# Software Tools and Surgical Guides in Dental-Implant-Guided Surgery

Maria A. Mora, DDS, MS[a,*], Douglas L. Chenin, DDS[a,b], Roger M. Arce, DDS, MS, PhD[c]

**KEYWORDS**

• Cone beam computed tomography • Implant-guided surgery • Software • Stereolithographic • Optical scanning • Accuracy

**KEY POINTS**

- Cone beam computed tomography (CBCT) and related hardware/software technologies enable surgeons to predictably perform prosthetically driven implant surgeries with adequate clinical accuracy.
- The use of stereolithographic drill guides requires the development of adequate planning protocols in all stages including:
  - Image acquisition and data manipulation.
  - Volume interpretation and treatment planning.
  - Surgical application.
- Clinical accuracy of surgical guides is affected by:
  - Errors in image acquisition.
  - Errors in orientation and cross-sectional principles.
  - Errors in surgical guide manufacturing.
  - Type of surgical guide support or guide fixation.
  - Full versus partial guidance during the osteotomy preparation.
  - Full versus partial guidance during implant placement.

## INTRODUCTION

With the introduction of CBCT technology in the past decade, the shortcomings of two-dimensional (2D) imaging have been eliminated, enabling clinicians to optimally diagnose and treat patients using three-dimensional (3D) data. There are numerous clinical applications for CBCT, such as for endosseous dental implant placement

[a] BeamReaders Inc, Richland, WA 99352, USA; [b] Clinically Correct Inc, Moraga, CA, USA; [c] Department of Periodontics, Georgia Regents University, Augusta, GA 30912, USA
* Corresponding author.
*E-mail address:* alejamora@hotmail.com

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planning, orthodontics, endodontics, periodontics, temporomandibular joint dysfunction, pathology, and trauma.

As dental implants increased in popularity as tooth replacement therapy, the accurate assessment of patient anatomy and the collaboration between restorative clinicians and surgeons have become critical determinants of successful outcomes.[1] Conventional periapical and panoramic imaging techniques combined with visual inspection and clinical palpation may be insufficient to obtain the best presurgical planning in complex or compromised cases.[2] To optimize implant placement and to reduce surgical complications, the clinician must have full knowledge of oral bone anatomy so that any osseous topography and bone volume excesses or deficiencies can be corrected before implant therapy.[3–5] Recently, emphasis has shifted from free-handed implant placement techniques in adequate available host bone (assessed by the surgeon at the time of surgery) to placing implants with nearly exact prediction of the final surgical/prosthetic outcome by means of computer-guided surgical systems.[6] To facilitate accurate translation from the desired surgical treatment plan to reality, templates or surgical guides can be used.[7]

Advances in computer technology (hardware/software) have enabled the development of systems that can assist the clinician in diagnosis, treatment planning, and the surgical treatment itself. Three-dimensional computer-assisted interactive implant planning software tools have sufficient accuracy and reliability required for predictable clinical use. Two methods for a computer-based transfer are available: direct navigation and stereolithographic drill guides.[8] The latter allows a reliable transfer of the surgical plan to the surgical field through guided drilling templates, helping the surgeon to achieve adequate dental implant placement in full prediction of the final prosthetic outcome, soft tissue management, emergence profile, and tooth morphology.[9] Using computer technology also aids in patient satisfaction because surgical times are shorter, treatment can be less invasive, healing times can be shorter, and there are less chances of clinical complications.[10,11] In certain cases, the implants and prosthesis can be placed in the same appointment using the "Immediate smile" or the "all-on-4" protocols.[12,13]

Ultimately, the main goal of implant placement is to adequately position the implant within the bone offering the best function without surgical complications and/or esthetic compromise. To do so, the complete implant therapy process has to be prosthetically driven.[14] There are several elements required for guided implant surgeries: the imaging data set (which may originate from computed tomography [CT] or CBCT), surgical planning software, a radiographic guide to transfer the prosthetic outcome to the planning software, and the surgical guide itself. The characteristics of the latter two are going to largely depend on the software program chosen. Implant planning software allows one to virtually plan the implant surgery and to derive surgical guides from the information acquired. A good surgical guide is the one that allows the practitioner to accurately place the implant in the desired position with a predefined insertion path with minimal tolerance that is nonflexible and stable during the surgical procedure.[15]

This article reviews some of the different software tools that are available for implant therapy planning using stereolithographic drill guides, discusses the correct sequencing steps (from image acquisition, interpretation, and surgical application), presents case-based examples, and considers the clinical accuracy/reliability of these systems when used in patients.

## IMPLANT-GUIDED SURGERY PLANNING SOFTWARE

At present, there are numerous third-party implant planning software programs such as Simplant (Materialise Dental Inc, Glen Burnie, MD, USA), Invivo5 (Anatomage, San Jose, CA, USA), NobelClinician (Nobel Biocare, Goteborg, Sweden), OnDemand3D (Cybermed Inc, Seoul, Korea), Virtual Implant Placement software (BioHorizons, Inc, Birmingham, AL, USA), coDiagnostiX (Dental Wings Inc, Montreal, CA, USA), and Blue Sky Plan (BlueSkyBio, LLC, Grayslake, IL, USA) among others. There are also a few companies that provide treatment planning in the proprietary software of the CBCT units such as Galileos system (Sirona Dental Systems, Inc, Charlotte, NC, USA), TxSTUDIO software (i-CAT®, Imaging Sciences International LLC, Hatfield, PA) and NewTom implant planning software (NewTom, Verona, Italy). After the CBCT data are acquired, the images are exported into DICOM (Digital Imaging and Communications in Medicine) files, a standard for the distribution and viewing of medical images regardless of their origin. This format is compatible with all the third-party software packages listed above; however, an additional file conversion step may be required in some software packages.

When the data set is uploaded to the proprietary or third-party software, the data need to be interpreted completely. A CBCT reconstruction is obtained from all the images that are created and visualized from a different perspective than how the data were initially captured. Thus, a cross section, panoramic view, multiplanar views, volume renderings, and others are all considered CBCT reconstructions. For implant planning purposes, the cross section is the primary diagnostic image used for the assessment of bone volume and quality. However, using the principle of correlation, many other reconstructions can and should be used to augment the diagnostic process.

All the software programs allow the visualization of the data set in the multiplanar reconstruction view, which is the default visualization mode in CT and CBCT imaging (Fig. 1). The 2D images can be visualized in 3 different planes (axial, coronal, and sagittal). Some software programs include a 3D-rendered image of the data set. Information on the 3 different planes requires for it to be fully interpreted because each plane provides different information of the different structures included in the field of view (FOV). The responsibility in diagnosing pathologic condition is not limited to the area of interest but to all the anatomic structures included in the FOV.

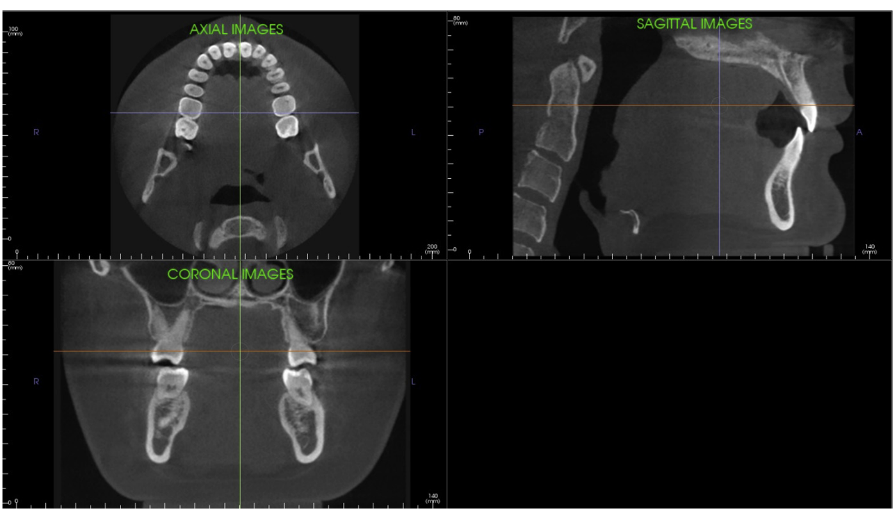


**Fig. 1.** Multiplanar reconstruction mode.

## PREIMPLANT-GUIDED SURGERY PLANNING: DATA MANIPULATION

With CBCT imaging there are specific imaging principles that must be followed to ensure that the images created and used for surgical planning are done so in a clinically correct protocol. Most CBCT imaging software packages allow for the end user to manipulate the images with flexible controls. This flexibility not only provides for a lot of creativity and image generation potential but also can lead to multiple imaging reconstruction errors if specific principles are not set as a standard. Most of these principles relate to how the volume data are oriented and how to specifically create cross-sectional images. Doing this incorrectly results in images that can lead to both visual and measurement errors.

### *Orientation and Cross-Sectional Principle*

A critical principle before implant planning is setting up a correct orientation of the patient's volume data. With most CBCT and third-party implant planning software, the ability to reorient the patient's volume is an essential feature due to the fact that orientation errors are translated to the cross-sectional images, resulting in incorrect measurements of anatomic sites and regions of interest.

To understand correct patient orientation, the position of the cranium is covered from the axial, sagittal, and coronal perspectives. The sagittal tilt is perhaps the most important because it affects the height of subsequent cross sections of the dental arches. The sagittal tilt should be leveled with the occlusal plane anteroposteriorly on the horizontal axis. If the mouth is open, an estimate of the occlusal plane for the arch should be used, and each arch may need its own orientation for proper cross sections to be created if the opening is extensive. The axial tilt should center the patient's midline in an anteroposterior manner so that when viewed the axial image shows the patient's face pointing straight forward without veering to the left or right. An anatomic landmark that may be used in this case is the alignment of the anterior and posterior nasal spines. The coronal view should also level the occlusal plane horizontally so that neither the left nor the right side of the arch is higher or lower contralaterally (**Fig. 2**).

Once the patient orientation is set up, all subsequent images are ready to be created, the most important of which are cross sections of the dental arch. CBCT imaging provides the flexibility to reformat the volume and visualize the data from many different perspectives. Knowing how to create accurate cross sections is an essential skill when using any CBCT imaging software. The essential principle is that cross sections of the implant sites must be perpendicular to the curve of the dental arch and level with the implant trajectory or occlusal plane. This principle ensures that accurate measurements can be performed for buccolingual width and vertical height assessments. From a visual perspective, these cross sections appear to resemble sagittal slices near the dental arch midline and gradually turn into coronal slices near the posterior regions of the dental arches.

It is certainly possible to create diagnostically unsound cross sections with the imaging software, which can lead to measurement errors. This mistake frequently happens when a cross section cuts through the buccolingual dimension of the implant site obliquely, thus cutting through an excessive amount of anatomy. The cross section appears and measures longer in the buccolingual dimension than it actually is (**Fig. 3**). Inaccuracies in the patient orientation, specifically the sagittal tilt, can perpetuate errors into the cross sections as well. If the patient's cranium is tilted too far backward or forward (chin down or up) the cross sections may obliquely cut through the vertical dimension excessively, again leading to measurement errors

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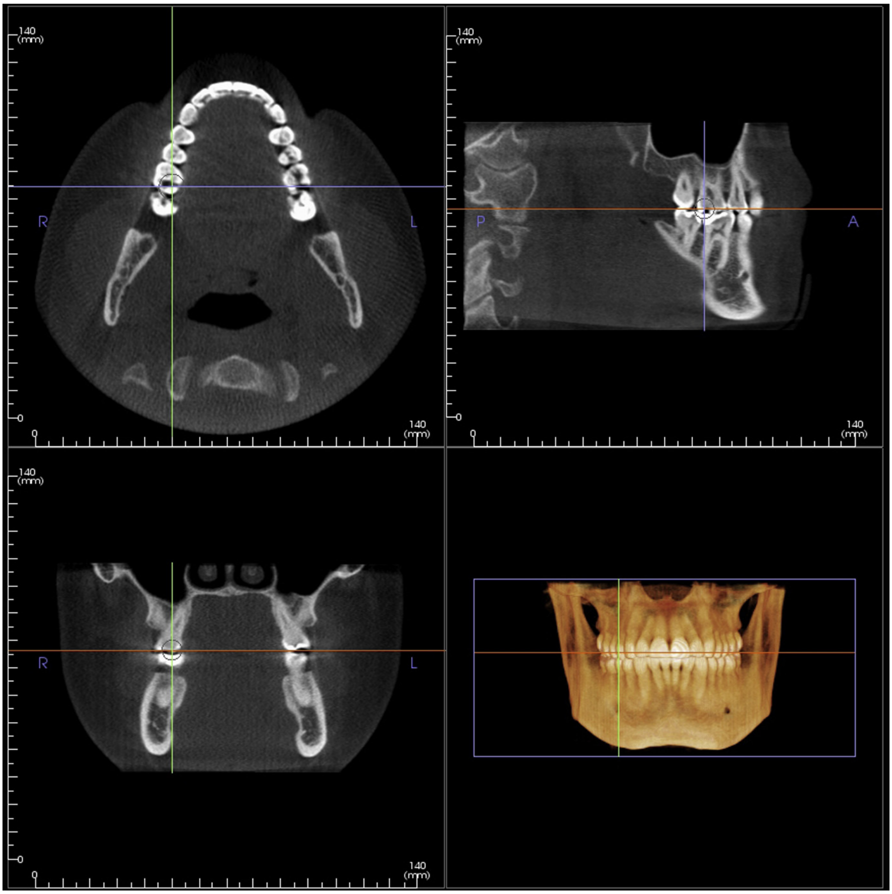


**Fig. 2.** Orientation and cross-sectional principle. (*A*) The correct orientation of patient's cranium according to right specifications. (*B*) An incorrect orientation most notably in the sagittal plane as the patient's chin is tilted too far down.

(**Fig. 4**). This cross-sectional error can be particularly dangerous when determining the length of an implant for a specific site and therefore can lead to unforeseen clinical complications (eg, nerve damage, sinus invasion).

### *Panoramic Reconstructions*

Panoramic reconstructions are images that attempt to reproduce traditional panoramic radiographs and that can be created in all the software packages available. Nonetheless, it should always be remembered that CBCT-based panoramic reconstructions, by their very nature, contain many of the same dimensional errors as traditional panoramic images. With reorientation tools and focal trough adjustments, the reconstructed panoramic image's dimensional distortions can be limited (**Fig. 5**). However, dimensional distortions and thus measurement errors are always present to some degree because reconstructed panoramic images are still just 2D flattened representations of curved 3D structures. These panoramic reconstructions

B

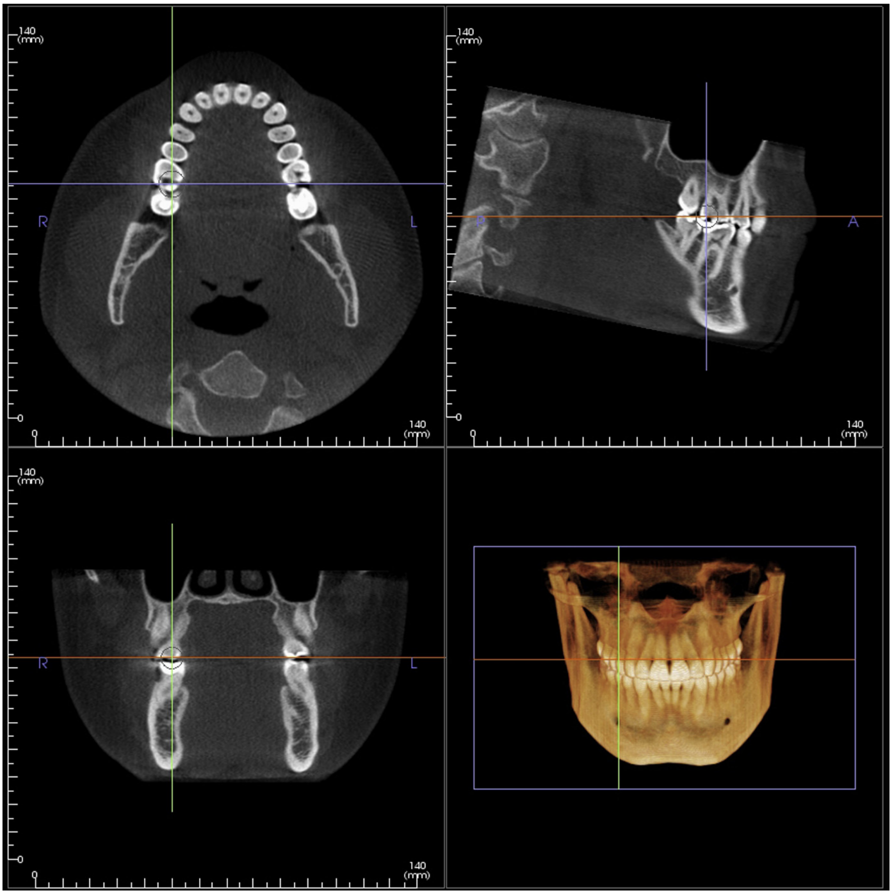


**Fig. 2.** (*continued*)

can help in the visual planning of implant cases and can also help in the principle of correlation; however, they should not be relied upon solely for clinical measurements such as vertical bone availability, interdental mesiodistal distance on edentulous spaces, alveolar bone level estimations, or any other measurement sensitive to boundary conditions.

When using implant planning software, images and slices should always be referenced back to the axial image from which they are created. In most software packages, a focal trough is set up to encompass and curve around the dental arch. Numbered tick marks are also a feature of this focal trough. The principle of correlation refers to both numbered tick marks and to the general method and shape of the focal trough, which guarantees that the exact mesiodistal location along the dental arch is known for each cross section and that each cross section was created correctly as previously mentioned. Panoramic reconstructions or panoramic slices are sometimes used as well to correlate the location of the cross section. Without the corresponding axial or panoramic cross sections, one can be absolutely certain of the mesiodistal location of a cross section, but more importantly, one does not know if it was created

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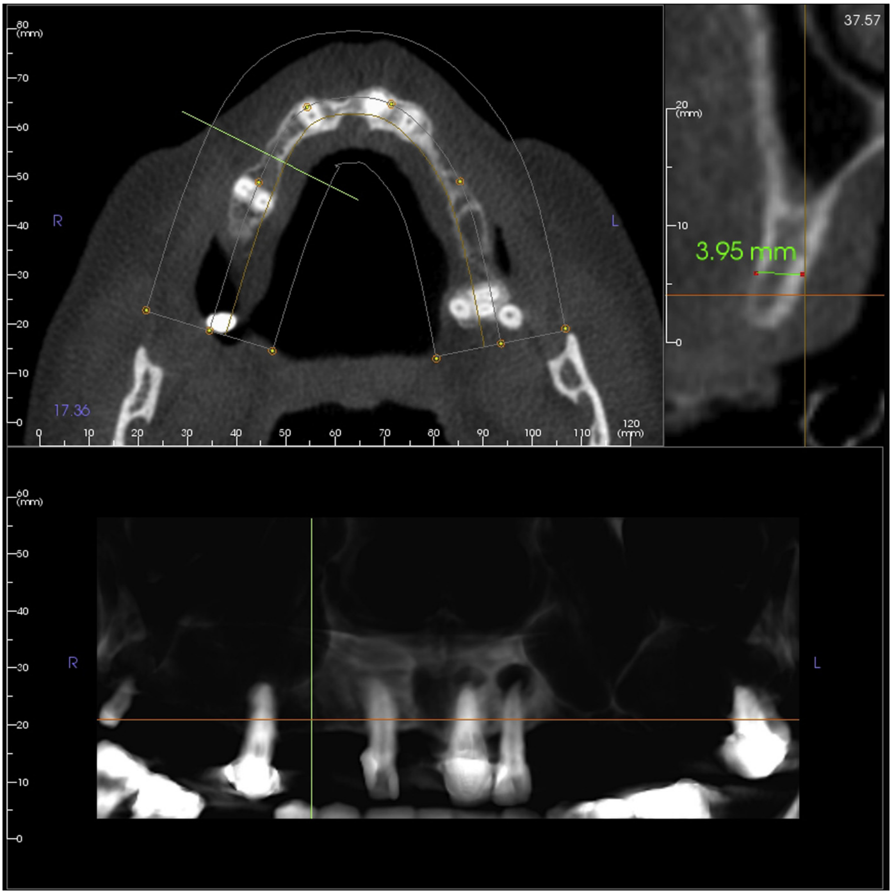


**Fig. 3.** Cross-sectional measurement errors. These images illustrate one of the most common errors with cross-sectional CBCT imaging, namely, oblique slicing of the buccolingual dimension of the arch. (*A*) A correctly sliced arch, as it goes through perpendicular to the arch. (*B*) An oblique slice and the resulting distorted image leading to measurement errors.

correctly. Thus, cross sections should always be assessed with correlated views of the focal trough, especially when using printouts or digital images when presenting or discussing the case.

Edentulous patients should be scanned wearing radiographic stents with radiopaque markers to aid in the localization of specific cross sections and/or proposed implant site locations (**Fig. 6**A, B). These radiopaque markers are important to correlate tooth position with respect to the alveolar bone and CBCT cross sections. If a surgical guide is to be produced, the exact protocols of the specific company must still be taken into consideration because the protocols may vary or require specific materials to be used. For most software programs, radiographic stents must be radiopaque using a combination of acrylic resin with barium sulfate to use as a reference of where the guide contacts the soft tissues. The teeth can be created with a higher concentration of radiopaque materials if the localization of specific teeth and/or intraoral positions is


**Fig. 3.** (*continued*)

desired, as previously mentioned. In other cases, a duplicate of the denture can be used with fiduciary markers. An important factor when using radiographic guides both for dentate and edentulous patients is that the guides are positioned correctly, fully seated, and in a stable position during the scanning process.

### *Segmentation Tools*

Volume renderings can greatly aid in the 3D visualization of implant locations and angulations and in the assessment of implant trajectories for restorative considerations. These renderings can also aid in assessing the available space for any particular restorative goal. However, they are generally lacking in the ability to accurately depict the internal anatomy and thus should only be used after or with simultaneous cross-sectional analysis. The exact surface morphology of volume renderings may also not accurately represent the patient's anatomy. Because of this, it is important to remember that the 3D models are to be used as a complement to the diagnostic and planning process. Three-dimensional models can offer a broad picture of the

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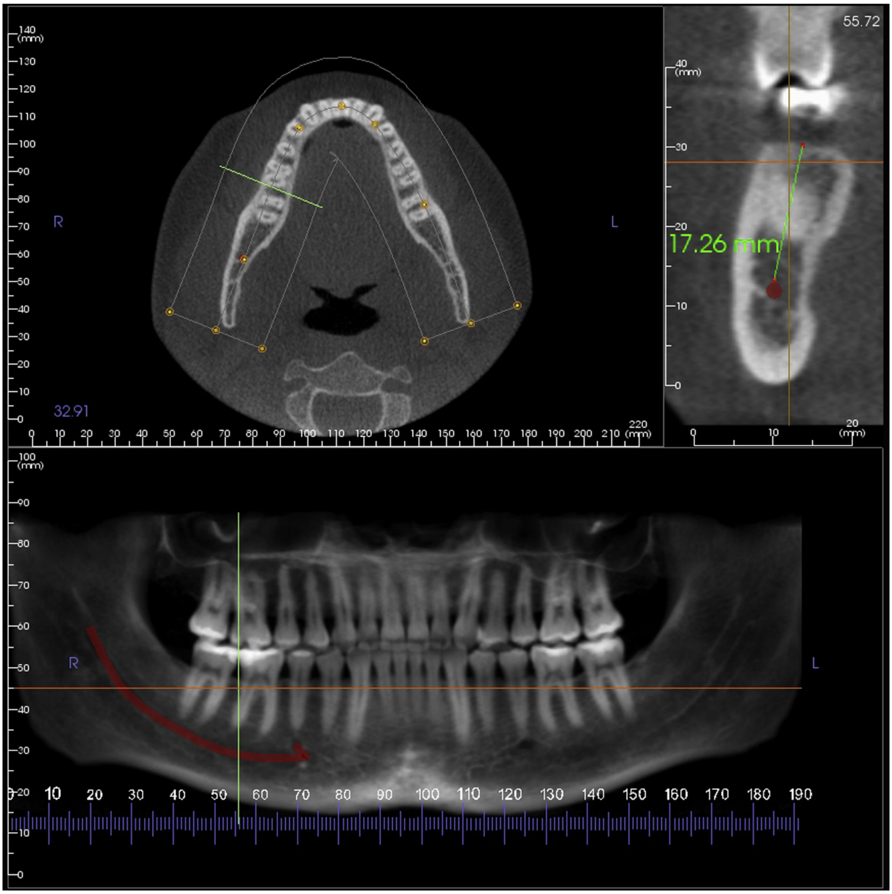


**Fig. 4.** Patient orientation inaccuracies. Correct (*A*) and incorrect (*B*) orientations from the previous images and how these orientation errors translate to incorrect cross sections. (*B*) An excess in the sagittal tilt (chin down). The cross section is oblique in the vertical dimension, creating a measurement error.

overall anatomy such as root eminences, bone defects that originate from healing irregularities or concavities caused by bone atrophy, excess sharp bony edges, and tooth positioning. Finally, volume renderings can serve as an educational tool for the patients to understand how the entire process works.

Some software programs allow manipulating the 3D volumes and creating high-resolution models by using advanced segmentation tools. Different structures can be segmented by means of creating masks or layers, allowing the user to separate and colorize different anatomic structures. The fact that the different structures can be turned off or on allows the user to see all the different masks separately to have a better understanding of the morphology of these structures. Some software programs offer a transparency tool, which allows the user to see structures as the maxilla or mandible semitransparent revealing opaque structures underneath the bone (Fig. 7).

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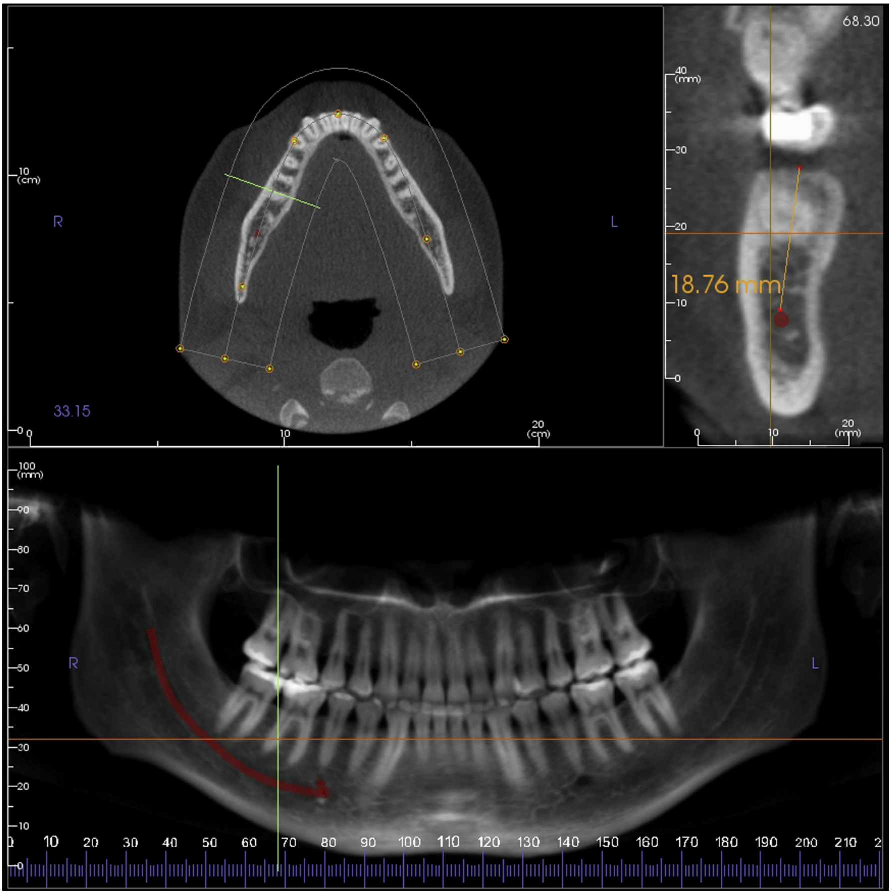


**Fig. 4.** (*continued*)

Scatter originated from metallic restorations causes a detriment in the image and 3D rendering quality (**Fig. 8**). Scatter can be manually erased or segmented with advanced tools from the 3D volume rendering but cannot be eliminated in the 2D images. Some CBCT units minimize this artifact by the use of built-in algorithms. With some software programs, this is a critical step that can be overcome with the superimposition of scanned or digitized stone models. It is, however, a time-consuming step, and when removing scatter, care should be taken to ensure that real anatomic structures are not eliminated.

### *Nerve Tracing Tools*

Because the inferior alveolar canal is one of the most common landmarks to be wary of when placing implants, it is imperative to trace its location through the mandible. Most of the planning software packages provide the tools to trace the inferior alveolar canal. Tracing is done by drawing points in the trajectory of the canal and by scrolling through the panoramic, axial, and cross-sectional images. This step needs to be carefully done, however, because the canal's position is not the same at the lingula and mental foramina

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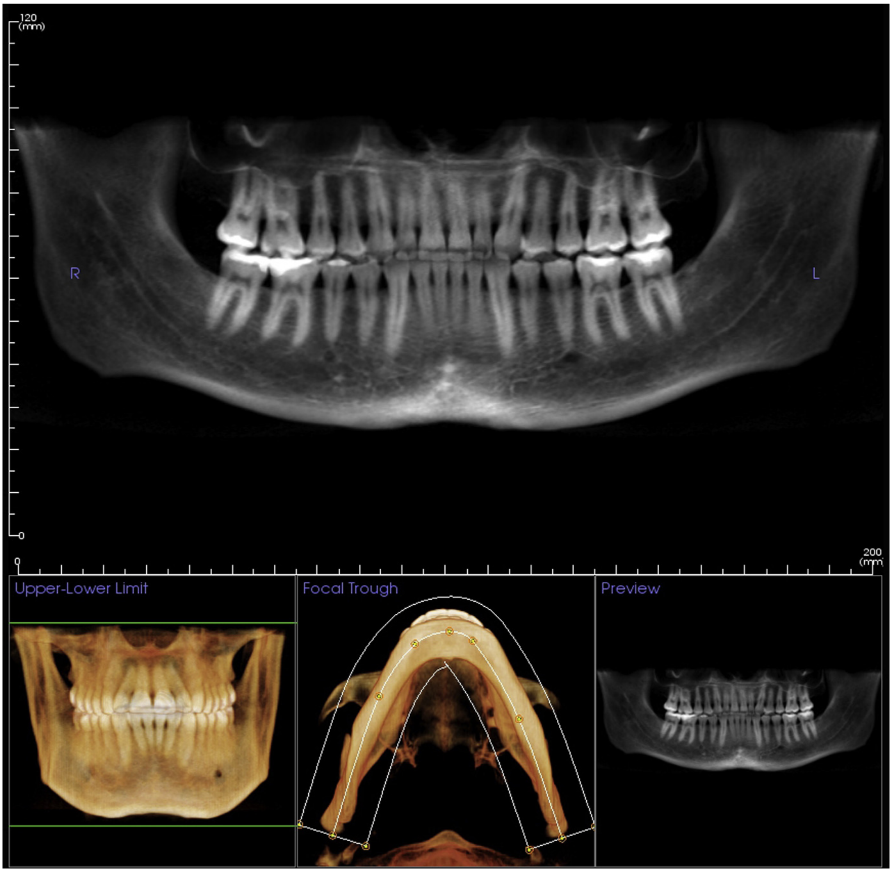


**Fig. 5.** Panoramic reconstructions. Panoramic images reconstructed from 3D CBCT data using focal troughs. (*A*) Reconstruction with principles that help minimize errors, such as proper orientation and balanced focal trough set up. The resulting panoramic image has its inherent distortions minimized. (*B*) A panoramic image with reorientation errors and focal trough errors, resulting in a panoramic image with excessive reconstruction errors.

levels. Some packages just require a couple of reference points, and based on algorithms that compare density levels (gray values), programs semiautomatically trace the canal (**Fig. 9**). These points can be moved around to adjust the locations accordingly. The width of the canal can be adjusted to accommodate to the patient's canal width as well. This task can become complicated if the patient is osteopenic or if there are motion artifacts because the margins of the canals may not be easily visualized.

## IMPLANT-GUIDED SURGERY PLANNING

The analysis of patient CBCT data, beyond using the software tools correctly, also includes the proper qualitative and quantitative assessments of all relevant anatomy and boundary conditions. A boundary condition is defined as any and all anatomic

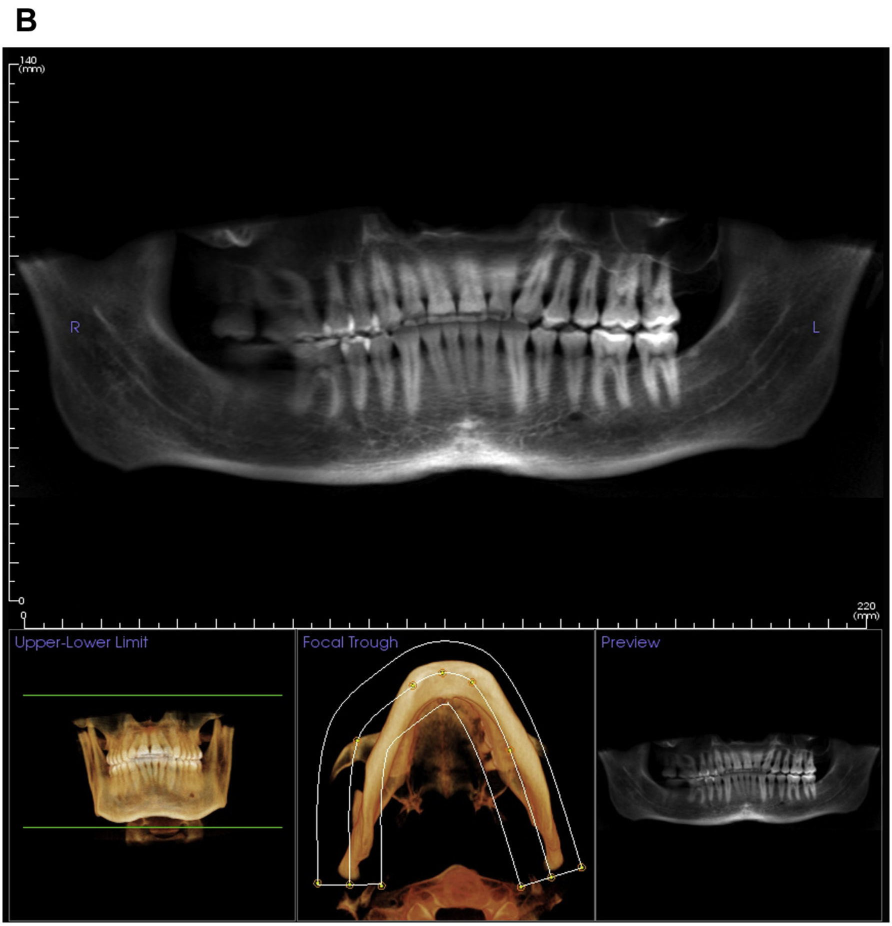


Fig. 5. (*continued*)

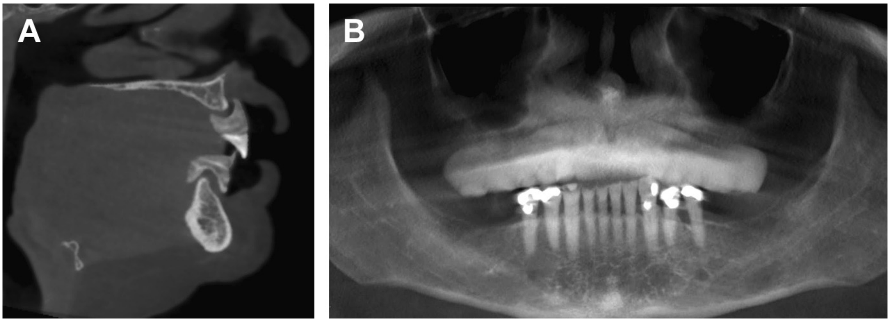


**Fig. 6.** Radiopaque stents in edentulous patients. (*A*) Sagittal cross section at the midline of the dental arch of a patient wearing a radiopaque duplicate denture during scanning. (*B*) Panoramic view of an upper denture radiopaque duplicate. This view helps for proper planning of fully edentulous cases and may be needed for some surgical guide protocols as well.

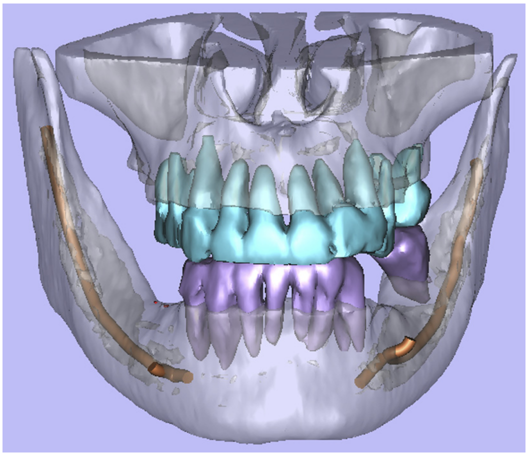

**Fig. 7.** Three-dimensional volume manipulation. Different anatomic structures segmented and colorized in the 3D volume rendering. The semitransparency tool allows users to see structures underneath the bone.

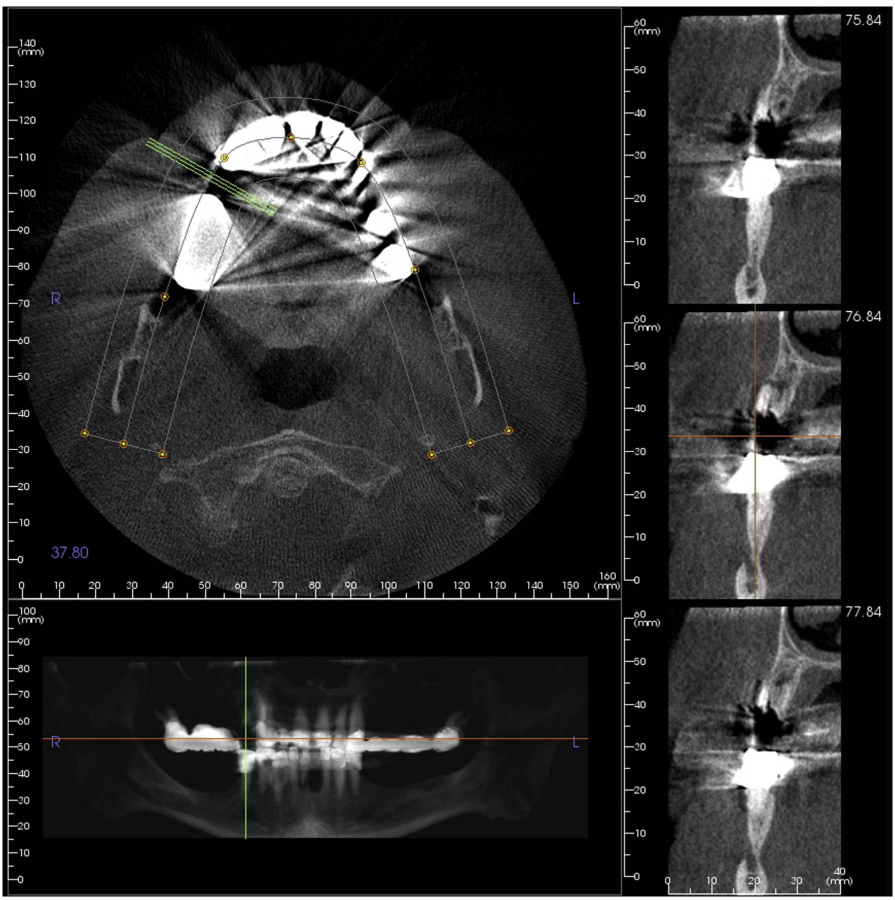


**Fig. 8.** CBCT scatter. Scatter from metallic restorations cause a detriment in the image quality.

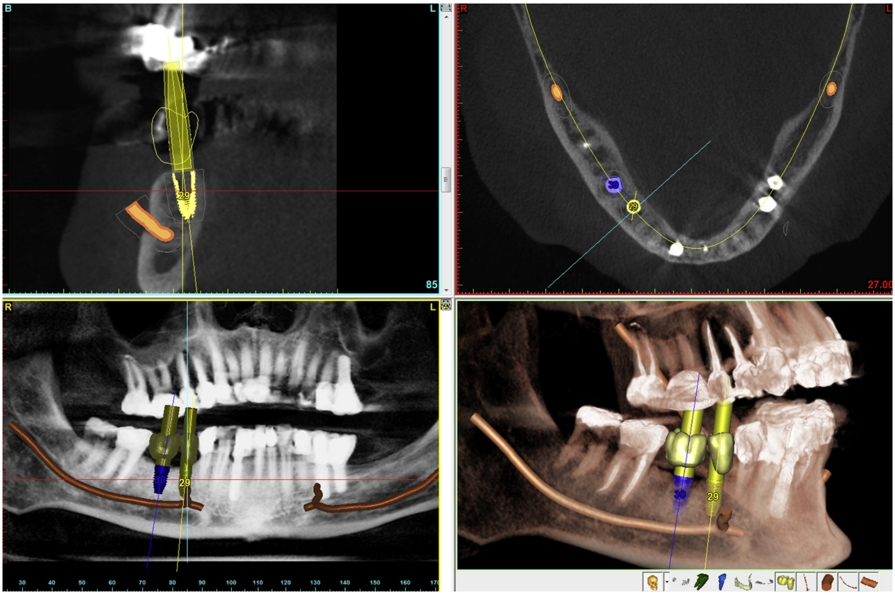

Fig. 9. Tools for nerve tracing. Adequate nerve tracing in areas where implant placement is evaluated during treatment planning. Notice the safety margin around both the nerve and the implant, which helps to minimize surgical complications.

constraints of an anatomic zone that may limit or influence implant placement and subsequent final restorations.

There are multiple boundary conditions that are common to both mandibular and maxillary arches. The primary boundary condition is the buccolingual width of alveolar bone at the alveolar crest continuing to the basal bone throughout the implant site or implants and thus its vertical height limitations as well. Special attention should be given to the alveolar crest to ensure that adequate bone surrounds the coronal aspect of the implant, as well as to the apex location to ensure that it is not violating any critical structure or boundaries. Software tools can alert the user when these critical boundaries/spaces are violated (**Fig. 10**). It is important to determine if any facial or lingual concavities are present throughout the implant site location and assess the general contour and quality of the bone. Visualizations and measurements should take place in both the buccolingual and mesiodistal dimensions, because it is quite common to be lacking space in both. Density measurements can also be obtained, but because of the nature of CBCT imaging, these measurements are not accurate. The proximity of adjacent implants and/or teeth roots and their angulations should also be assessed. A helpful tool for this is the parallelism tool, which can aid in making these structures as parallel as possible to adjacent teeth or other implants (**Fig. 11**).

Once measurements are done in the cross-sectional images, the clinician can virtually select and place implants in the region of interest with the characteristics that were obtained from the preliminary measurements. Most implant planning software packages do include implant libraries with most of the available implants in the market and all the compatible abutments (stock abutments, both conventional and angled). These libraries are constantly updated. Most software allow the creation of a safety zone around the virtual implant body (which can be set to 1–2 mm) helping to minimize

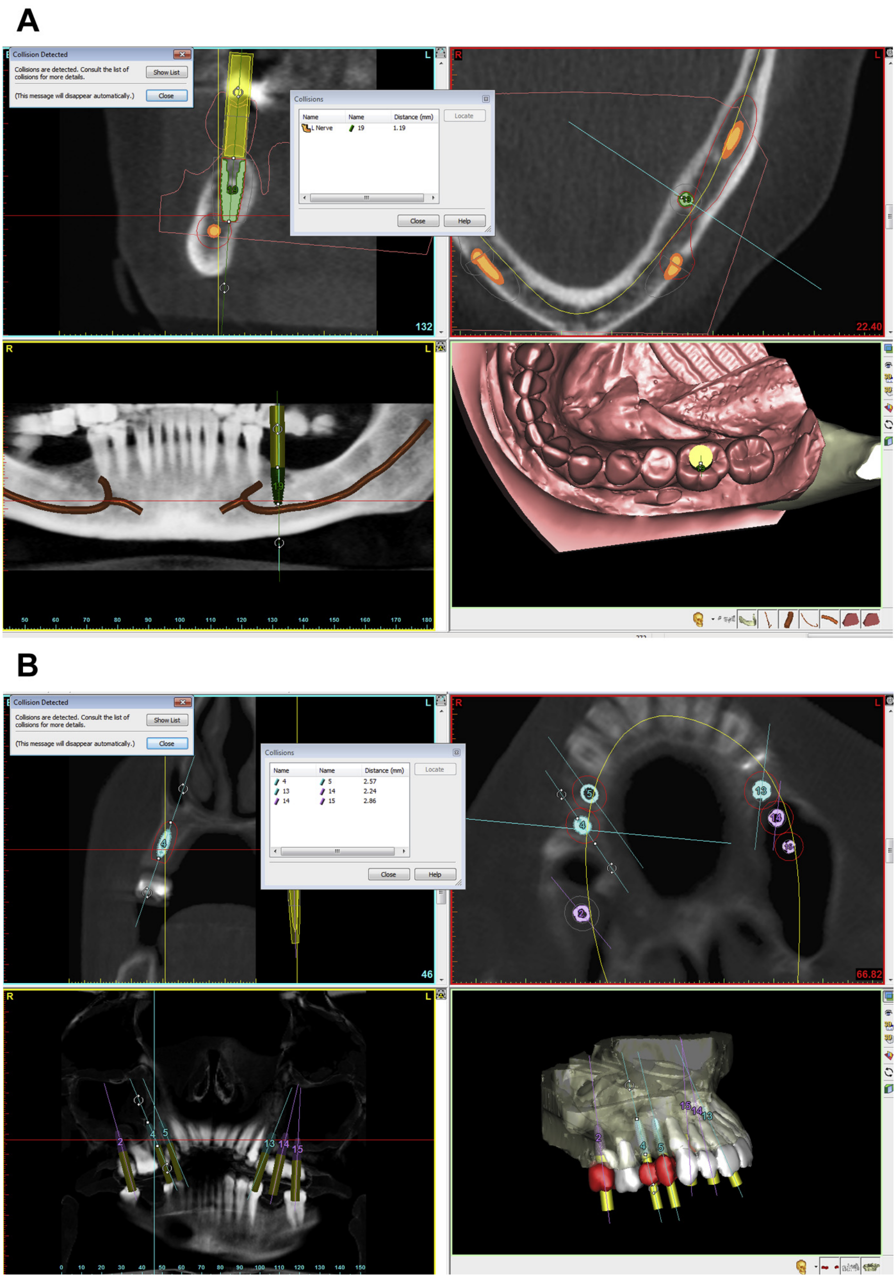


**Fig. 10.** (*A, B*) Collision detection tools. Some software systems can alert the user when boundary spaces are violated.

invasion of the boundary condition caused by data manipulation errors. Emergence profiles can also be identified by using the abutment projections and with some software packages; virtual teeth forms can be placed for simulation of the final crown (cement retained or screw retained). These virtual teeth can be scaled and sized for

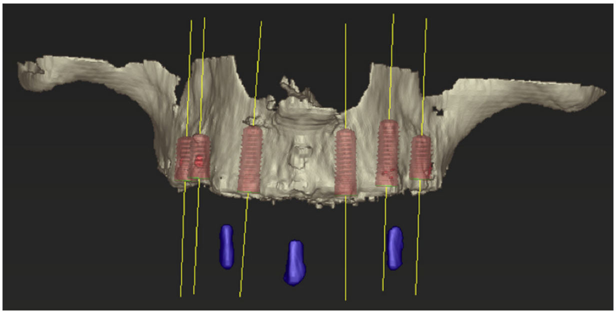

**Fig. 11.** Tools for implant parallelism. Implant parallelism tools become very useful in the planning of implant-retained overdentures.

each patient and allows the simulation of the restorative needs of the receptor site (**Fig. 12**).

Some other tools allow the user to simulate bone augmentation procedures. With this feature one can calculate how much grafting is needed in volume (cc) and where the fixation or tenting screws should be located (**Fig. 13**).

The clipping tools provided in different packages are helpful to identify the position of the implant within the bone in the different planes. This identification offers information of the cortical thickness and the position of the implant with respect to the cortical borders (**Fig. 14**).

### *Anatomic Considerations When Planning Implant Surgery*

Dental implants within the maxilla have unique and specific boundary conditions to be aware of in addition to the general ones mentioned above. For anterior implants, the location and size of the nasopalatine canal and foramen should be identified at the midline. For implants distal to the midline, the location, boundary, and morphology of the maxillary sinus floor should be assessed. It is possible for the maxillary sinus to extend to an area inferior to the nasal cavity (**Fig. 15**). The nasal floor is most commonly seen in the anterior regions and limits the amount of vertical height possible for many anterior implant sites.

Mandibular implant sites also have unique boundary conditions to be cognizant of that can lead to serious and permanent complications. For the mandible, the boundary conditions are the proximity and locations of multiple neural and/or vascular canals. The most common (and extensive one) is the pathway of the inferior alveolar nerve (IAN) canal, which limits the height of the available bone in most posterior mandibular implant cases. Violations of the IAN canal can lead to permanent paresthesia of that side of the patient's jaw, teeth, and lips (**Fig. 16**). IAN canal anomalies are also possible, such as bifid canals that can further limit implant placement potential. The location of the mental foramen exit point of the inferior alveolar canal should be identified, and a careful evaluation should be done to determine the presence and extent of the anterior loop. In fact, the IAN canal may extend significantly beyond the mental foramen as an intra-osseous anterior loop. The presence of symmetric anterior loops can be as frequent as 76% to 88%.[16] Placing implants anterior to the mental foramen does not protect from violation of prominent anterior loops; the functional consequences could include paresthesia of the anterior mandibular teeth if present. Anterior projections or incisive branches of the inferior alveolar canal can also be present and may or may not pose problems with implants placed anterior to the mental foramen.

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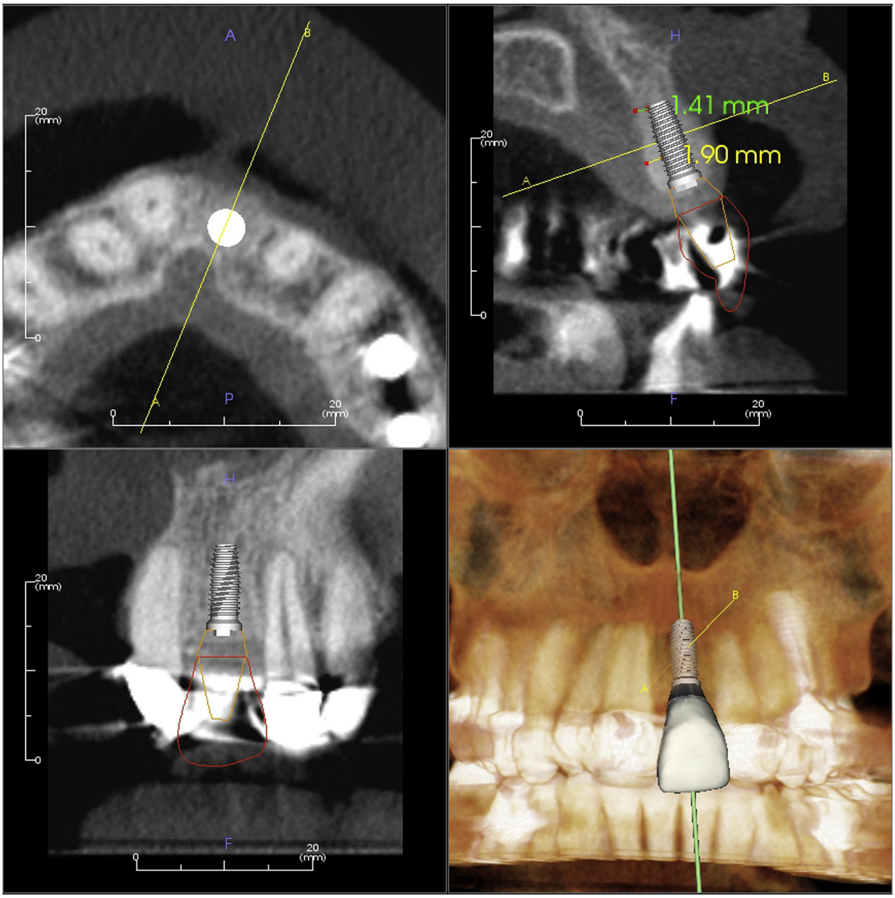


**Fig. 12.** (*A, B*) Tools for abutment/crown simulation. Virtual treatment plan including the proposed implant, abutment, and crown, along with other boundary condition assessments, depicted from different software. Emergence profile depicted.

Another canal to consider is the median lingual vascular canal located at the lingual midline of the mandible. Hemorrhages can also occur that lead to serious complications after the invasion of this important anatomic structure, in some cases reported to be fatal.[17] Violations of this canal can lead to serious hemorrhagic scenarios.[18] These canals are often overlooked, and its complications are largely unknown; critical attention is needed for any case with implants being placed near the mandibular midline (**Fig. 17**).

### *Optical Scanning*

CBCT imaging information of hard tissues is highly accurate, but because of the poor contrast resolution of this technology, the information for soft tissue is inaccurate. For this reason, optical scanning technology incorporated to implant planning software packages is increasing in popularity. With optical scanning, stone models or intraoral scans provide soft tissue profile information as well as accurate information of teeth

B

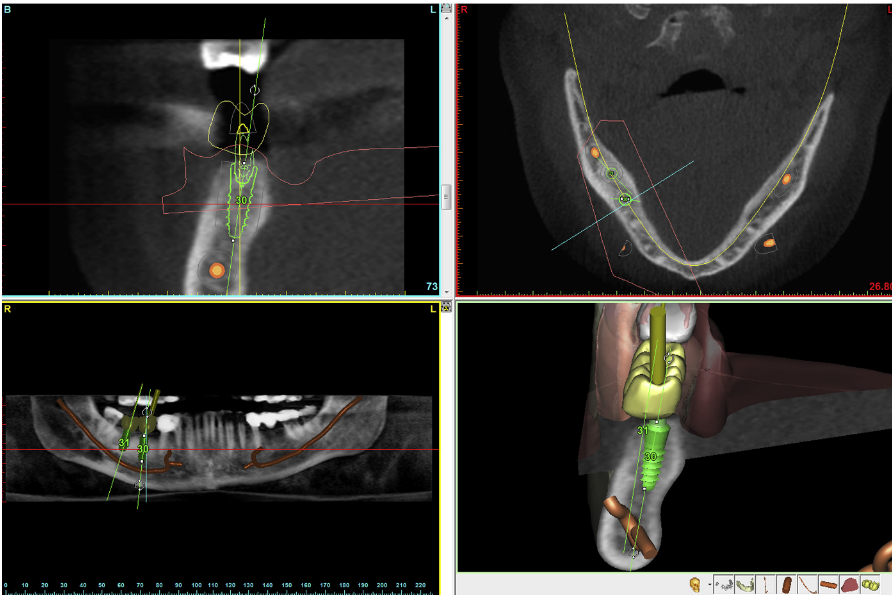

**Fig. 12.** (*continued*)

contours because optically scanned models are scatter free. When using optical scan technology, 2 scans are required, one of the patient using the radiographic guide and a second one of an optical scanned plaster cast or intraoral scan. The scanning system provides a .STL (Standard Tessellation Language) file. These STL files are merged into the planning software where the geometries of the structures are semiautomatically recognized. The files can be used not only to define soft tissue and teeth contours but also to fabricate stereolithographic models and surgical guides. Most software packages require advanced modules to use this technique. Nonetheless, implants and abutments can be virtually preplanned based on the information acquired of both soft and hard tissues, which greatly facilitates the immediate loading and restoration of implants in selected cases (Fig. 18).[19]

## RESTORATIVE CONSIDERATIONS FOR CBCT-BASED IMPLANT-GUIDED SURGERY PLANNING

It should always be remembered that the ultimate objective of placing dental implants is the final prosthetic restoration. Patients are seeking teeth and not implants, so a restorative-driven mind-set should always be maintained. There are multiple factors that influence the restorability of implants, which can be assessed within CBCT scans. When planning implants, the ideal trajectory toward the opposing occlusion should be assessed. This assessment is not always possible because the opposing arch may not be included in the FOV; thus, knowing the limitations of both stock and custom abutment designs becomes critical. Excessive implant to crown angulations, although feasible to restore, can cause unfavorable force distribution and lead to implant failure.[20] An assessment of the height between the opposing arches can help to determine if there is enough room for the implant to be restored. It is common for opposing teeth to supraerupt into the edentulous space making the restorative

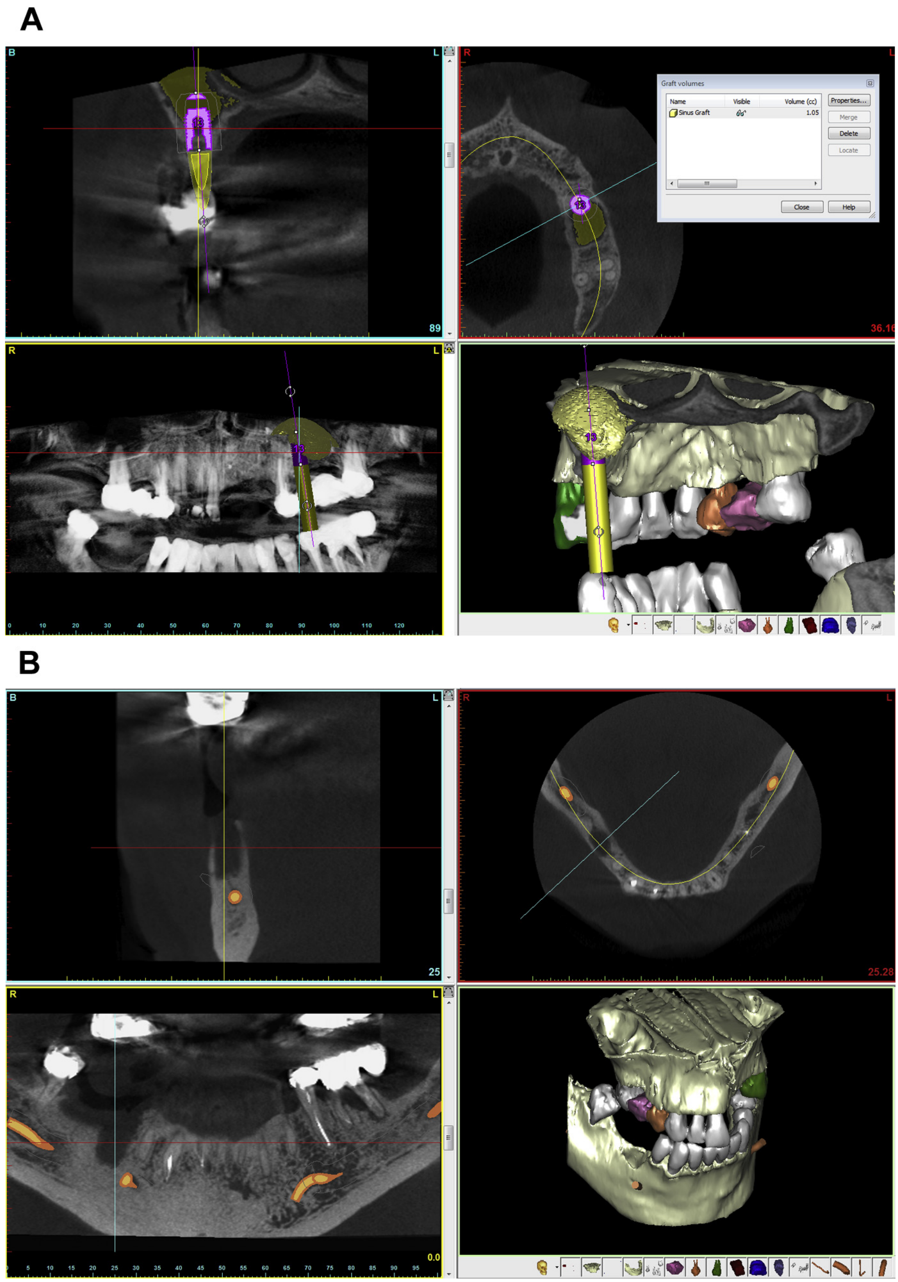


**Fig. 13.** Tools for bone augmentation simulation. Surgeons can directly calculate the amount of bone grafting material needed for sinus lift (*A*) or site preservation (*B, C*) procedures.

C

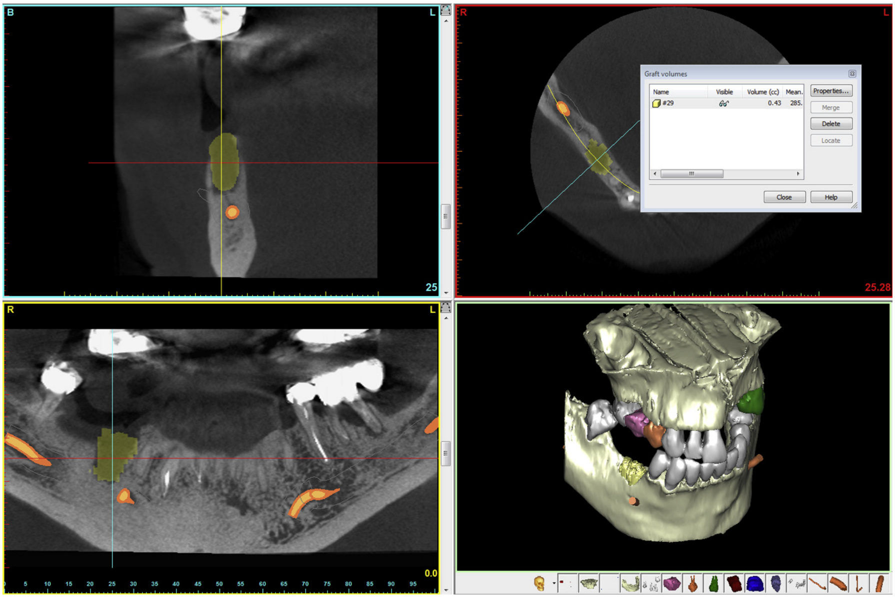


**Fig. 13.** (*continued*)

aspects more complicated. Ridge augmentation is sometimes a solution to gain vertical height for adequate restoration designs. The mesiodistal width of space between adjacent teeth and/or other implants can also limit or preclude an implant or its restoration from being placed (Fig. 19).

Implant-supported dentures can be planned with greater ability by scanning the patient while wearing a scanning appliance (Fig. 6). A radiopaque duplicate denture can

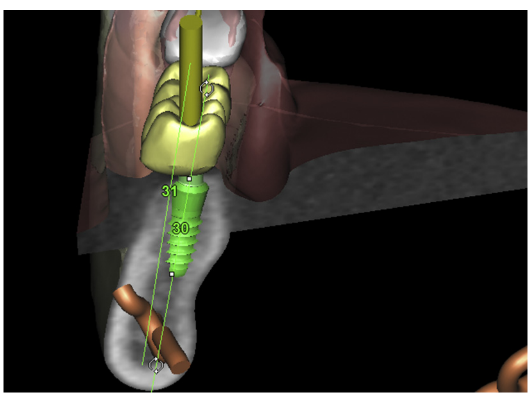


**Fig. 14.** Tools for clipping. Clipping tools provided in different packages are helpful to identify the position of the implant within the bone in the different planes, providing information of the bone thickness around the implant body as well as the position of the implant with respect to the cortical borders.

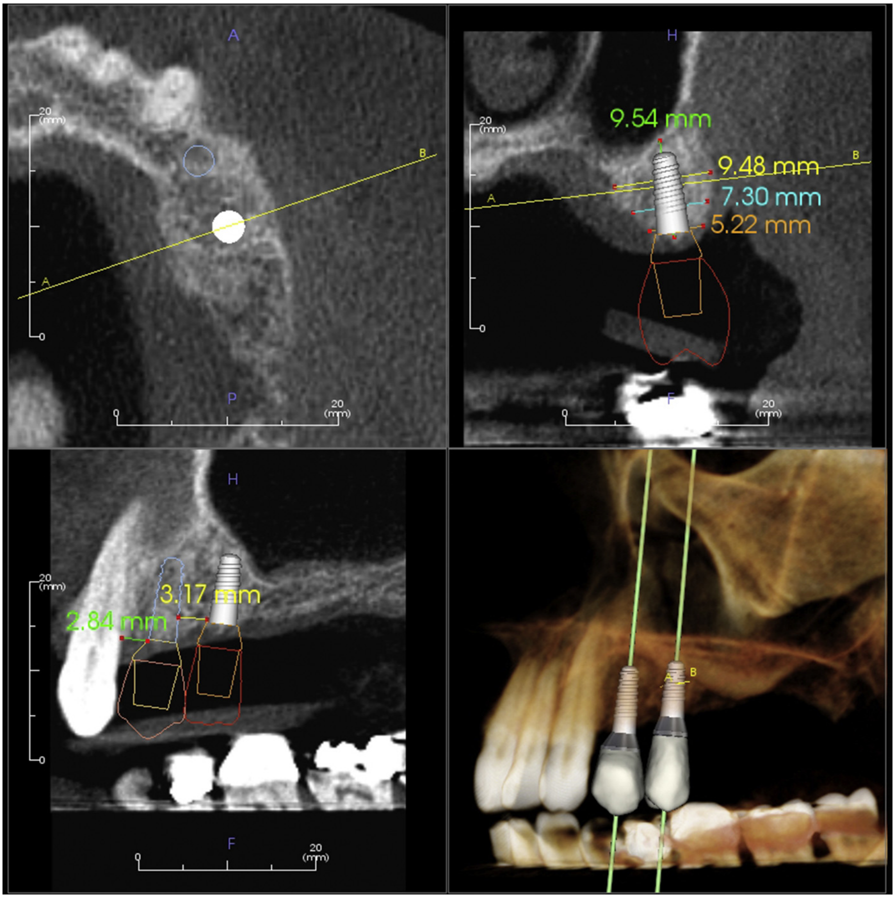


**Fig. 15.** Anatomic considerations, maxillary sinus. Limitations of placing implants within the posterior maxilla near the maxillary sinus floor (if sinus lift is not considered). In some instances, the maxillary sinus can pneumatize to an area inferior to the nasal cavity. The image also shows how measurements can be calculated between implants to make sure there is enough space between them.

become a scanning appliance and be worn during the scan to delineate the soft tissue boundaries and also show the teeth. This procedure makes planning the location and trajectory of implants within the proposed denture much easier. The gingival thickness can be assessed as well, which is useful for denture locator considerations. Placing implants in an ideal location and angulation for prosthesis stability is greatly enhanced with this technique.

## SURGICAL GUIDES

Once the implant is virtually planned, the project can be transferred to the clinical setting by using a surgical guide. Surgical guides are appliances that are computer designed and are fabricated of an acrylic resin by a process called stereolithography. The surgical guides contain steel sleeves with a predefined diameter to guide the drills

**Fig. 16.** Anatomic considerations, inferior alveolar canal. Postoperative CBCT cross section where a dental implant perforated the inferior alveolar canal causing permanent sensory damage to the patient.

during the osteotomy process. There are different types of surgical guides such as a pilot guide, which allows the clinician to create the initial osteotomy. After the pilot osteotomy is created, the guide is removed and the rest of the process is done freehanded. Other guides allow completing all the osteotomy processes by using the entire drill sequence; however, the implant is placed freehanded, whereas there are others that require a guide that allows going through all the drilling sequence and placement of the implant. Some protocols include depth control systems that allow the surgeon to control vertical preparation by using a stop at the drill or at the sleeve insert levels. In addition, surgical guides can be categorized according to the type of stabilization they have such as teeth, bone, or soft tissue (**Fig. 20**A, B). Surgical guides for edentulous patients are stabilized through temporary fixation pins that can also be planned using advanced tools in the software packages (see **Fig. 20**C).

## CLINICAL ACCURACY OF SURGICAL GUIDES

It is difficult to draw final conclusions when defining the clinical accuracy and precision of all guided implant surgery systems, specially because there are many protocols available in the market. Moreover, there is a lack of scientific documentation for most systems regarding clinical accuracy.[21] Like any other automated system, guided implant surgery is not entirely perfect and is prone to minimal errors that can be magnified when protocols are not strictly followed.[22] Sources of these minimal errors can result in a total error, which can ultimately influence the final position of the implants and potentially cause surgical or prosthetic complications[23]; these errors can originate at all different planning stages.

### *Image Acquisition*

Accuracy errors can be introduced with poor image quality, motion, or metal artifacts. Errors can also be introduced when radiographic templates or stents are not fully

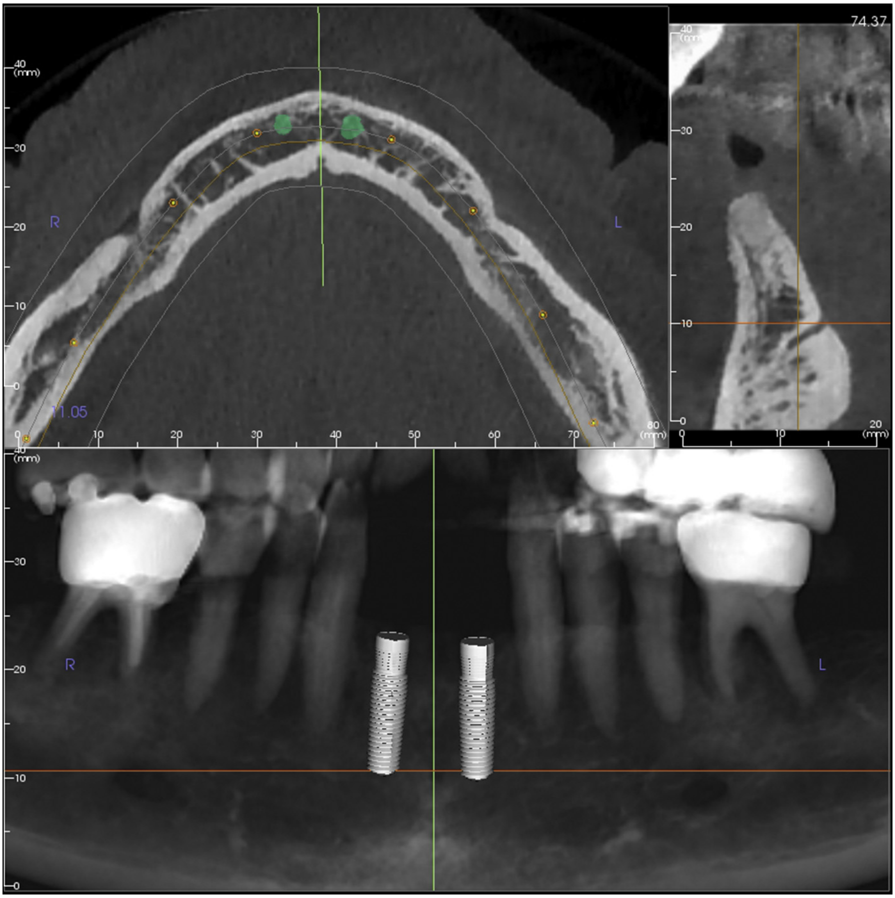

**Fig. 17.** Anatomic considerations, median lingual vascular canal. This canal is located at the lingual midline of the mandible. This anatomic structure may vary in size. If not considered during treatment planning, implant placement can lead to serious surgical complications (hemorrhage).

seated during image acquisition. This error can easily be detected in the volume when radiolucent areas are noted between the stent and the teeth or mucosa (**Fig. 21**). Hence, an important goal in this step is to have a stable and reproducible fitting position of the stent during the initial scanning.[24,25]

### *Image Processing (Orientation and Cross-Sectional Principle)*

As discussed above, inadequate data manipulation can lead to underestimation or overestimation of direct measurements on slices.

### *Surgical Guide Manufacturing (Stereolithography vs Radiographic Stent)*

Unintentional deformation of stereolithographically produced surgical guides is possible and can result in accuracy errors.[26] Gray value thresholds can also influence 3D reconstruction of surgical guides and affect the final fit and the thickness of the surgical guide.[27]

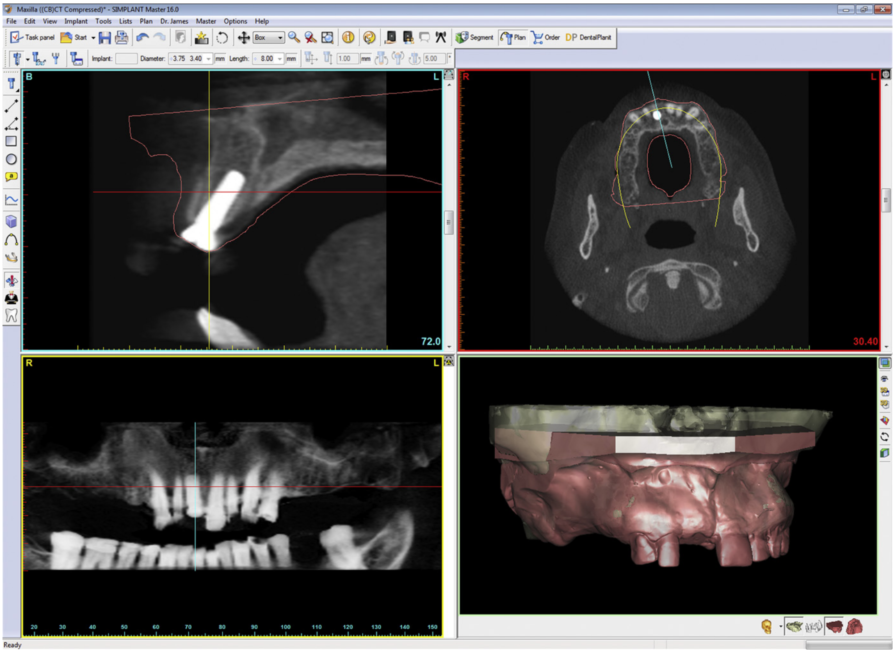


**Fig. 18.** Optical scanning.

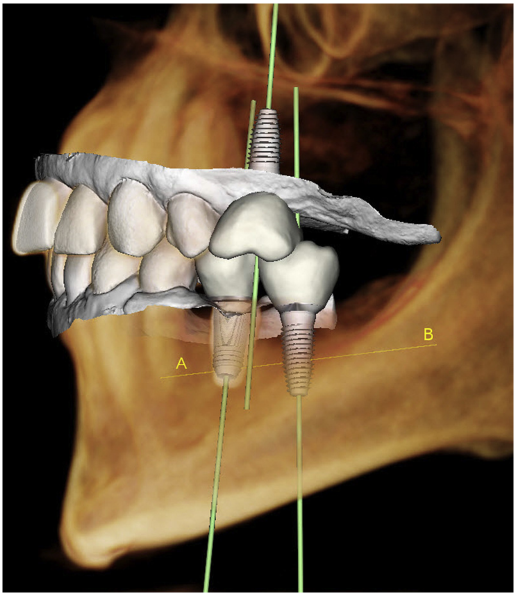


**Fig. 19.** Restorative considerations; 3D representation of a case. Image shows the planned implants and proposed restorations. The collision of the restorations illustrates the problem of interarch height limitations of this case.

A

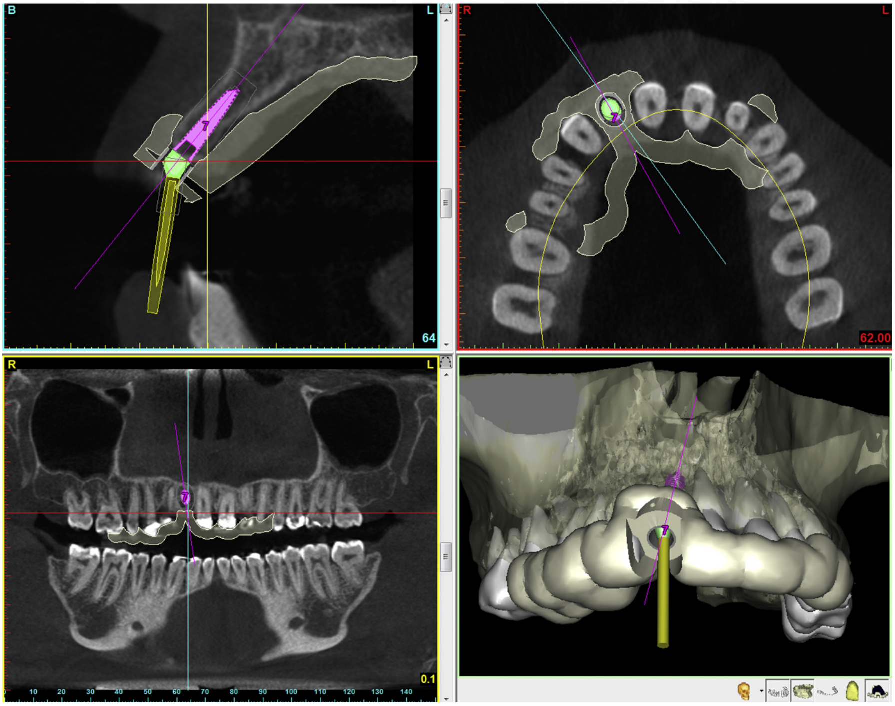


**Fig. 20.** Surgical guides. Examples of tooth-borne (*A*) or bone-borne (*B*) planning of surgical guides. (*C*) Mucosa-borne guide with temporary fixation pins.

### *Surgical Guide Support (Bone, Tissue, or Tooth Supported) or Fixation (Fixation Pins)*

In general, tooth- or bone-supported surgical guides are more accurate than tissue-supported guides. Bone-supported guides offer the best accuracy because of the decreased distance between the guide tube/sleeve and the entry point, but they do require an open flap approach. Similarly, guides for single tooth gaps display less variation when compared with guides designed for total edentulous patients.[28] The most common accuracy error occurs during the positioning of mucosa-supported surgical guides; inexact positioning of the template affects accuracy, which is more affected by a translational movement than a rotational one.[21] Contrary to general belief, neither reduced area of mucosa support (ie, maxilla vs mandible) nor mucosa thickness seems to affect accuracy significantly. The use of fixation screws during the surgical procedure does reduce random accuracy errors.[2]

### *Fully Guided Versus Partially Guided Osteotomy Protocols*

Fully guided protocols display less accuracy errors than partially guided protocols. However, fully guided protocols display tolerance between the sleeve in the guide, the directional guides, and the twist drills, which do introduce some error during implant placement.[29] Similarly, the diameter and length of the guide tube/sleeve, as well as the distance between the underside of the surgical guide and the implant site at the alveolar crest (ie, mucosal thickness) do influence accuracy errors.

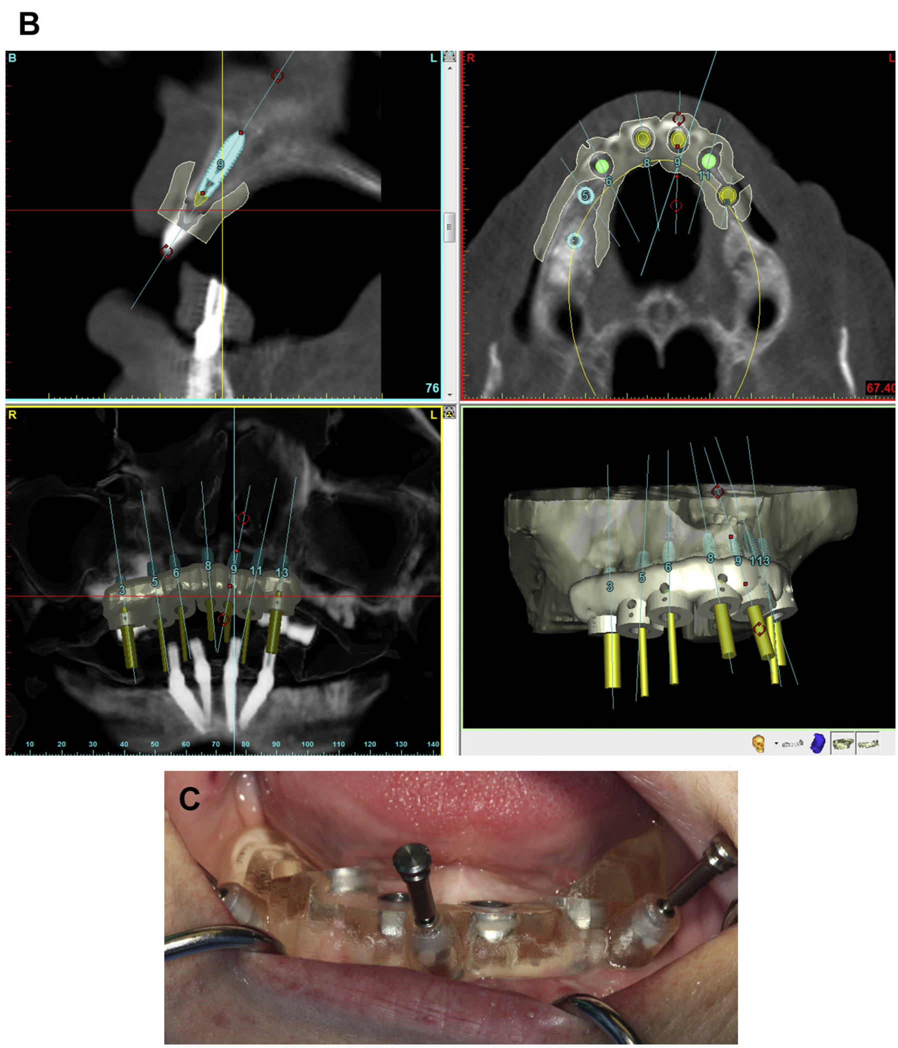


**Fig. 20.** (*continued*)

In general, longer sleeve lengths reduce angular deviation errors and shorter implants reduce apical deviations.[30]

#### *Final Implant Placement (Fully/Partially Guided Placement vs Freehanded Placement)*

In vitro experiments simulating clinical conditions have demonstrated that fully guided placement is more accurate than freehanded placement.[31] Other reports have found full and partial guidance to be clinically similar, although fully guided protocols show smaller variation when compared with partially guided protocols.[32]

Other literature reviews (including systematic reviews and meta-analyses) of accuracy and complications related to guided implant surgery are available.[11,33–39] Most reviews include information from cadavers or in vitro artificial models to in vivo patient-based evidence, and support different guided surgical clinical indications

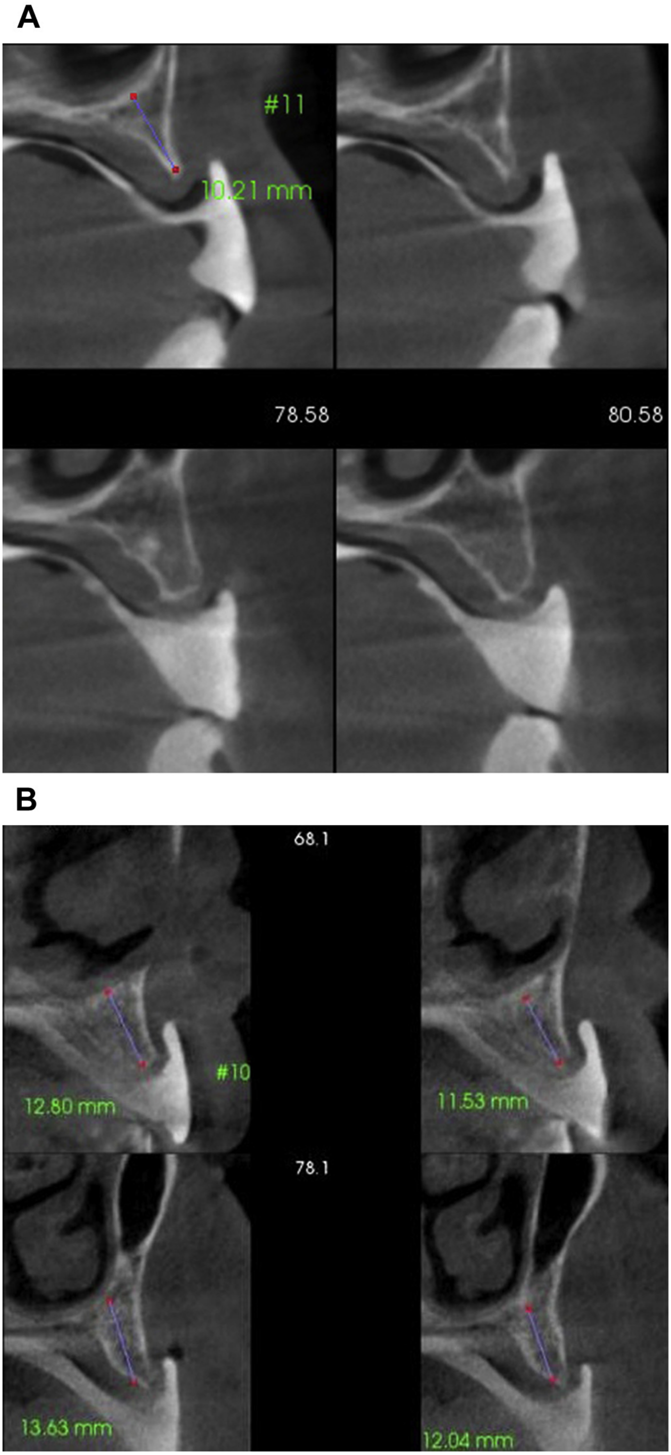


**Fig. 21.** Errors in image acquisition. Examples of poorly seated (*A*) and fully seated (*B*) radiographic stents. Notice the radiolucent areas between the stent and mucosa.

reporting reasonable levels of accuracy when applied clinically with similar implant success rates when compared with conventional implant therapy.[40] Broadly speaking, accuracy errors of guided surgery are generally reported within the range of approximately 0.3 to 1.6 mm or 3° to 5°, usually exemplified in the following 3 different aspects of the final implant placement position:

1. Coronal deviation (distance in millimeters), frequently defined as the horizontal or vertical (depth) distances between the midaxial coronal point of the planned implant and that of the placed implant position.
2. Apex deviation (distance in millimeters), frequently defined as the horizontal or vertical distances between the midaxial apical point of the planned implant and that of the placed implant position.
3. Angular deviation (in degrees), frequently defined as the angular difference of the axial projections of both virtual and final implant placements.

Researchers have used multiple different ways of measuring these accuracy errors by means of direct measurement in sagittal, coronal, or frontal slices; percentage of 3D superimpositions of reconstructed implant images, or in vitro direct measurements with caliper or other image software. Because of the use of a wide array of CT or CBCT machines, different guided implant surgical systems, different types of accuracy definitions, and different types of study designs (retrospective or prospective), it is difficult to make generalizable conclusions that can easily be extrapolated to all clinical scenarios. Nonetheless, general clinical recommendations can be formulated to reduce the error to minimum (or at least predictable) levels that do not result in the aforementioned surgical complications.

## SUMMARY

Virtual implant planning and guided surgery is gaining popularity and has been recommended to be the standard of care in many complex dental situations.[41] As the technology is adopted by different implant specialties, there is a related learning curve for each specific software package. This article has detailed different software tools that facilitate implant therapy planning in clinical practice and has also emphasized the need to develop a strict planning protocol that results in successful outcomes. Similarly, accuracy errors can be kept to minimal levels when sources of error are kept in mind during the planning of a case.

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