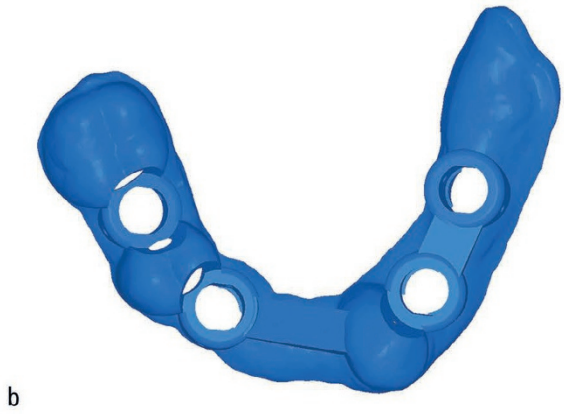
a

Implant position	Implant Art. No.	Implant	Sleeve height	Sleeve position	Basic implant bed preparation: Milling cutter	Basic implant bed preparation: Guided drill	Basic implant bed preparation: Cylinder of drill handle
11	021.4312	BL, Ø 4.1 mm RC, SLActive® 12 mm, Roxolid®, Loxim®	5 mm	H6	Ø 3,50 mm	Long 24 mm	+1 mm



b

c

Fig. 5 a) Excerpts from the drilling protocol (ImplantStudio; 3Shape) specifying the correct surgical procedure; b) the construction data set for a surgical template; c) and the additively manufactured surgical templates with supporting structures

Fabricating the surgical template

Once the design process has been completed, the data set can be exported as an STL file (Fig. 5b) and converted directly into the physical surgical template by means of additive or subtractive CAM procedures (Figs 5c and 6). Methods frequently used for this purpose include 3D printing or rapid prototyping technologies, especially stereolithography (SLA), digital light processing (DLP), or selective laser sintering (SLS). Integrating the guide sleeves is a manual process, as is the removal of holding or support structures and the finish of the template.

Implant surgery

At the time of implant surgery, the correct position of the surgical template in the mouth is verified, *inter alia*, by means of special verification windows (Fig. 7a). Exact implementation of the planned implant positions is only ensured if the surgical template fits exactly and securely. First, a flap has to be reflected to access the surface of the bone. When a flapless approach is performed, the tissue is punched.

This is followed by guided preparation of the implant site according to a standardised drilling protocol defined by the implant system used (Fig. 7). Inspections can be carried out at any time of the procedure, provided the surgical template has not been secured with bone pins. Care must be taken during the actual drilling to ensure sufficient irrigation, which may be made more difficult by the presence of the surgical template.[17–19] Once the implant has been inserted, depending on the healing mode, sutures are placed or a healing abutment or an immediate restoration is inserted.

Discussion

Digital implant planning, including prosthetic driven backward planning and guided implant surgery, offer a variety of interesting benefits. To recognise and avoid pitfalls, knowledge of the parameters affecting the outcome is necessary. These include the quality of the three-dimensional data, the precision of registration and a reasonable position of the implant defined during the planning stage. In addition, the manufacturing precision of the surgical template, the surgical protocol, and the knowledge and experience of the planning team – as well as the skills and circumspectness of the surgeon – are also important. The cumulative error resulting from all steps of the process, from data collection to surgical implementation, defines the overall accuracy of the procedure.[20] Here, the factors, which are most decisive for the overall reliability, shall be discussed and assessed in greater detail.

Factors influencing the accuracy of data acquisition and processing

Achieving the best possible registration of DICOM and STL data sets requires high-quality basic data. The clinical accuracy of CBCT scans is limited by artefacts, the field of view, voxel size, contrast resolution, as well as patient movements.[21–24] A certain influence on data quality might also be attributed to the CBCT device,[25] which is why only sophisticated systems should be used. Movement artefacts can often be avoided by adhering to the correct radiographic procedure, whereas scattering artefacts caused by highly radiopaque restorations can prevent a reliable registration in some cases. Fluegge *et al.* demonstrated that an increasing number of restorations had a significant negative influence on the quality of data registration.[13] In cases presenting severe restoration-associated artefacts the use of a scan prosthesis or radiographic template can be recommended. This technique is synonymous with placing the structures to be superimposed at an adequate distance to interfering materials but is inevitably resulting in a complication of the procedure.

To subsequently allow for the correct registration with the STL data, the field of view, which is the anatomical section acquired by the CBCT, must be placed precisely and of adequate size to capture enough superimposable data.

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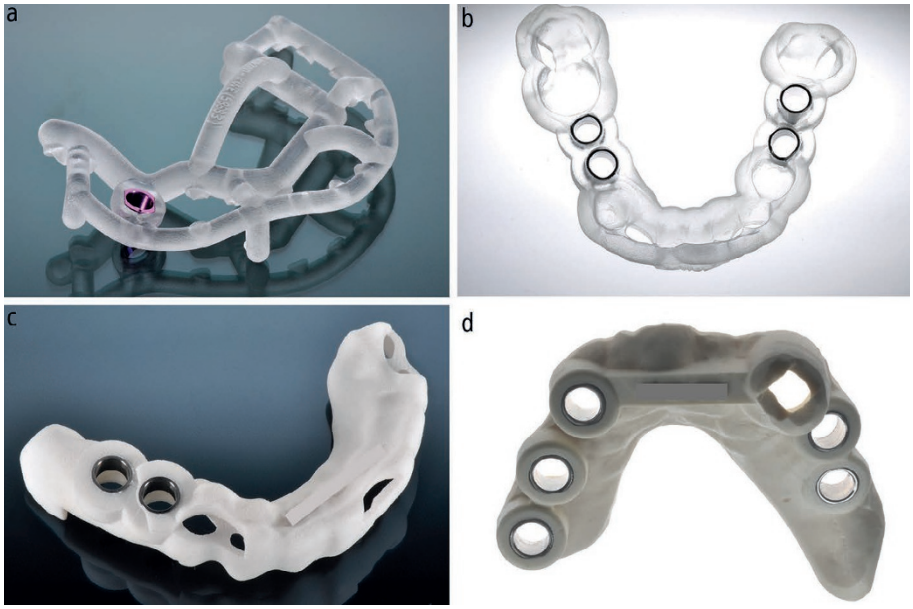

Fig. 6 a) Various surgical templates created by means of the polyjet technique (Smop; Swissmeda); b) the DLP technique (digital light processing; SHERAdigital); c) and SLS technique (selective laser sintering; EOS); d) as well as a subtractively manufactured (milled) surgical template

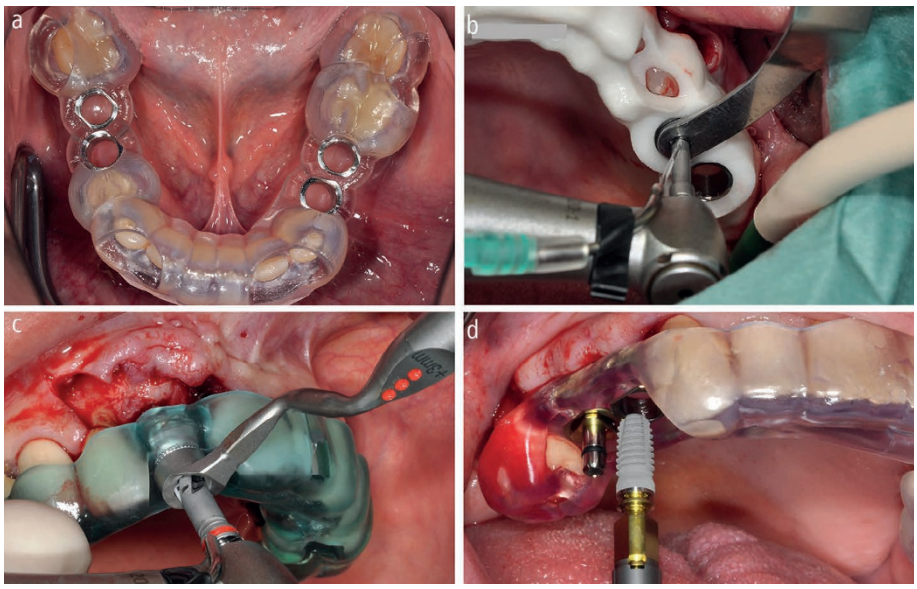

Fig. 7 Surgical protocol for guided implantation (different patients): a) Optimal seating of the surgical template; b) guided pilot drilling (Zimmer Guided Surgery); c) guided implant site preparation (Straumann Guided Surgery); d) and guided implant placement (Camlog Guide System)

Fluegge *et al.* also showed that manual image segmentation, in other words digitally separating the different tissues in the CBCT, produced more accurate results in terms of registration than automated segmentation and that the result was highly influenced by the operator. They concluded that even before virtual implant planning and template fabrication the cumulative errors can produce unacceptable deviations.[13]

STL data can be collected by indirect digitalisation of the impression or cast, as well as directly by intraoral scanners. Modern intraoral scanners are considered to be as accurate as conventional impressions[26] and extraoral scanning regarding small areas.[27] When considering full-arch scans the situation is ambiguous.[28–30] Therefore, Ahlholm *et al.* recommend the conventional impression technique for full-arch impressions for fixed prosthodontics in a recent review.[31] Ender *et al.* stated that deviations larger than 100 microns across the complete arch may lead to inadequate fitting of larger restorations.[29] It may be assumed, however, that maximum accuracy is more indispensable in fixed prosthodontics than in surgical template planning. Thus intraoral scanning has successfully been implemented in this field of application.[13,32]

Ritter *et al.* calculated mean distances after registration of DICOM and STL surface data to be between 0.03 (±0.33) and 0.14 (±0.18) mm and considered the results to be sufficiently accurate for digital implant planning.[33]

Accuracy of the manufacturing process of the surgical template

The manufacturing accuracy, that is, the precision of the conversion of the CAD data into a physical template, primarily depends on the type of CAM-technology deployed. Van Steenberghe *et al.* found the typical accuracy for additive fabrication to be between 0.1 to 0.2 mm.[34] In general, subtractive milling, which is more laborious and expensive, seems superior in terms of production accuracy of surgical templates compared with rapid prototyping technologies.[35] Today, the most common method of surgical template production is represented by photopolymerisation, more precisely SLA and DLP technologies. Using these technologies, layer thickness ranging from about 50 to 100 microns or even less is possible.[36,37]

In this context, Sommacal *et al.* recently found significantly lower manufacturing accuracy using a fused filament fabrication (FFF) consumer 3D printer compared to a professional DLP printer. They concluded that not any additive manufacturing device can meet the requirements for surgical template production.[38]

Impact of the surgical protocol and the surgeon on the accuracy of the result

In terms of the surgical procedure, possible sources of error are manifold. First, the selection of adequate surgical equipment is important, as the guided implant surgery system itself may have a noticeable impact on the surgical outcome.[39,40]

One system inherent factor is the gap between implant drill and guiding sleeve

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which can effect angular deviations.[41] Valente *et al.* estimated the resulting approximate lateral deviation to be 1 mm under certain conditions.[42] Schneider *et al.* proved a small gap, a high guiding sleeve and a short drill to be beneficial in terms of overall accuracy.[43] As the vertical positioning of the guide sleeves is often variable, it is thus important to note that the increasing distance between the guide sleeve and the bone potentially reduces accuracy. Furthermore, with guide sleeves positioned very high above the mucosa, a correct insertion of the drill into the sleeve can be difficult, especially in patients with limited mouth opening.

If, on the other hand, the guide sleeve is positioned very low, the surgical template may interfere with the oral mucosa, which makes it impossible to proceed with the selected protocol if a flapless technique is planned.

Concerning the surgical protocol, Bencharit *et al.* just recently found that the fully guided protocol is more accurate in terms of implant position than partly guided performed surgery.[44] Two current reviews came to the same conclusion[45,46] and it may be deduced that, whenever the highest level of accuracy is demanded, the fully guided protocol should be preferred.

Surgical templates can be supported either by teeth, bone, or mucosa. It seems plausible that a sound support by teeth provides most predictability and thus accuracy.[40,47–49] Ozan *et al.* found a mean angular deviation of 2.91° in tooth-supported placed implants, 4.51° in implants placed with mucosa-supported templates, and 4.63° in implants placed with bone-supported templates. The mean coronal and apical deviations displayed a similar picture.[48] Also the use of fixation pins can help achieve greater precision,[40,49,50] especially in non-tooth-supported templates. Anyway, adequate positioning of the template is a fundamental prerequisite for success.

As tooth-supported templates provide most reliability, it seems plausible that the number and location of the remaining teeth has a certain impact too. For instance, it was shown that guided implant placement in single tooth gaps shows noticeably less deviation than in distal gaps or partially edentulous situations.[51–53] With regard to the arch, it appears that the maxilla seems slightly more prone to deviations than the mandible which might be explained by different bone densities and the anatomy.[48,51–53]

With respect to the impact of the surgeon's experience, it can be seen that experienced surgeons tend to achieve more accurate results performing guided surgery, though practitioners of any experience level can greatly benefit from the procedure.[54,55] Cushen *et al.* revealed that experienced surgeons performed significantly better in terms of the alignment of planned and achieved implant position using bone-supported templates.[56] Van de Velde *et al.* found no differences when comparing implants placed flaplessly without using a surgical template by surgeons with different experience levels. However, they observed a notable level of imprecision and therefore recommended the use of a surgical template.[57] Moraschini *et al.* confirmed that guided flapless surgery demonstrates high survival rates, but also found that there is a noteworthy learning curve to attain a desirable treatment outcome.[58] When using a surgical template, both approaches (flapless/open flap) do not differ very explicitly in terms of accuracy.[52,53]

Finally, all human mistakes, like inaccurate positioning of the guide or falsely using equipment, contribute to overall inaccuracy.[42] Thus they are to be avoided, although their ultimate impact is hard to quantify.

Overall accuracy of guided implant surgery

Van Assche *et al.* found mean deviations of 1.09 mm at the entry point, 1.28 mm at the apex and 3.9° in angulation in their meta-analysis in 2012.[40] A systematic review conducted by Tahmaseb *et al.* in 2014 revealed a mean deviation of 0.93 mm at the entry point and 1.29 mm at the apex. The overall mean deviation in angulation was 3.53°. This review included *in vitro* studies using models or human cadavers but also *in vivo* patient studies.[49] A recent review article of Bover-Ramos *et al.* looking at, *inter alia*, 2.244 implants placed *in vivo* showed a mean horizontal deviation of 1.4 mm at the implant apex and a mean axial deviation of 3.98 degrees. *In vitro* studies included in the same publication demonstrated more accurate results, presenting horizontal deviation of 0.85 mm and a mean axial deviation of 2.39.[45] This seems plausible since the clinical situation is limited in terms of confined space, less visual control and patient movement, as well as the presence of blood and saliva.[20]

However, the guided procedure seems to be superior to the classical free-hand protocol with regard to overall deviations between planned and placed implant positions.[49,59,60] Vermeulen *et al.* observed axial deviations of 7.63 degrees for the free-hand protocol and 2.19 degrees for the guided implantation in an *in vitro* study. The horizontal deviations in the area of the implant shoulder were 1.27 mm (freehand) and 0.42 mm (guided) and the vertical offset of the implant position at the implant apex averaged 0.73 mm (freehand) and 0.54 mm (navigated), respectively.[60] This fact should be taken into account when examining the deviation data stated above. The observed implant survival rates are comparable for both surgical protocols.[61]

It could also be demonstrated that CAD/CAM-generated templates showed advanced accuracy when compared to conventional surgical guides[10,51,62] which can be attributed, to a certain degree, to extensive three-dimensional implant pre-planning.

Applying the procedure described above, the multiple aspects of information available even before embarking on the physical procedure are a considerable benefit of digital implant planning and guided implant surgery. The surgical procedure can be accordingly adapted beforehand and the patient can be given more detailed and accurate advance information. In addition, prosthetic alternatives can be discussed and defined in more detail at an early stage.

Accurate knowledge about the quality, quantity and position of the bone assists in the planning of any augmentative measures that might be needed, or might support the decision to dispense with them if no relevant adverse effect on the outcome is expected.[63]

A sensible combination of anatomical information and virtual prosthetic planning enables a considerably more reliable process and allows for positioning of the implant according to the prosthetic needs. This provides a high degree of predictability and can positively influence the prosthetic outcome in terms of function, aesthetics and phonetics.[61]

However, for all the advantages, it must not be assumed that guided implant surgery is less demanding than the conventional procedure.[61] Technology cannot replace prosthetic expertise and surgical skills, but can help make it more safe and efficient to apply to existing knowledge.

Digital implant planning for guided implantology is a possible field of application for three-dimensional radiological diagnostics. Possible indications for guided implantology,

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in turn, include minimally invasive techniques in high-risk patients, difficult prosthetic objectives or special prosthetic concepts such as immediate restoration. Limitations include inadequate mouth opening and certain pre-existing conditions that prevent a three-dimensional diagnosis and guided implant surgery.[64]

The European Association for Osseointegration ran a workshop on the possible indications of CBCT-scanning[65] and a follow up-congress in 2011.[66] The consensus group recommended three-dimensional imaging whenever two dimensional imaging fails to provide sufficient data, particularly in association with extensive bone augmentation, guided surgery and some special surgical techniques.[66] As the members of the International Congress of Oral Implantologists noted in their consensus report of 2012, it is extremely hard to tell in advance which patient would not benefit from having three-dimensional information before acquiring the same.[67] Due to a lack of solid clinical scientific background, Colombo *et al.* demand greater efforts to provide guided implant surgery with more scientific proof and to asses which situations profit most from guided implant surgery.[68] Basically, difficult or unclear anatomical situations benefit the most from guided implantology, provided that the planner has interpreted the data correctly.

The CBCT-related radiation exposure can vary between 10 µSv and 1000 µSv, depending on the device, the settings, and the size of the FOV.[69] Three-dimensional imaging procedures must therefore always be subject to a cost-benefit analysis for the individual case as benefits to the patients ought to outweigh the potential risks.[67]

There is no obligation to apply three-dimensional imaging, digital implant planning or guided implant surgery in any case, especially since radiation exposure opposes comprehensive data collection, but it should be taken into consideration at least.

A detriment of digital implant planning and guided implantation is still the high cost of the procedure, both for the three-dimensional imaging itself and for the planning and fabrication of the surgical templates. In addition, the technical effort required is considerable, which, besides the necessary hardware and software, demands highly specialised expertise. However, the added preoperative time needed is made up for by the increased efficiency of the subsequent surgical procedure and higher predictability of the overall treatment outcome.

Conclusion

Digital implant planning and guided implant surgery offer many advantages in terms of optimised surgical and prosthetic treatment preparation and their predictable and successful implementation. In terms of overall accuracy, guided implant surgery seems to be superior to the conventional approach. Disadvantages of this method are its higher cost and the need for special expertise.

Experienced and responsible surgeons as well as skilled dental technicians who are aware of the possibilities and limits of this technology are needed to avoid complications and to make reasonable use of the undeniable advantages, for the benefit of the patient.

1. Beuer F, Schweiger J, Edelhoff D. Digital dentistry: an overview of recent developments for CAD/CAM generated restorations. *Br Dent J* 2008; **204:** 505–511.
2. Miyazaki T, Hotta Y, Kunii J, Kuriyama S, Tamaki Y. A review of dental CAD/CAM: current status and future perspectives from 20 years of experience. *Dent Mater J* 2009; **28:** 44–56.
3. van Noort R. The future of dental devices is digital. *Dent Mater* 2012; **28:** 3–12.
4. Beuer F, Schweiger J, Stimmelmayr M, Edelhoff D. CAD/CAM-fabricated high-performance polymers in implant dentistry. *Implantologie* 2010; **18:** 397–404.
5. Tinschert J, Natt G, Hassenpflug S, Spiekermann H. Status of Current CAD/CAM Technology in Dental Medicine. *Int J Comput Dent* 2004; **7:** 25–45.
6. Tran D, Nesbit M, Petridis H. Survey of UK dentists regarding the use of CAD/CAM technology. *Br Dent J* 2016; **221:** 639–644.
7. Scherer M D. Presurgical implant-site assessment and restoratively driven digital planning. *Dent Clin North Am* 2014; **58:** 561–595.
8. Ganz S D. Cone beam computed tomography-assisted treatment planning concepts. *Dent Clin North Am* 2011; **55:** 515–536, viii.
9. Nickenig H J, Eitner S. Reliability of implant placement after virtual planning of implant positions using cone beam CT data and surgical (guide) templates. *J Craniomaxillofac Surg* 2007; **35:** 207–211.
10. Sarment D P, Sukovic P, Clinthorne N. Accuracy of implant placement with a stereolithographic surgical guide. *Int J Oral Maxillofac Implants* 2003; **18:** 571–577.
11. Flugge T V, Nelson K, Schmelzeisen R, Metzger M C. Three-dimensional plotting and printing of an implant drilling guide: simplifying guided implant surgery. *J Oral Maxillofac Surg* 2013; **71:** 1340–1346.
12. Lanis A, Alvarez Del Canto O. The combination of digital surface scanners and cone beam computed tomography technology for guided implant surgery using 3Shape implant studio software: a case history report. *Int J Prosthodont* 2015; **28:** 169–178.
13. Flugge T, Derksen W, Te Poel J, Hassan B, Nelson K, Wismeijer D. Registration of cone beam computed tomography data and intraoral surface scans – A prerequisite for guided implant surgery with CAD/CAM drilling guides. *Clin Oral Implants Res* 2017; **28:** 1113–1118.
14. Sammartino G, Marenzi G, Citarella R, Ciccarelli R, Wang H L. Analysis of the occlusal stress transmitted to the inferior alveolar nerve by an osseointegrated threaded fixture. *J Periodontol* 2008; **79:** 1735–1744.
15. Tay A B, Zuniga J R. Clinical characteristics of trigeminal nerve injury referrals to a university centre. *Int J Oral Maxillofac Surg* 2007; **36:** 922–927.
16. Vercruyssen M, Laleman I, Jacobs R, Quirynen M. Computer-supported implant planning and guided surgery: a narrative review. *Clin Oral Implants Res* 2015; **26 Suppl 11:** 69–76.
17. Misir A F, Sumer M, Yenisey M, Ergioglu E. Effect of surgical drill guide on heat generated from implant drilling. *J Oral Maxillofac Surg* 2009; **67:** 2663–2668.
18. dos Santos P L, Queiroz T P, Margonar R *et al.* Evaluation of bone heating, drill deformation, and drill roughness after implant osteotomy: guided surgery and classic drilling procedure. *Int J Oral Maxillofac Implants* 2014; **29:** 51–58.
19. Sannino G, Gherlone E F. Thermal Changes During Guided Flapless Implant Site Preparation: A Comparative Study. *Int J Oral Maxillofac Implants* 2018; **33:** 671–677.
20. Jung R E, Schneider D, Ganeles J *et al.* Computer technology applications in surgical implant dentistry: a systematic review. *Int J Oral Maxillofac Implants* 2009; **24 Suppl:** 92–109.
21. Hassan B, Couto Souza P, Jacobs R, de Azambuja Berti S, van der Stelt P. Influence of scanning and reconstruction parameters on quality of three-dimensional surface models of the dental arches from cone beam computed tomography. *Clin Oral Investig* 2010; **14:** 303–310.
22. Spin-Neto R, Gotfredsen E, Wenzel A. Impact of voxel size variation on CBCT-based diagnostic outcome in dentistry: a systematic review. *J Digit Imaging* 2013; **26:** 813–820.
23. Widmann G, Bale R J. Accuracy in computer-aided implant surgerya review. *Int J Oral Maxillofac Implants* 2006; **21:** 305–313.
24. Pettersson A, Komiyama A, Hultin M, Nasstrom K, Klinge B. Accuracy of virtually planned and template guided implant surgery on edentate patients. *Clin Implant Dent Relat Res* 2012; **14:** 527–537.
25. Dreiseidler T, Tandon D, Kreppel M *et al.* CBCT device dependency on the transfer accuracy from computer-aided implantology procedures. *Clin Oral Implants Res* 2012; **23:** 1089–1097.
26. Guth J F, Keul C, Stimmelmayr M, Beuer F, Edelhoff D. Accuracy of digital models obtained by direct and indirect data capturing. *Clin Oral Investig* 2013; **17:** 1201–1208.
27. Keul C, Stawarczyk B, Erdelt K J, Beuer F, Edelhoff D, Guth J F. Fit of 4unit FDPs made of zirconia and CoCr-alloy after chairside and labside digitalizationa laboratory study. *Dent Mater* 2014; **30:** 400–407.
28. Ender A, Mehl A. Full arch scans: conventional *versus* digital impressionsan in-vitro study. *Int J Comput Dent* 2011; **14:** 11–21.
29. Ender A, Attin T, Mehl A. *In vivo* precision of conventional and digital methods of obtaining complete-arch dental impressions. *J Prosthet Dent* 2016; **115:** 313–320.
30. Patzelt S B M, Emmanouilidi A, Stampf S, Strub J R, Att W. Accuracy of full-arch scans using intraoral scanners. *Clin Oral Invest* 2014; **18:** 1687–1694.
31. Ahlholm P, Sipila K, Vallittu P, Jakonen M, Kotiranta U. Digital Versus Conventional Impressions in Fixed Prosthodontics: A Review. *J Prosthodont* 2018; **27:** 35–41.
32. Lee C Y, Ganz S D, Wong N, Suzuki J B. Use of cone beam computed tomography and a laser intraoral scanner in virtual dental implant surgery: part 1. *Implant dent* 2012; **21:** 265–271.
33. Ritter L, Reiz S D, Rothamel D *et al.* Registration accuracy of three-dimensional surface and cone beam computed tomography data for virtual implant planning. *Clin Oral Implants Res* 2012; **23:** 447–452.
34. van Steenberghe D, Naert I, Andersson M, Brajnovic I, Van Cleynenbreugel J, Suetens P. A custom template and definitive prosthesis allowing immediate implant loading in the maxilla: a clinical report. *Int J Oral Maxillofac Implants* 2002; **17:** 663–670.
35. Park JM, Yi TK, Koak JY, Kim SK, Park EJ, Heo SJ. Comparison of five-axis milling and rapid prototyping for implant surgical templates. The International journal of oral & maxillofacial implants 2014; 29: 374-83
36. Ligon S C, Liska R, Stampfl J, Gurr M, Mulhaupt R. Polymers for 3D Printing and Customized Additive Manufacturing. *Chem Rev* 2017; **117:** 10212–10290.
37. Stansbury J W, Idacavage M J. 3D printing with polymers: Challenges among expanding options and opportunities. *Dent Mater* 2016; **32:** 54–64.
38. Sommacal B, Savic M, Filippi A, Kuhl S, Thieringer F M. Evaluation of Two 3D Printers for Guided Implant Surgery. *Int J Oral Maxillofac Implants* 2018; **33:** 743–746.
39. Laederach V, Mukaddam K, Payer M, Filippi A, Kuhl S. Deviations of different systems for guided implant surgery. *Clin Oral Implants Res* 2017; **28:** 1147–1151.

Official journal of the British Dental Association.

40. Van Assche N, Vercruyssen M, Coucke W, Teughels W, Jacobs R, Quirynen M. Accuracy of computer-aided implant placement. *Clin Oral Implants Res* 2012; **23 Suppl 6:** 112–123.
41. Koop R, Vercruyssen M, Vermeulen K, Quirynen M. Tolerance within the sleeve inserts of different surgical guides for guided implant surgery. *Clin Oral Implants Res* 2013; **24:** 630–634.
42. Valente F, Schiroli G, Sbrenna A. Accuracy of computer-aided oral implant surgery: a clinical and radiographic study. *Int J Oral Maxillofac Implants* 2009; **24:** 234–242.
43. Schneider D, Schober F, Grohmann P, Hammerle C H, Jung R E. In-vitro evaluation of the tolerance of surgical instruments in templates for computer-assisted guided implantology produced by 3D printing. *Clin Oral Implants Res* 2015; **26:** 320–325.
44. Bencharit S, Staffen A, Yeung M, Whitley D, 3rd, Laskin D M, Deeb G R. In Vivo Tooth-Supported Implant Surgical Guides Fabricated With Desktop Stereolithographic Printers: Fully Guided Surgery Is More Accurate Than Partially Guided Surgery. *J Oral Maxillofac Surg* 2018; **76:** 1431–1439.
45. Bover-Ramos F, Vina-Almunia J, Cervera-Ballester J, Penarrocha-Diago M, Garcia-Mira B. Accuracy of Implant Placement with Computer-Guided Surgery: A Systematic Review and Meta-Analysis Comparing Cadaver, Clinical, and In Vitro Studies. *Int J Oral Maxillofac Implants* 2017; **33:** 101–115.
46. Younes F, Cosyn J, De Bruyckere T, Cleymaet R, Bouckaert E, Eghbali A. A randomized controlled study on the accuracy of free-handed, pilot-drill guided and fully guided implant surgery in partially edentulous patients. *J Clin Periodontol* 2018; **45:** 721–732.
47. Ozan O, Turkyilmaz I, Yilmaz B. A preliminary report of patients treated with early loaded implants using computerized tomography-guided surgical stents: flapless *versus* conventional flapped surgery. *J Oral Rehabil* 2007; **34:** 835–840.
48. Ozan O, Turkyilmaz I, Ersoy A E, McGlumphy E A, Rosenstiel S F. Clinical accuracy of 3 different types of computed tomography-derived stereolithographic surgical guides in implant placement. *J Oral Maxillofac Surg* 2009; **67:** 394–401.
49. Tahmaseb A, Wismeijer D, Coucke W, Derksen W. Computer technology applications in surgical implant dentistry: a systematic review. *Int J Oral Maxillofac Implants* 2014; **29 Suppl:** 25–42.
50. Kauffmann P, Rau A, Engelke W *et al.* Accuracy of Navigation-Guided Dental Implant Placement with Screw Versus Hand Template Fixation in the Edentulous Mandible. *Int J Oral Maxillofac Implants* 2018; **33:** 383–388.
51. Farley N E, Kennedy K, McGlumphy E A, Clelland N L. Split-mouth comparison of the accuracy of computer-generated and conventional surgical guides. *Int J Oral Maxillofac Implants* 2013; **28:** 563–572.
52. Ersoy A E, Turkyilmaz I, Ozan O, McGlumphy E A. Reliability of implant placement with stereolithographic surgical guides generated from computed tomography: clinical data from 94 implants. *J Periodontol* 2008; **79:** 1339–1345.
53. Behneke A, Burwinkel M, Behneke N. Factors influencing transfer accuracy of cone beam CTderived template-based implant placement. *Clin Oral Implants Res* 2012; **23:** 416–423.
54. Hinckfuss S, Conrad H J, Lin L, Lunos S, Seong W J. Effect of surgical guide design and surgeon's experience on the accuracy of implant placement. *J Oral Implantol* 2012; **38:** 311–323.
55. Fernandez-Gil A, Gil H S, Velasco M G, Moreno Vazquez J C. An In Vitro Model to Evaluate the Accuracy of Guided Implant Placement Based on the Surgeon's Experience. *Int J Oral Maxillofac Implants* 2017; **32:** 151–154.
56. Cushen S E, Turkyilmaz I. Impact of operator experience on the accuracy of implant placement with stereolithographic surgical templates: an *in vitro* study. *J Prosthet Dent* 2013; **109:** 248–254.
57. Van de Velde T, Glor F, De Bruyn H. A model study on flapless implant placement by clinicians with a different experience level in implant surgery. *Clin Oral Implants Res* 2008; **19:** 66–72.
58. Moraschini V, Velloso G, Luz D, Barboza E P. Implant survival rates, marginal bone level changes, and complications in full-mouth rehabilitation with flapless computer-guided surgery: a systematic review and meta-analysis. *Int J Oral Maxillofac Surg* 2015; **44:** 892–901.
59. Arisan V, Karabuda C Z, Mumcu E, Ozdemir T. Implant positioning errors in freehand and computer-aided placement methods: a single-blind clinical comparative study. *Int J Oral Maxillofac Implants* 2013; **28:** 190–204.
60. Vermeulen J. The Accuracy of Implant Placement by Experienced Surgeons: Guided vs Freehand Approach in a Simulated Plastic Model. *Int J Oral Maxillofac Implants* 2017; **32:** 617–624.
61. Hultin M, Svensson K G, Trulsson M. Clinical advantages of computer-guided implant placement: a systematic review. *Clin Oral Implants Res* 2012; **23 Suppl 6:** 124–135.
62. Nokar S, Moslehifard E, Bahman T, Bayanzadeh M, Nasirpouri F, Nokar A. Accuracy of implant placement using a CAD/CAM surgical guide: an *in vitro* study. *Int J Oral Maxillofac Implants* 2011; **26:** 520–526.
63. Fortin T, Isidori M, Bouchet H. Placement of posterior maxillary implants in partially edentulous patients with severe bone deficiency using CAD/CAM guidance to avoid sinus grafting: a clinical report of procedure. *Int J Oral Maxillofac Implants* 2009; **24:** 96–102.
64. S2-kLeitlinie. Indications for implantological 3D X-ray diagnostics and navigational implantology [Indikationen zur implantologischen 3D-Ro¨ntgendiagnostik und navigationsgestu¨tzten implantologie]. AWMF-Registernummer: 083–011 aktueller Stand: 12/2011.
65. Harris D, Buser D, Dula K *et al.* E A O. guidelines fo the use of diagnostic imaging in implant dentistry. A consensus workshop organized by the European Association for Osseointegration in Trinity College Dublin. *Clin Oral Implants Res* 2002; **13:** 566–570.
66. Harris D, Horner K, Grondahl K *et al.* E A O. guidelines for the use of diagnostic imaging in implant dentistry 2011. A consensus workshop organized by the European Association for Osseointegration at the Medical University of Warsaw. *Clin Oral Implants Res* 2012; **23:** 1243–1253.
67. Benavides E, Rios H F, Ganz S D *et al.* Use of cone beam computed tomography in implant dentistry: the International Congress of Oral Implantologists consensus report. *Implant Dent* 2012; **21:** 78–86.
68. Colombo M, Mangano C, Mijiritsky E, Krebs M, Hauschild U, Fortin T. Clinical applications and effectiveness of guided implant surgery: a critical review based on randomized controlled trials. *BMC Oral Health* 2017; **17:** 150.
69. Jacobs R, Quirynen M. Dental cone beam computed tomography: justification for use in planning oral implant placement. *Periodontol 2000* 2014; **66:** 203–213.

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