DOI: 10.1111/prd.12411

Periodontology 2000 WILEY

REVIEW ARTICLE

Reducing errors in guided implant surgery to optimize treatment outcomes

Tali Chackartchi[1] | Georgios E. Romanos[2] | Laszlo Parkanyi[3] | Frank Schwarz[4] | Anton Sculean[5]

[1]Department of Periodontology, Hadassah Medical Center, Faculty of Dental Medicine, Hebrew University of Jerusalem, Jerusalem, Israel
[2]Department of Periodontology, School of Dental Medicine, Stony Brook University, Stony Brook, NY, USA
[3]Department of Periodontology, Faculty of Dentistry, University of Szeged, Szeged, Hungary
[4]Department of Oral Surgery and Implantology, Carolinum, Johann Wolfgang Goethe-University Frankfurt, Frankfurt, Germany
[5]Department of Periodontology, School of Dental Medicine, University of Bern, Bern, Switzerland

Correspondence
Tali Chackartchi, Department of Periodontology, Hadassah Medical Center, Faculty of Dental Medicine, Hebrew University of Jerusalem, Jerusalem, Israel.
Email: tali@perioexpert.co.il

1 | INTRODUCTION

1.1 | Defining success in contemporary implant dentistry

Implant survival rates, per se, are no longer accepted as an outcome assessment of the clinical efficacy of current implant-prosthetic rehabilitations. The current criteria to define success are more comprehensive and include reporting the success of the implant/prosthetic complex rather than just implant survival, together with the desired long-term mechanical stability and tissue health.[1-4] Prosthetically driven implant surgery has become a standard of care to improve short and long-term treatment success. Precise implant positioning has obvious advantages, such as favorable esthetic and prosthetic outcomes, long-term stability of peri-implant hard and soft tissues as a result of easier oral hygiene, and the potential to ensure optimal occlusal contacts and implant loading.[5-7] A correct three-dimensional positioning of implants enables the final prostheses to be optimally designed. It enables fabrication of retrievable screw-retained superstructures, thereby avoiding nonretrievable cemented restorations,[8] reducing potential for both biological and mechanical complications.[9]

1.2 | The added value of using a guide in implant placement

During implant surgery, the dental surgeon is required to integrate his/her knowledge of the patient's anatomy with surgically related technical parameters. Several studies have shown that complications usually arise from poor application of knowledge and intraoperative distractions, rather than from a lack of experience or knowledge.[10-12] Additionally, failure to distinguish the position of bone volume during surgery and to place the implant in a correct three-dimensional position is a common error in implant dentistry.[11] In flapless free-hand surgery, these mistakes are compounded, since the true topography of the underlying available bone cannot be clearly seen. Clinical palpation alone is not advisable in complex cases because thick epithelium and thick mucosa may mask a narrow ridge (Figure 1). There is a risk of unexpected perforation of the bone that may lead to esthetic problems or even implant loss.[13] The potential risk for perforation during flapless freehand surgery was evaluated in a preclinical study on models. Frequently, perforations through the crest and on the crest occurred because clinicians were not able to fully utilize the morphology of the available bone as visualized on two-dimensional and even on three-dimensional radiographs, during the surgery.[14]

The use of data from cone-beam computed tomography scans has substantially improved the three-dimensional understanding of anatomical structures, and virtual planning of the ideal implant position. Various requirements, such as the desired inter-implant distance, implant depth and other aspects, have made virtual implant planning an important tool when aiming for optimal treatment success.[15,16] Adding images created by intra-oral scanning devices can contribute to the digital data gathered for treatment planning.[17] An addition of a digital set-up (wax-up) assists dental professionals to achieve a "top-down" planning (Figure 2) considering the future

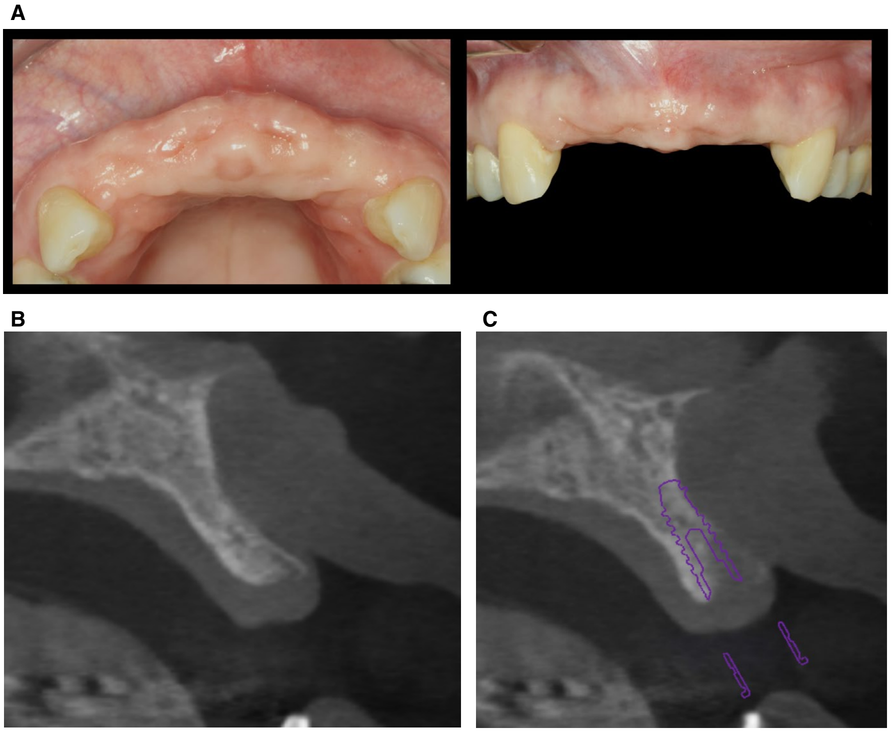

FIGURE 1 A, Clinical appearance of an edentulous ridge might be deceiving. This patient's thick mucosa was covering a narrow ridge. B, Bone imaging using cone-beam computed tomography preoperatively is mandatory to analyze the bone morphology correctly. C, Implant position simulation using planning software clarifies the need for bone augmentation

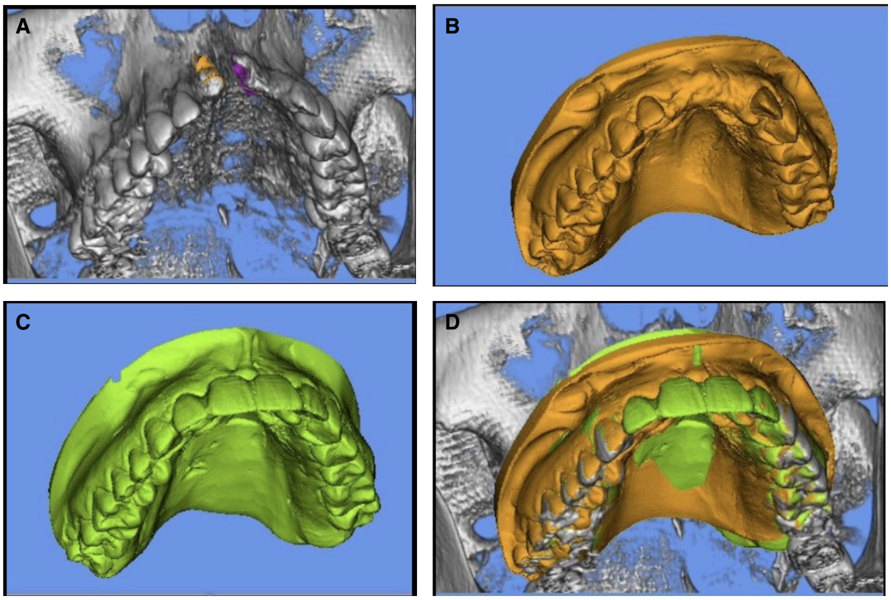

FIGURE 2 In order to be able to plan implant position "top down" (ie, considering the available bone, the proximity of important anatomical structures, and the ideal position of future restoration), a cone-beam computed tomography scan together with a digital variation of an impression (intraoral scanning or scanning of a cast model produced by an elastomeric impression) and a "wax-up" are made. The three layers of data are then superimposed on the software to create a digital file for planning

prosthetic restoration in relation to available tissues.[18-25] The addition of a wax-up in the digital data set is often omitted, which in turn may lead to exclusion of important data with the consequence of suboptimal implant planning. A computer-guided approach, supported by preplanning of implant position and inclination, according to the available bone, soft tissue, and future prosthesis, may improve accuracy of implant position and surgical treatment results.[26-28] To transform the digital treatment plan from the digital environment to the surgical field, a virtual template/guide can be designed. The virtual guide is then converted into a "real" resin template/guide using a 3D-printer or a milling machine (Figure 3).[29]

1.3 | Dynamic vs static guides

In general, two types of guided implant surgical protocols are described in the literature—static and dynamic guidance. The static approach refers to the use of a prefabricated surgical template, a physical instrument to guide the drills to the digitally preplanned position.[6] This protocol does not allow intra-operative modification of the implant position and is therefore referred to as "static."[26,30]

Dynamic navigation enables a "real-time" guidance of the drills during drilling. Implant position is dynamically illustrated directly on computed tomography data on a viewer. Drill location is illustrated

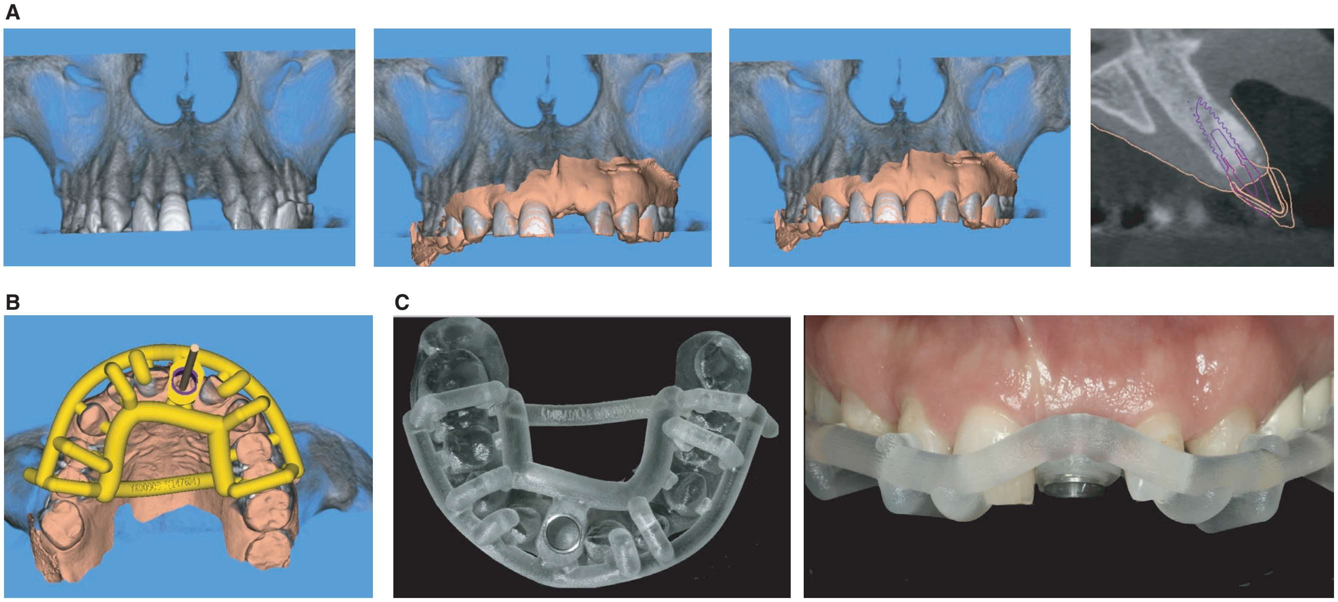

FIGURE 3 A, According to the superposition of the digital data, the implant position is virtually planned in software. B, In order to correctly transform the digital treatment plan from the digital environment to the surgical field, a digital template/guide is digitally designed (yellow structure). C, The virtual guide is then converted into a resin template/guide by using a 3D-printer, to be used during surgery in the patients' mouths

on the computed tomography image using an optical bur tracking system. Sensors attached both to the patient and the surgical handpiece transmit three-dimensional positional information to a camera or detector that allows the computer to calculate and immediately display the virtual position of the instruments relative to the image data.[30,31] Using dynamic navigation systems, the operator can change the implant position during surgery, without the need to restrict any instruments. The surgeon should note that the cone-beam computed tomography image is not a "real-time" image, but rather a pre-scan that serves as an "anatomical map" for the orientation of the hand instrument and the drills. To keep reliable orientation, a continuous calibration of the instruments on this static image of the bone is crucial.

Both types of guides, static and dynamic, show equal failure rates.[7] Hermann et al[15] concluded that static guided surgery, using a pre-made template, is associated with fewer errors than "real-time" navigation, whereas other authors[30] could not find statistically significant differences. Currently, the dynamic navigation systems remain expensive and complicated for the private practitioner, especially when compared with cost-efficient stereolithographic alternatives. Therefore, the static approach is used more frequently than the dynamic approach.[7]

2 | CALIBRATION AS A KEY FACTOR FOR A PREDICTABLE SURGICAL TREATMENT OUTCOME

The accuracy of a guided implant surgery system is defined as the deviation between the planned and placed position of the implant.[32] The accuracy of the entire procedure involves a quantitative evaluation of positional and angular discrepancies in three-dimensional coordinates.[33] The use of implant planning software has been established in preoperative planning and creation of individual surgical guides.[18,21,23,33-37] Nevertheless, variability has been reported in the accuracy of guided implant surgery because of errors originating from intrinsic and extrinsic sources.[32,38-40] Reducing such errors is very dependent upon calibration in both static and dynamic guidance.[41] Calibration refers to the verification that the virtual world matches the clinical arena. Calibration is required at two time points during the workflow. The first is the transformation of data from the clinical field to the digital platform, and the second point of calibration is the shift back from the digital planning to the physical environment of patients' mouths. Each transition carries a potential for errors that may influence the final position of the implant.

2.1 | Data transfer from the clinical field to the software (patient to software)

This is the process of data registration and superimposition of the registered information in layers in the software. Data registration includes impression taking (represented in STL files) and imaging (cone-beam computed tomography). This part of the process has potential for errors depending on the choice of impression materials, impression techniques, casting materials and techniques, choice of a computed tomography machine, and the methodology of computed tomography scanning. The accurate three-dimensional merging of cone-beam computed tomography and STL file images, produced by the digital scanning of the impression, is a prerequisite for planning the position of the implants.[42] Remaining teeth are generally used as compatible areas for matching all images.[42,43] When the number of remaining teeth is insufficient or teeth are missing (as in fully edentulous cases), the accuracy of image superposition decreases dramatically.

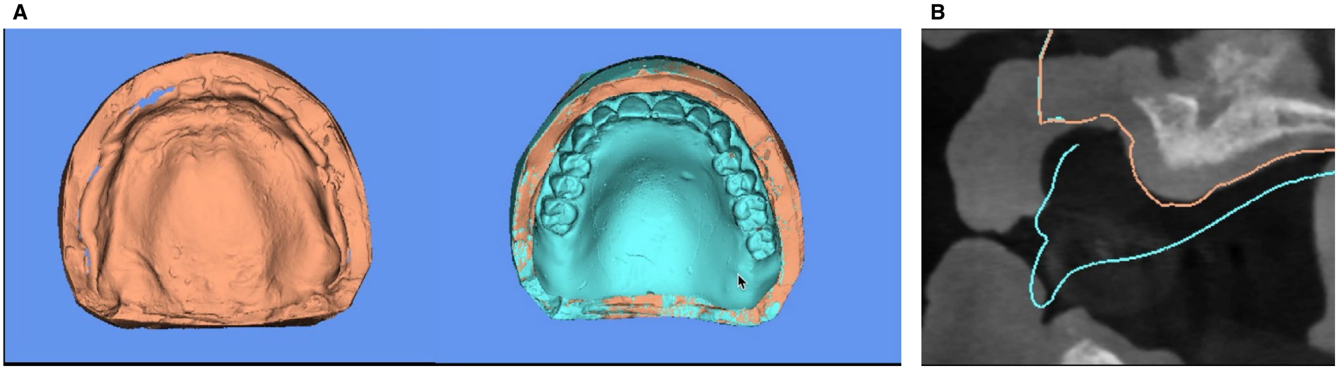

FIGURE 4 In fully edentulous jaws, the soft-tissue outline can be illustrated in the cone-beam computed tomography scan by the reflection of the lip and of the tongue. The outline of the soft tissue will provide endless points of reference for the superposition of the STL file images of the impression and wax-up on the computed tomography image

2.2 | Potential errors during data transfer from the software to the patients' mouths (software to patient)

An important source of error in implant placement relates to the proper three-dimensional positioning of a guide in the patients' mouths and its three-dimensional immobility during surgery,[39] especially in edentulous patients.[44] Widmann and Bale[33] postulated human error may affect many steps in the workflow of guided implant placement protocols. The continuous control of the stable and secure fit of the template is essential for an accurate transformation of the desired planned implant position to the surgical field. Two studies have documented a measurable maximal deviation that was substantially outside the acceptable range.[45,46] Di Giacomo et al[46] proposed that movements of the surgical guide during surgery might be responsible to these differences and deviations. The fit of the surgical template is better on dentate than on edentulous ridges because of available rigid components for guide positioning (teeth vs soft tissue).[47,48] An increased mucosal thickness may affect reproducibility of template position, as well as the initial seat of the template, especially for purely mucosa-supported applications.[49-53]

In dynamic guidance, calibration requires different attention. The cone-beam computed tomography scan is undertaken prior to surgery and is not a "real-time," actively acquired image. Therefore, to reassure the accuracy in implant drilling and placement, it is crucial to calibrate the relationships of the hand instruments and the orientation of the head of the patient with the cone-beam computed tomography "static" image. Calibration has to be performed prior to drilling and with every change of drills.

3 | THE CHALLENGES OF USING A GUIDE IN FULLY EDENTULOUS CASES

In edentulous patients, patient-to-software and software-to-patient calibration is a challenge due to the lack of reference points. In patients with extensive tooth loss, attempts have been made to increase the accuracy of matching cone-beam computed tomography and digital surface scan images with the use of additional markers as reference points.[54,55] Oh et al[56] suggested the insertion of radiopaque resin markers on the palatal gingiva prior to cone-beam computed tomography scanning. Widmann et al[55] demonstrated the use of implants with ball attachments as a fixed reference. Chackartchi et al[57] suggested two protocols (the "full retraction" protocol and the "beads" protocol) based on the ability to visualize the soft-tissue outline on the cone-beam computed tomography image. In these protocols, the soft-tissue outline provided endless points of reference for the superposition of the STL file images on the computed tomography image (Figure 4).

Full edentulous ridges pose a further challenge in the second step of calibration (software to patient). The fit of the surgical template is expected to be better on dentate than on edentulous ridges because of possible mobility and potential compression of the soft tissues.[47,48] An increased mucosal thickness may affect reproducibility of template position, as well as the initial seat of the template, especially for purely mucosa-supported applications.[49-53] As was reported by Vasak et al,[49] an increase of mucosal thickness of 1 mm resulted in an average increase in deviation of 0.41 mm. Furthermore, when the guide is positioned directly on the soft tissues, local anesthesia might change the soft-tissue volume, deviating the guided position.[58,59]

3.1 | Fixation pins and screws

In cases of a long edentulous span or full edentulous cases, template fixation is often implemented (Figure 5). The surgeon should be aware of possible deviation derived from compression of the soft tissue on one side leading to unnoticed lifting of the guide on the opposite side.[47] This lifting is difficult to distinguish and verify intraoperatively and may lead to a deviation in final implant position. The initial positioning of the guide on the soft tissue determines the position of the implants. Once the guide is sited in its correct position on the ridge, fixation pins are inserted, trying to avoid any pressure on the guide. If the guide was not initially positioned correctly, the fixating tools will perpetuate the error. Kauffmann et al[60] compared the use of fixation

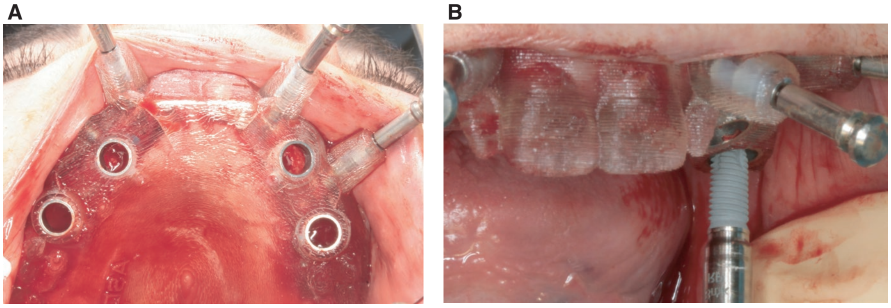

FIGURE 5 A guide for a full edentulous jaw with the use of fixation pins

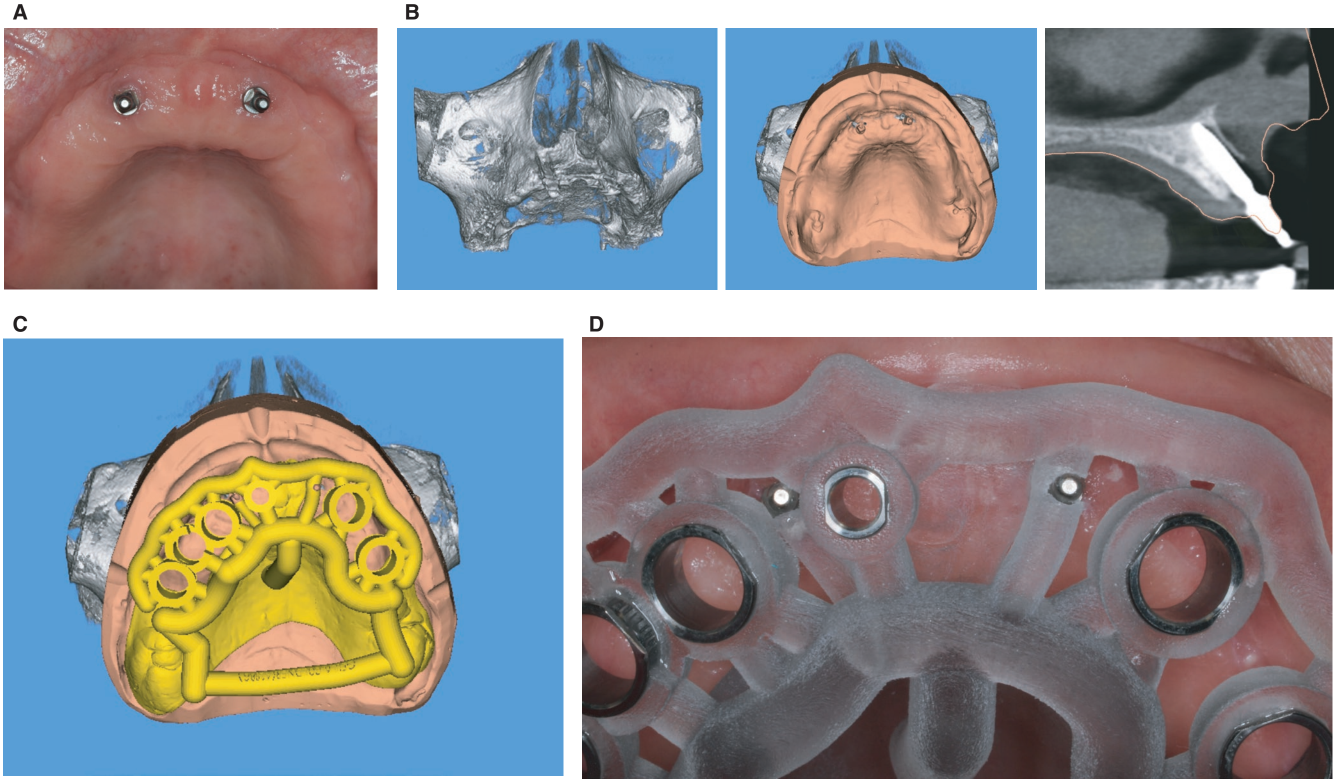

FIGURE 6 Temporary implants can be used as an addition of rigid reference points for both patient to software and software to patient in full edentulous cases. A, Temporary implants will be inserted prior to computed tomography scan. B, The patient will have a cone-beam computed tomography scan, and an impression will be taken and scanned to produce an STL file. The temporary implants will serve as reference points for the calibration of data on the software. C, The designed template (guide) will be supported by the temporary implants as rigid components in addition to the thick, soft tissue

pins with that of hand fixation. The results were in favor of the fixated group, but the benefit was not substantial. It is important to note that guide fixation does not guarantee its correct initial three-dimensional position; rather, it reduces possible movements during surgery.

3.2 | Temporary implants

Micro/mini/temporary implants were suggested as an addition to rigid reference points for both patient to software and software to patient (Figure 6).[61] Tahmaseb et al[61] showed that a high level of accuracy could be achieved when mini-implants were used to support the computed tomography scan template (wax-up) and the final surgical guide. These metal elements present a major advantage by simultaneously acting as a marker for image superposition (STL file images over cone-beam computed tomography image) during data registration and transfer from the patient to software, and as a retrievable anchor for guide positioning during surgery (software to patient); Therefore, the accuracy of the guide, that is now an "implant supported guide" is comparable to that of a tooth-supported guide.[55] A major disadvantage of inserting provisional implants prior to computed tomography scan includes the risk for perforating the bone, since three-dimensional imaging of the bone is still not available. In highly atrophic edentulous ridges, the limited alveolar residual ridge volume must be used to its full extent for implant positioning. Owing to these limitations, provisional implants are usually short and located in posterior parts of the

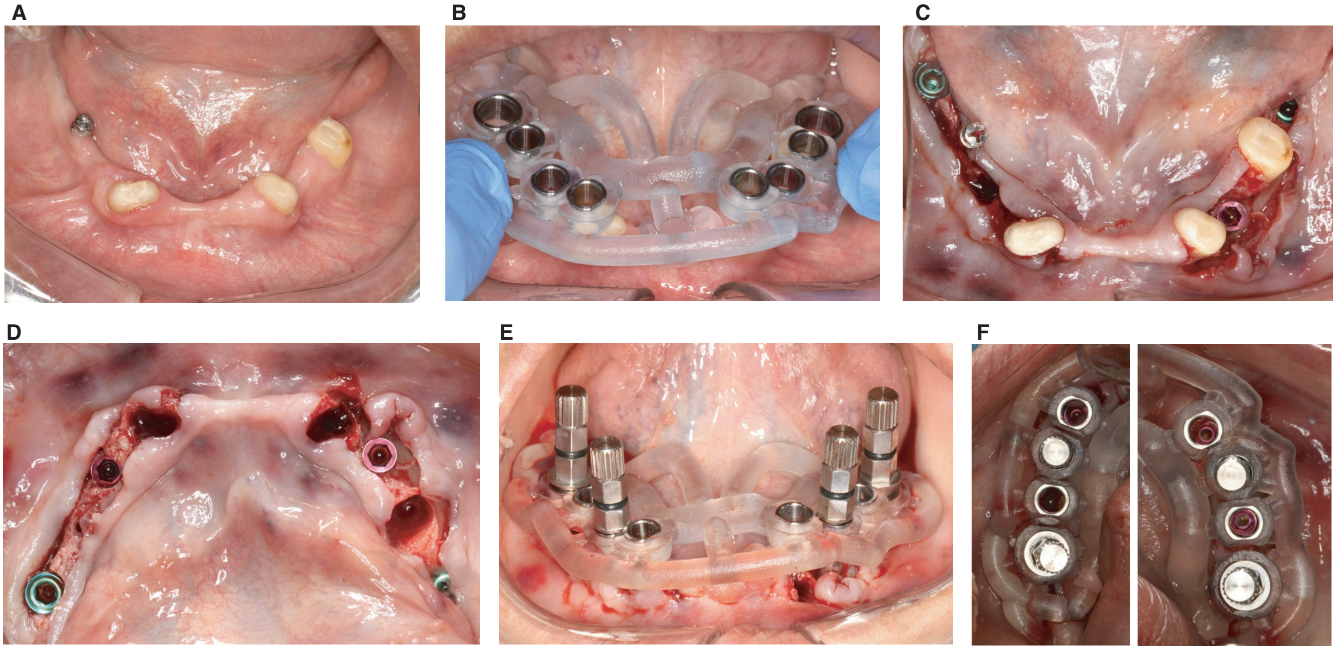

FIGURE 7 In case there are remaining clinically stable teeth or roots that can support the guide prior to extraction, a staged implantation can be implemented. A, B, The guide will be supported initially by the remaining roots and additional mini implants. C, First implants will be positioned between the roots and implants. D, Following, the remaining roots and mini implants will be extracted and E, the guide will be fixated on the implants previously positioned using fixation tools. F, This will allow the insertion of the remaining planned implants, keeping calibration while proceeding through the two steps of implant positioning

jaw, characterized by lightly dense bone (type 3-4 bone). Therefore, there is a risk for loosening of these provisional implants in the time frame between taking the cone-beam computed tomography scan and the start of the surgery. The risk is especially high in cases where the denture will be located over these implants and lateral forces are applied. Therefore, to avoid disintegration of provisional implants prior to surgery, it is recommended to minimize the time between provisional implant placement and implant surgery.

3.3 | Staged extractions

In cases where there are remaining and clinically stable teeth or roots that can support the guide prior to extraction, a staged implantation can be undertaken. In the first stage, the guide is supported by the remaining roots/teeth while the implants are accommodated in-between these roots in the correct positions (Figure 7A). During the second stage, the supporting roots are extracted and the guide is then fixed to the implants and the remaining implants inserted, maintaining the correct position of the guide (Figure 7B). The secure anchoring of the template to the existing dentition is considered an advantage when this type of serial extraction protocol is employed.[33,62,63]

3.4 | Guide design

Various surgical guide designs are described in the literature, based upon their supporting surfaces:

- Mucosa-supported surgical guides, where the surgical guide is positioned on the mucosa.
- Bone-supported surgical guides, where the surgical guide is placed directly on the bone after opening a mucoperiosteal flap.

A systematic review from the Fifth International Team for Implantology Consensus Conference[26] concluded that the bone-supported surgical guides showed the highest inaccuracy. This can be attributed to the fact that this guide is fabricated using the information registered by the cone-beam computed tomography image, which is subject to several distortions. As was previously discussed, the addition of temporary implants prior to cone-beam computed tomography (to be used as anchorage for the surgical guide during surgery) and fixation pins after guide position in the mouth can be beneficial to reduce process errors and improve the final outcomes.

4 | THE DRILLING PROCESS

A systematic review by Tahmaseb et al[26] recorded fractures of the guide as one of the most common intraoperative complications. Template fracture or metal sleeve disintegration from the guide may result from improper force implementation on the template. The drill should first be inserted to the sleeve, and only then should the motor be activated (Figure 8). The drill should be used in a centric position and parallel to the internal wall of sleeve.[64,65]

Van Assche and Quirynen[32] reported a noticeable tolerance of surgical implant instruments within the metal sleeve. This tolerance

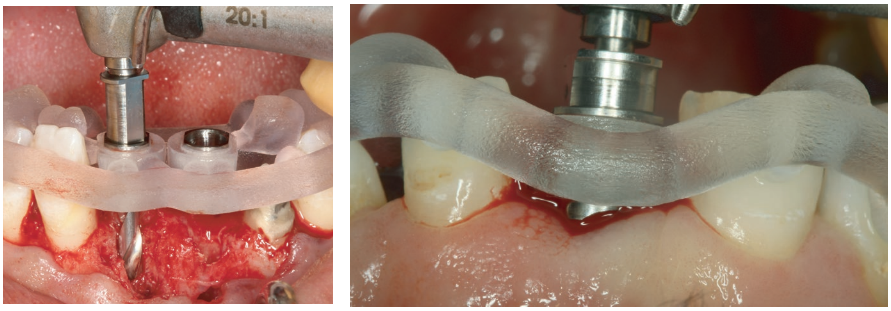

FIGURE 8 The drill should first be inserted in the sleeve, keeping a centric position and parallel to the internal wall of the sleeve. Only then is the motor activated

is caused by the gap between the drill and the guide sleeve, which allows rotation of the drill in the sleeve. Unwanted lateral osteotomy may occur when the drill is not parallel to the sleeve during drilling.[40] On the other hand, if there is no tolerance, the friction generated from mechanical components hinders the drilling process, which may result in sleeve deformation or disintegration. To reduce lateral movements of the drill within the sleeve, the design of the drills was accommodated. Several drilling systems feature shank-modified drills that use the shank portion of surgical instruments as a guiding component to limit lateral drilling motion. The shank of the drill was widened to fit the guide sleeve, to eliminate the need for additional insertion of a metal guide spoon into the guide template. This modification of the drills reduces the tolerance, therefore improving the accuracy of implant positioning in all dimensions measured.[38]

The addition of depth control to the drills is an essential element of the guide system.[66] The addition of a stopper physically restricts the depth of the osteotomy by allowing drill advancement only to the level of the stopper.[67,68] This depth control enhances safety by preventing drills from intruding onto vital anatomical structures, such as the maxillary sinus and the inferior alveolar nerve.[69] Hence, final implant insertion should also be executed using the guide.

5 | CONCLUSIONS

Computer-guided implant surgery offers the ability to plan “top down” implant positioning, maximizing accuracy, whilst taking into consideration hard-tissue anatomy, soft-tissue volume, and the location of future prostheses. There are still inherent deviations and errors when using computer-guided implant systems that may cause injury to essential anatomical structures or prosthetic misfit[70]; therefore, the clinical demands upon the surgeon are no less during guided implant placement.[71] There are a limited number of studies available addressing the variables that can cause discrepancy between the planned implant position and the actual position achieved using surgical guides. The accumulation of individual errors produces the total deviation between the planned and postoperative outcomes. However, if the possible process errors are taken into consideration, and potential deviations minimized, an accurate, stable, and long-lasting result can be achieved. There remains a need for greater experience of surgeons in using guided systems, as well as understanding of the potential process errors, in order to make this surgical method a standard of care. This will improve confidence in such systems, and their use will become mainstream.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding this paper.

REFERENCES

1. Fürhauser R, Florescu D, Benesch T, Haas R, Mailath G, Watzek G. Evaluation of soft tissue around single-tooth implant crowns: the pink esthetic score. *Clin Oral Implant Res*. 2005;16:639-644.
2. Meijer HJ, Stellingsma K, Meijndert L, Raghoebar GM. A new index for rating aesthetics of implant-supported single crowns and adjacent soft tissues—the implant crown aesthetic index. *Clin Oral Implant Res*. 2005;16(6):645-649.
3. Annibali S, Bignozzi I, La Monaca G, Cristalli MP. Usefulness of the aesthetic result as a success criterion for implant therapy: a review. *Clin Implant Dent Relat Res*. 2012;14:3-40.
4. Belser UC, Grütter L, Vailati F, Bornstein MM, Weber HP, Buser D. Outcome evaluation of early placed maxillary anterior single-tooth implants using objective esthetic criteria: a cross-sectional, retrospective study in 45 patients with a 2 to 4-year follow-up using pink and white esthetic scores. *J Periodontol*. 2009;80:140-151.
5. Buser D, Bornstein MM, Weber HP, Grütter L, Schmid B, Belser UC. Early implant placement with simultaneous guided bone regeneration following single-tooth extraction in the esthetic zone: a cross-sectional, retrospective study in 45 subjects with a 2 to 4-year follow-up. *J Periodontol*. 2008;79:1773-1781.
6. Buser D, Halbritter S, Hart C, et al. Early implant placement with simultaneous guided bone regeneration following single-tooth extraction in the esthetic zone: 12-month results of a prospective study with 20 consecutive patients. *J Periodontol*. 2009;80:152-162.
7. Buser D, Wittneben J, Bornstein MM, Grütter L, Chappuis V, Belser UC. Stability of contour augmentation and esthetic outcomes of implant-supported single crowns in the esthetic zone: 3-year results of a prospective study with early implant placement postextraction. *J Periodontol*. 2011;82:342-349.
8. Linkevicius T, Puisys A, Vindasiute E, Linkeviciene L, Apse P. Does residual cement around implant-supported restorations cause peri-implant disease? A retrospective case analysis. *Clin Oral Implant Res*. 2013;24:1179-1184.
9. Ramanauskaite A, Becker J, Sader R, Schwarz F. Anatomic factors as contributing risk factors in implant therapy. *Periodontol 2000*. 2019;81:64-75.
10. Graber ML, Franklin N, Gordon R. Diagnostic error in internal medicine. *Arch Intern Med*. 2005;165:1493-1499.
11. Renouard F, Amalberti R, Renouard E. Are "Human Factors" the primary cause of complications in the field of implant dentistry? *Int J Oral Maxillofac Implants*. 2017;32(2):e55-e61.

12. Le TT, Scheller EL, Pinsky HM, Stefanac SJ, Taichman RS. Ability of dental students to deliver oxygen in a medical emergency. *J Dent Educ*. 2009;73:499-508.
13. Campelo LD, Camara JR. Flapless implant surgery: a 10-year clinical retrospective analysis. *Int J Oral Maxillofac Implants*. 2002;17:271-276.
14. 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 Implant Res*. 2008;19:66-72.
15. Hermann JS, Schoolfield JD, Schenk RK, Buser D, Cochran DL. Influence of the size of the microgap on crestal bone changes around titanium implants. A histometric evaluation of unloaded non-submerged implants in the canine mandible. *J Periodontol*. 2001;72:1372-1383.
16. Tarnow DP, Cho SC, Wallace SS. The effect of inter-implant distance on the height of inter-implant bone crest. *J Periodontol*. 2000;71:546-549.
17. Joda T, Gallucci GO. The virtual patient in dental medicine. *Clin Oral Implant Res*. 2015;26:725-726.
18. Jabero M, Sarment DP. Advanced surgical guidance technology: a review. *Implant Dent*. 2006;15:135-142.
19. Brief J, Edinger D, Hassfeld S, Eggers G. Accuracy of image-guided implantology. *Clin Oral Implant Res*. 2005;16:495-501.
20. Almog DM, Torrado E, Meitner SW. Fabrication of imaging and surgical guides for dental implants. *J Prosthet Dent*. 2001;85:504-508.
21. Besimo CE, Lambrecht JT, Guindy JS. Accuracy of implant treatment planning utilizing template-guided reformatted computed tomography. *Dentomaxillofac Radiol*. 2000;29:46-51.
22. Chiu WK, Luk WK, Cheung LK. Three-dimensional accuracy of implant placement in a computer-assisted navigation system. *Int J Oral Maxillofac Implants*. 2006;21:465-470.
23. Gaggl A, Schultes G, Karcher H. Navigational precision of drilling tools preventing damage to the mandibular canal. *J Craniomaxillofac Surg*. 2001;29:271-275.
24. Scherer MD, Kattadiyil MT, Parciak E, Puri S. CAD/CAM guided surgery in implant dentistry. A review of software packages and step-by-step protocols for planning surgical guides. *Alpha Omegan*. 2014;107:32-38.
25. Greenberg AM. Digital technologies for dental implant treatment planning and guided surgery. *Oral Maxillofac Surg Clin North Am*. 2015;27:319-340.
26. 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.
27. Sicilia A, Botticelli D. Computer-guided implant therapy and soft- and hard-tissue aspects. The Third EAO Consensus Conference 2012. *Clin Oral Implant Res*. 2012;6(23 Suppl):157-161.
28. Tatakis DN, Chien HH, Parashis AO. Guided implant surgery risks and their prevention. *Periodontol 2000*. 2019;81(1):194-208.
29. D'Souza KM, Aras MA. Types of implant surgical guides in dentistry: a review. *J Oral Implantol*. 2012;38:643-652.
30. Jung RE, 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.
31. Winter AA, Pollack AS, Frommer HH, Koenig L. Cone beam volumetric tomography vs. medical CT scanners. *N Y State Dent J*. 2005;71:28-33.
32. Van Assche N, Quirynen M. Tolerance within a surgical guide. *Clin Oral Implant Res*. 2010;21:455-458.
33. Widmann G, Bale RJ. Accuracy in computer-aided implant surgery—a review. *Int J Oral Maxillofac Implants*. 2006;21:305-313.
34. Meyer U, Wiesmann HP, Runte C, et al. Evaluation of accuracy of insertion of dental implants and prosthetic treatment by computer-aided navigation in minipigs. *Br J Oral Maxillofac Surg*. 2003;41:102-108.
35. Jacobs R, Adriansens A, Verstreken K, Suetens P, van Steenberghe D. Predictability of a three-dimensional planning system for oral implant surgery. *Dentomaxillofac Radiol*. 1999;28:105-111.
36. Gulati M, Anand V, Salaria SK, Jain N, Gupta S. Computerized implant-dentistry: advances toward automation. *J Indian Soc Periodontol*. 2015;19:5-10.
37. Engelke W, Capobianco M. Flapless sinus floor augmentation using endoscopy combined with CT scan-designed surgical templates: method and report of 6 consecutive cases. *Int J Oral Maxillofac Implants*. 2005;20:891-897.
38. Lee DH, An SY, Hong MH, Jeon KB, Lee KB. Accuracy of a direct drill-guiding system with minimal tolerance of surgical instruments used for implant surgery: a prospective clinical study. *J Adv Prosthodont*. 2016;8:207-213.
39. Cassetta M, Di Mambro A, Giansanti M, Stefanelli LV, Barbato E. How does an error in positioning the template affect the accuracy of implants inserted using a single fixed mucosa-supported stereolithographic surgical guide? *Int J Oral Maxillofac Surg*. 2014;43:85-92.
40. Cassetta M, Di Mambro A, Giansanti M, Stefanelli LV, Cavallini C. The intrinsic error of a stereolithographic surgical template in implant guided surgery. *Int J Oral Maxillofac Surg*. 2013;42:264-275.
41. Miller RJ, Bier J. Surgical navigation in oral implantology. *Implant Dent*. 2006;15:41-47.
42. Flügge 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 Implant Res*. 2017;28:1113-1118.
43. Vercruyssen M, Laleman I, Jacobs R, Quirynen M. Computer-supported implant planning and guided surgery: a narrative review. *Clin Oral Implant Res*. 2015;26(Suppl 11):69-76.
44. 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.
45. Cassetta M, Giansanti M, Di Mambro A, Calasso S, Barbato E. Accuracy of two stereolithographic surgical templates: a retrospective study. *Clin Implant Dent Relat Res*. 2013;15:448-459.
46. Di Giacomo GA, Cury PR, de Araujo NS, Sendyk WR, Sendyk CL. Clinical application of stereolithographic surgical guides for implant placement: preliminary results. *J Periodontol*. 2005;76:503-507.
47. Ersoy AE, Turkyilmaz I, Ozan O, McGlumphy EA. Reliability of implant placement with stereolithographic surgical guides generated from computed tomography: clinical data from 94 implants. *J Periodontol*. 2008;79:1339-1345.
48. Van Assche N, van Steenberghe D, Guerrero ME, et al. Accuracy of implant placement based on pre-surgical planning of three-dimensional cone-beam images: a pilot study. *J Clin Periodontol*. 2007;34:816-821.
49. Vasak C, Watzak G, Gahleitner A, Strbac G, Schemper M, Zechner W. Computed tomography-based evaluation of template (NobelGuide)-guided implant positions: a prospective radiological study. *Clin Oral Implant Res*. 2011;22:1157-1163.
50. D'Haese J, Van De Velde T, Elaut L, De Bruyn H. A prospective study on the accuracy of mucosally supported stereolithographic surgical guides in fully edentulous maxillae. *Clin Implant Dent Relat Res*. 2012;14:293-303.
51. Ochi M, Kanazawa M, Sato D, Kasugai S, Hirano S, Minakuchi S. Factors affecting accuracy of implant placement with mucosa-supported stereolithographic surgical guides in edentulous mandibles. *Comput Biol Med*. 2013;43:1653-1660.
52. Raico Gallardo YN, da Silva-Olivio IRT, Mukai E, Morimoto S, Sesma N, Cordaro L. Accuracy comparison of guided surgery for dental implants according to the tissue of support: a systematic review and meta-analysis. *Clin Oral Implant Res*. 2017;28:602-612.
53. Reyes A, Turkyilmaz I, Prihoda TJ. Accuracy of surgical guides made from conventional and a combination of digital scanning and rapid prototyping techniques. *J Prosthet Dent*. 2015;113:295-303.
54. Kim JE, Amelya A, Shin Y, Shim JS. Accuracy of intraoral digital impressions using an artificial landmark. *J Prosthet Dent*. 2017;117:755-761.
55. Widmann G, Zangerl A, Keiler M, Stoffner R, Bale R, Puelacher W. Flapless implant surgery in the edentulous jaw based on three fixed intraoral reference points and image-guided surgical templates: accuracy in human cadavers. *Clin Oral Implant Res*. 2010;21:835-841.

56. Oh JH, An X, Jeong SM, Choi BH. Digital workflow for computer-guided implant surgery in edentulous patients: a case report. *J Oral Maxillofac Surg*. 2017;75:2541-2549.
57. Chackartchi T, Neeman T, Zabrovsky A. Guided implant placement in fully edentulous patients. The full retraction protocol: registration technique to improve treatment outcome. *Int J Periodontics Restorative Dent*. 2020;40(5):721-729.
58. Sun Y, Luebbers HT, Agbaje JO, et al. Accuracy of dental implant placement using CBCT-derived mucosa-supported stereolithographic template. *Clin Implant Dent Relat Res*. 2015;17:862-870.
59. Verhamme LM, Meijer GJ, Boumans T, de Haan AF, Berge SJ, Maal TJ. A clinically relevant accuracy study of computer-planned implant placement in the edentulous maxilla using mucosa-supported surgical templates. *Clin Implant Dent Relat Res*. 2015;17:343-352.
60. 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.
61. Tahmaseb A, De Clerck R, Wismeijer D. Computer-guided implant placement: 3D planning software, fixed intraoral reference points, and CAD/CAM technology. A case report. *Int J Oral Maxillofac Implants* 2009;24:541-546.
62. Ganz SD. Presurgical planning with CT-derived fabrication of surgical guides. *J Oral Maxillofac Surg*. 2005;63:59-71.
63. Gillot L, Cannas B, Friberg B, Vrielinck L, Rohner D, Pettersson A. Accuracy of virtually planned and conventionally placed implants in edentulous cadaver maxillae and mandibles: a preliminary report. *J Prosthet Dent*. 2014;112:798-804.
64. Koop R, Vercruyssen M, Vermeulen K, Quirynen M. Tolerance within the sleeve inserts of different surgical guides for guided implant surgery. *Clin Oral Implant Res*. 2013;24:630-634.
65. Lee JH, Park JM, Kim SM, Kim MJ, Lee JH, Kim MJ. An assessment of template-guided implant surgery in terms of accuracy and related factors. *J Adv Prosthodont*. 2013;5:440-447.
66. De Kok IJ, Thalji G, Bryington M, Cooper LF. Radiographic stents: integrating treatment planning and implant placement. *Dent Clin North Am*. 2014;58:181-192.
67. Greenstein G, Greenstein B, Desai RN. Using drill stops on twist drills to promote safety and efficiency when creating osteotomies for dental implants. *J Am Dent Assoc*. 1939;2014(145):371-375.
68. Schwarz L, Pommer B, Bijak M, Watzek G, Unger E. Auto-stop drilling device for implant site preparation: in vitro test of eccentric sensor position. *Int J Oral Maxillofac Implants* 2015;30:1041-1046.
69. Juodzbalys G, Wang HL, Sabalys G, Sidlauskas A, Galindo-Moreno P. Inferior alveolar nerve injury associated with implant surgery. *Clin Oral Implant Res*. 2013;24:183-190.
70. Di Giacomo GA, da Silva JV, da Silva AM, Paschoal GH, Cury PR, Szarf G. Accuracy and complications of computer-designed selective laser sintering surgical guides for flapless dental implant placement and immediate definitive prosthesis installation. *J Periodontol*. 2012;83:410-419.
71. Sicilia A, Botticelli D, Working G. Computer-guided implant therapy and soft and hard-tissue aspects. The Third EAO Consensus Conference 2012. *Clin Oral Implant Res* 2012;6(23 Suppl):157-161.

How to cite this article: Chackartchi T, Romanos GE, Parkanyi L, Schwarz F, Sculean A. Reducing errors in guided implant surgery to optimize treatment outcomes. *Periodontol 2000*. 2022;88:64–72. doi:10.1111/prd.12411