Dynamic Navigation for Dental Implant Surgery

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KEYWORDS

• Dental implant navigation • Dental implant surgery • Dental navigation
• Cone-beam computer tomography

KEY POINTS

- Many of the complications associated with the placement of dental implants can be directly related to inaccurate positioning.
- Implant placement using static guided surgery is very accurate; however, it is possible, due to cone-beam computer tomography (CBCT) discrepancy and/or incorrect placement of the guide, for gross deviations in implant position to occur.
- The current dynamic navigation workflow requires (1) a CBCT with fiducials, (2) virtual implant planning, (3) calibration, and (4) implant placement in accordance to the 3-D image on the navigation screen.
- Implant surgeons are able to evaluate a patient, scan the patient, plan the implant position, and perform the implant surgery in the same day without the delay or cost of fabrication of a static surgical guide stent.

INTRODUCTION

Implantologists have several options when it comes to implant planning and placement. Dental implant treatment planning and placement has benefited from accelerating technological capability in office-based imaging and complex simulation and planning software. The combination of software and imaging allowed for the development of static implant guides to achieve predictable accuracy in implant placement. Dynamic navigation (DN) has improved the process by providing surgeons a real-time navigation tool to improve the accuracy of implant placement.

Currently, DN is used by many medical specialties, including ophthalmology, otolaryngology, orthopedics, vascular surgery, neurosurgery, and surgical oncology. These specialties routinely use DN to perform simple and complex procedures with increased accuracy and precision.[1,2] In the field of dentistry, DN historically has been used primarily by oral and maxillofacial surgeons in the hospital. The medical DN systems used were designed primarily for craniomaxillofacial-based procedures, such as orthognathic, trauma, pathology reconstructive procedures and locating foreign bodies within the head and neck.[3,4] In the United States, a DN system was introduced in 2000 to assist in the placement of dental implants in the outpatient office setting. Subsequently, additional systems have been approved for this indication. The current DN workflow requires (1)

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obtaining a three-dimensional (3-D) scan with rigidly fixed or predictably reproducible and accurate fiducial marking systems; (2) virtual implant planning; (3) calibration and registration of fiducial markers, implant drill, and drill lengths with attached tracking arrays; and (4) implant osteotomy and placement in accordance to the 3-D image on the navigation screen.

FREEHANDED APPROACH

Currently, a majority of dental implants are placed freehand, without any form of computer 3-D planning. The surgeon creates an osteotomy using only adjacent and opposing teeth as a reference for position, and places the implant freehanded. When placing multiple implants to restore multiple missing adjacent teeth, a caliper or periodontal probe often is used to ensure appropriate spacing of the implants in a mesiodistal dimension. Intraoperative radiographs may or may not be taken to evaluate the osteotomy and implant position. The most important factor, however, is the clinical emergence of the implant in a restorable position. Position and angulation can be estimated with the use of direction indicators, but the final position must be evaluated at the time of placement by the surgeon. Many of the complications associated with the placement of dental implants can be related directly to inaccurate positioning. These include the following:

- Damage to the inferior alveolar nerve
- Floor of mouth hematoma
- Damage to adjacent roots
- Sinus infections secondary to inadvertent sinus perforations
- Fractured implants due to off-axis loading
- Periimplantitis due to food impaction and off-axis loading
- Poor esthetics secondary to thin buccal, labial bone, and soft tissue
- Interproximal bone loss secondary to placing implants to close to adjacent teeth and implants.
- Increased prosthetic complexity and cost

The intraoperative decision making, predictability, and difficulty in visualizing ideal position and angulation with a freehand approach have steered dentists toward the use of more advanced techniques in implant planning and placement.

STATIC GUIDED APPROACH

In order to aid in position and angulation, multiple types of surgical guides can be used. The most basic type is a stone cast-based static surgical guide. Cast-based surgical implant guides aid in ensuring appropriate restorable position of the implant but do not take into consideration the bone morphology. Further advancement with computer-guided implant surgery, also referred to as guided surgery or static navigation, uses computer-aided design and computer-aided manufacturing surgical templates based on digital planning of implant position, taking into consideration both the restoration and the bony anatomy, on specialized planning software.[5] Several factors have been identified in influencing the accuracy of implants placed using guided surgery. Cone-beam computed tomography (CBCT) precision, model matching to CBCT file, guide fabrication accuracy, guide sleeve tolerance, tissue support of the guide, accurate seating of the guide, patient maximum opening, fully or semiguided technique, and operator experience have all been cited[5–11] Implants placed using a guided approach show less deviation and more predictability than freehand placement, even for experienced surgeons.[9] There also are several clinical scenarios where a static guided surgery may be challenging or not possible, such as a patient with a narrow maximum opening that does not allow for the use of the guide and longer implant drills or limited interdental distance that does not allow for fitting of guide tubes. Although on average, implant placement using static guided surgery is very accurate, it is possible, due to CBCT discrepancy and/or incorrect placement of the guide, for gross deviations in position to occur.

DYNAMIC NAVIGATION TECHNOLOGY

The DN systems available in the United States are a form of computer-assisted surgery (CAS) that use optical tracking. There are 2 types of optical motion tracking systems: active and passive. Active tracking system arrays emit infrared light that is tracked to stereo cameras, and passive tracking system arrays use reflective spheres to reflect infrared light emitted from a light source back to a camera. The patient and drill must be over the line of sight of the tracking camera[12] (**Fig. 1**).

The current most commonly utilized DN technology is passive. Light is projected from a light-emitting diode light source above the patient. The light is projected down to the patient and the surgical field. The light is reflected off tracking arrays (passive patterned arrays) attached to the patient and the surgical instrument being tracked. The reflected light is captured by a pair of stereo cameras above the patient. The DN system then calculates the position of the patient and the

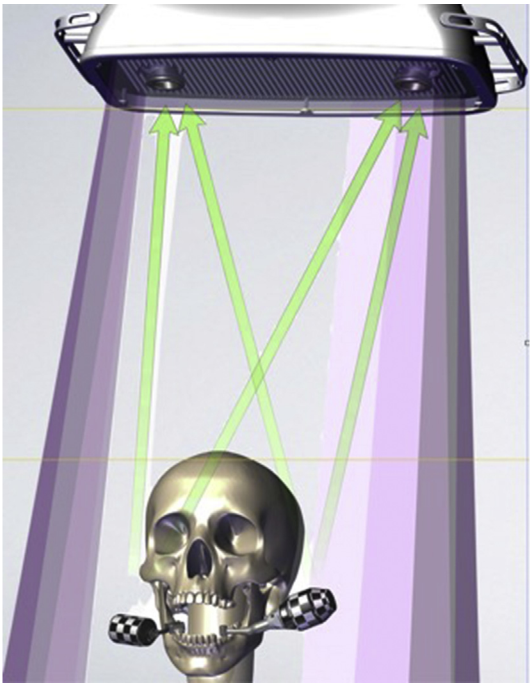

Fig. 1. The patient and drill must be over the line of sight of the tracking camera. (*Courtesy of* X-Nav Technologies, Lansdale, Pennsylvania.)

instruments relative to the presurgical plan. This is done real-time, or dynamically. A virtual image is then projected onto a monitor for the surgeon and staff. This virtual reality device allows the surgeon to work dynamically on the patient and execute the planned implant surgery. At any time, the surgeon can change the plan based on the clinical situation.[13]

DENTATE PATIENT FIDUCIAL

In the dentate patient, the fiducial clip allows for an impression of a patient's teeth to be taken (Fig. 2). This impression ensures that the fiducial clip is firmly supported by teeth and the fiducial clip goes into the same location in the patient's mouth every single time when being seated. It is important that the computer tomography (CT) scan is taken with the fiducial clip seated properly in the patient's mouth without any movement or rocking of the fiducial clip. The tracker arm attachment section of the fiducial clip should be on the buccal or cheek side of the patient. The fiducial clip must be placed on the arch where the surgeon is placing the implants but does not interfere with the drilling of the implants. In addition, it should be placed to minimize optical interference by the surgeons or assistants' hands and instruments. Teeth that are mobile, serve as pontics on a bridge, or have orthodontics wires should be avoided.

Fig. 2. In the dentate patient, the fiducial clip allows for an impression of the patient's teeth to be taken. (*Courtesy of* X-Nav Technologies, Lansdale, Pennsylvania.)

The fiducial clip is placed in a hot water bath at a temperature of 140°F to 160°F (60°C–71°C) for approximately 3 minutes to 5 minutes. When the thermoplastic on the fiducial clip is clear, it is ready to be used. The fiducial clip should cool for approximately 1 minute to reach a surface temperature less than 104°F (40°C). The fiducial clip is placed on 3 teeth, ensuring an equal distance on the buccal and lingual sides, with the tracker arm positioned on the buccal side. Vertical pressure is applied until the plastic surface cannot go further. Once an adequate impression is taken, the fiducial clip is removed without any rocking motion and then placed in a cold water bath. The fiducial clip then is tried again in the patient's mouth for confirmation of accuracy and to ensure there is no impingement of soft tissue. The fiducial clip should not have any mobility when seated. If there are short clinical crowns or teeth without undercuts, composite can be added to the buccal and occlusal surfaces of the associated teeth to help create immobile fiducial clip insertion. If multiple fiducial clips are placed in the mouth for a dual arch case or additional accuracy, the surgeon must ensure the fiducial clips do not touch.

EDENTULOUS PATIENT FIDUCIAL

An edentulous patient case requires edentulous fiducials (small screws) to be placed in the patient's bone to facilitate registration in the CT scan. The fiducials can be placed through the soft tissue of the patient via small stab incisions apical to the mucogingival junction or directly into the exposed bone by laying a flap. The surgeon must use careful discretion when deciding the location of the edentulous fiducials. The edentulous fiducials are also used in the preoperative process to register with the software prior to surgery. When placing the edentulous fiducials in the mandible, short 4-mm screws should be placed to avoid damage to the inferior alveolar nerve. The screws should be 1.5 mm in diameter, 4 mm or 5 mm in length, self-drilling, self-tapping, low profile, and stable. Typically, a 4-mm screw is recommended in the posterior mandible or in areas of dense cortical bone and 5-mm or greater screws in the maxilla or regions of immature, soft grafted bone. The edentulous fiducials must be placed in the arch where implants will be placed. If implants are to be placed in both the maxilla and the mandible, then edentulous fiducials must be placed in both arches. If vertical bone reduction is anticipated, the edentulous fiducials must be placed apical to the area of proposed bone reduction. The inferior alveolar nerve and the infraorbital nerve must be considered and avoided when placing fiducials. A minimum of 4 fiducials should be placed and spread out throughout the arch, leaving room for an edentulous fiducial plate (Fig. 3) to be inserted at the time of surgery.

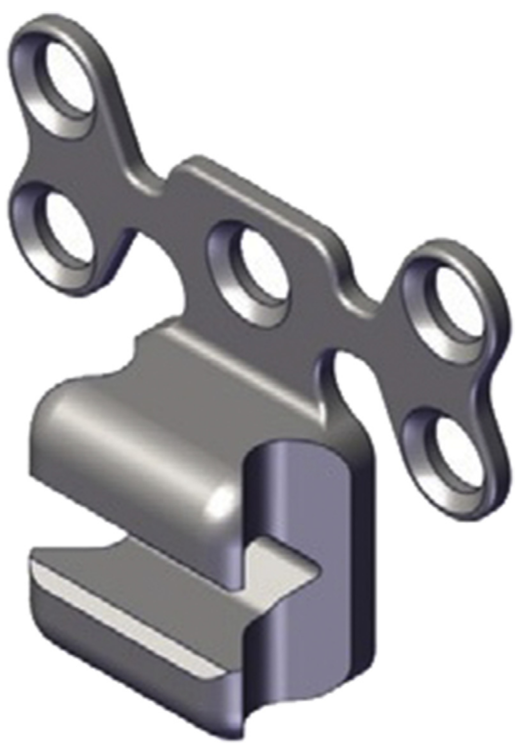

Fig. 3. A minimum of 4 fiducials should be placed and spread out throughout the arch, leaving room for an edentulous fiducial plate to be inserted at the time of surgery. (*Courtesy of* X-Nav Technologies, Lansdale, Pennsylvania.)

IMAGE ACQUISITION AND SOFTWARE PLANNING

Image acquisition includes obtaining 3-D files, usually a CBCT in a Digital Imaging and Communications in Medicine format (.dicom). The field of view of the CBCT or CT should include the surgical site and all fiducials. The scan is obtained with the plane of occlusion of the implant site parallel to floor. An important point related to the acquisition of the CBCT that is often overlooked is the separation of soft tissues while taking the image. For dental implant planning purposes, a cotton roll or radiolucent material place between the dentition and the buccal/labial mucosa creates an air contrast zone. This allows the soft tissue in the region of the free gingival margin to be visualized on the CBCT.

Dual scan is the term used when a dental appliance, such as a set of dentures, is superimposed over a patient's CT scan. If a dual scan technique is utilized, then at least five 2-mm fiducials should be applied to the denture. A high-resolution CT scan is obtained of the denture on its own and then a separate CT scan is obtained with the denture in the patient's mouth, ensuring not to disturb the fiducials on the patient and on the denture.

Another alternative is the use of an intraoral scanner (IOS). An IOS provides a 3-D surface image of the patients' dentition and occlusion. These are not volumetric images; IOS images are a surface. IOS images have a high degree of accuracy for single and quadrant impressions. When full arches are scanned, the accuracy decreases.[8] The implant team may wish to obtain IOS of the patient before teeth are extracted. If the occlusion is not going to be changed, these images can be saved for later use for planning of ideal implant position and provisional fabrication.

Once the images are acquired and stored, they are loaded into treatment planning software. There are numerous software packages available, but some key features should be present related to image processing and analysis. The software should be able to import and export generic file formats (.dicom and .stl), superimpose the 3-D files, perform dual scan .dicom superimposition and be able to export the images in a common coordinate system as an individual or merged item. When these clean .stl images are superimposed on the CBCT data, the combined images allow the implant team to plan, with the osseous, dental, and soft tissue structures clearly visible along with the patient's occlusion.

When starting to plan on the DN software, a panoramic curve for the arch requiring implants is developed on the axial plane of the patient's scan. On the mandible, the inferior alveolar nerve also can be identified and marked. Merger of the patient's scan and the IOS image or denture scan is performed, ensuring there are multiple area of coordination between the images for accuracy of the merger.

The planning of implants should be restoratively driven. This starts with evaluating the occlusion and placing the restorative envelope of the virtual teeth in the proper occlusal position. This can be done using virtual implant crowns available in the DN software. Another option is to use a separate prosthetic software to plan the restorations. The plan is then exported from the prosthetic software and imported as a .stl file into the DN software. Once the implant crown is finalized, the virtual implants should be properly aligned below the virtual crowns for ideal emergence into the prosthetic space. The DN software allows design of a generic implant or previously specified implant, implant platform diameter, implant apex diameter, implant length, and abutment height and angle (Fig. 4). Additional tools in the DN software allow mirroring to align implants across an arch and paralleling of adjacent implants.

Calibration

The instruments to be tracked by the system during surgery must be calibrated. The geometry of the tracking arrays relative to the instrument being used must be determined by the tracking system. The assembled parts must be placed in front of the stereo cameras so the software can "learn" their geometry. The instruments to be calibrated include the contra-angle handpiece, straight handpiece and probe tool.

Registration

The DN system must also be "taught" the geometry of the patient tracking array relative to the fiducials and thus the planned implants. This process is called registration. There is a specific registration workflow for both the dentate and the edentulous patient.

Workflow

The user may select a contra-angle handpiece, probe tool, and straight handpiece. At a minimum, the user must select a handpiece. The workflow adjusts to allow for calibration of the selected items. The calibration of the instrumentation occurs approximately 60 cm to 80 cm from the camera. The contra-angle handpiece along with the handpiece tracker is assembled and calibrated (Fig. 5). The handpiece is rotated such that the camera can locate and identify the patterns on the handpiece tracker. After calibration of the handpiece, there is a contra-angle handpiece chuck calibration (Fig. 6). The handpiece is attached to the chuck and then the drill motor is

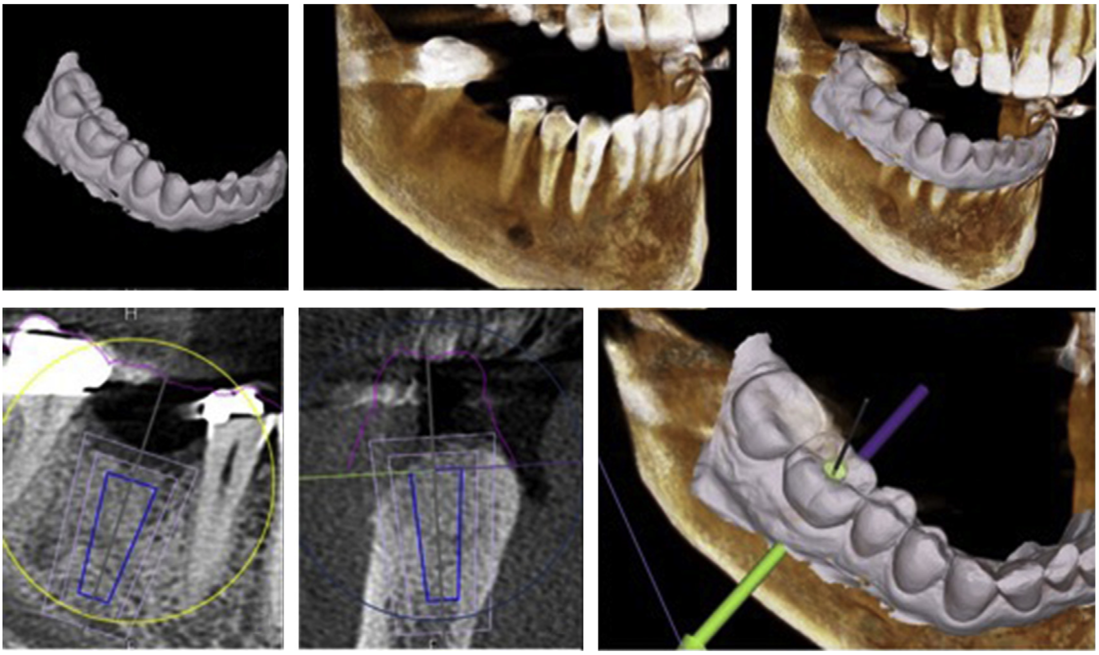

Fig. 4. The DN software allows design of a generic implant or previously specified implant, implant platform diameter, implant apex diameter, implant length, and abutment height and angle.

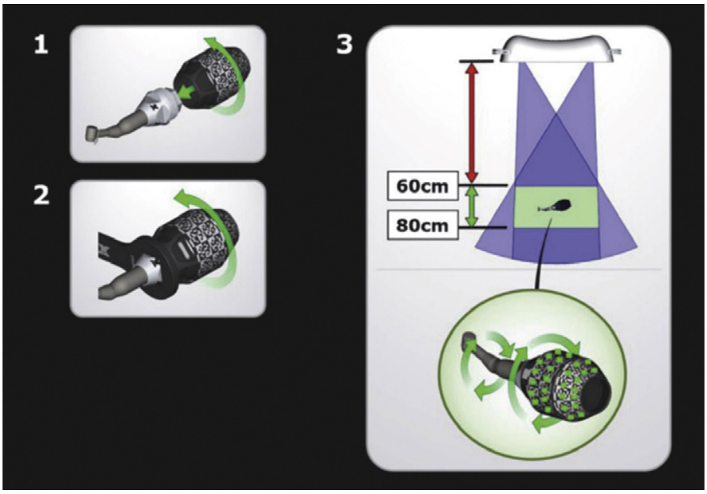

Fig. 5. The contra-angle handpiece along with the handpiece tracker is assembled and calibrated. (*Courtesy of* X-Nav Technologies, Lansdale, Pennsylvania.)

run at 10 to 20 revolutions per minute over the camera to calibrate the chuck plate to the handpiece. A Go Plate (X-Nav Technologies, LLC, Lansdale, Pennsylvania) and probe are calibrated by placing the probe in the pivot hole of the Go Plate. An implant drill bit is placed on the handpiece and the implant drill bit is placed on the Go Plate perpendicular to the center target (Fig. 7). The drill length is then verified by the DN system. If drill length measurement registration fails, then the handpiece chuck calibration may need to be executed again.

In the edentulous patient, an edentulous patient calibration probe is calibrated (Fig. 8). Then, the edentulous tracker plate is placed on the bone of the patient underneath a subperiosteal flap in an area of the bone where there are no edentulous fiducial screws. The tracker plate is attached to a patient tracker arm and patient tracker. The patient tracker and the edentulous fiducial screws are then registered to the DN system by touching the screws (fiducials) with the probe as the system tracks them. For the dentate patient, the fiducial clip attached to a patient tracker arm and patient tracker is registerd automatically by the system at the time of calibration.

The calibration accuracy is verified between the fiducials and the drill. The drill bit is placed on 3 fiducial spheres on the fiducial clip for the dentate patient or the edentulous fiducial screws. The doctor looks at the two-dimensional (2-D) views for accuracy data in green colors. If all three fiducials have green indicators the system calibration is within 200 micrometers. This step is not performed with edentulous patients.

Prior to the start of surgery and after every drill bit is changed there is a "system check" performed by the doctor. This step ensures the instruments are calibrated and the system is properly registered to the patient.

PERFORMING DYNAMIC NAVIGATION SURGERY

It is important to always confirm the accuracy of the tracking system by performing frequent system checks. Anatomical landmarks on the patient are touched with the instruments. The doctor then visually confirms that the radiographic landmarks on the screen are exactly correlating. The optimal landmarks are adjacent teeth or boney landmarks close to the planned implant site or fiducial markers on edentulous patients. The operator looks at the screen as the drill is positioned over the surgical site. The navigation system screen allows viewing of a virtual drill with demonstration of the depth in tenths of a millimeter, angular deviation of the drill bit axis from the planned implant axis to the tenths of a degree and the implant

Fig. 6. After calibration of the handpiece, there is a contra-angle handpiece chuck calibration. (*Courtesy of* X-Nav Technologies, Lansdale, Pennsylvania.)

Fig. 7. An implant drill bit is placed on the handpiece and the implant drill bit is place on the Go Plate perpendicular to the center target. (*Courtesy of* X-Nav Technologies, Lansdale, Pennsylvania.)

timing. The tip of the drill, a blue dot, is positioned over the target to indicate ideal planned platform position. The top of the drill a small circle is then centered over the blue dot to indicate ideal planned angle. Depth is indicated by color, yellow, green the red. The planned depth is always at the 45 position on the target. The surgical assistant is in charge of suctioning and looking into the surgical field to notify the surgeon of any irregularities such as lack of irrigation or grossly off-positioned drill placement (Fig. 9). As implant drilling occurs,

Fig. 8. In the edentulous patient, an edentulous patient calibration probe is calibrated. (*Courtesy of* X-Nav Technologies, Lansdale, Pennsylvania.)

Fig. 9. The surgical assistant is in charge of suctioning and looking into the surgical field to notify the surgeon of any irregularities, such as lack of irrigation or grossly off-positioned drill placement. (*Courtesy of* X-Nav Technologies, Lansdale, Pennsylvania.)

the depth indicator changes in color from green to yellow when the drill is 0.5mm from the targeted depth. The yellow will turn to red indicating when to stop the depth of the osteotomy (Fig. 10). During the implant surgery the implant size, width, type and location can be adjusted based on intraoperative factors deemed necessary for a stable and appropriately restorable implant.

DYNAMIC NAVIGATION ADVANTAGES

Implant surgeons are able to evaluate a patient, scan the patient, plan the implant position, and perform the implant surgery in the same day without the delay or cost of fabrication of a static surgical guide stent. This technology also allows the implant surgeon to change the implant size, system, and location parameters intraoperatively when clinical situations dictate a change. DN allows surgeons the confidence to know implant placement is appropriately in bone without having to open a flap, thus minimizing trauma to the patient.

The major benefit of DN is that it allows the surgeon to verify accuracy at all times of the surgery, as opposed to the static technique, where, if the splint is not appropriately positioned and fixated, there can be significant gross error of the entire implant surgery. The inaccurate placement of dental implants placed freehand has been documented in the dental literature.[14–16] There is a mean angular deviation for edentulous mucosal born guides of 2.71° (SD 1.36) versus freehand of 9.92° (SD 6.01). The mean angular deviations are similar for DN placed implants of 2.97° (SD 2.08) compared with freehand of 6.50° (SD 4.21).[16] Any form of CAS is statistically more accurate and precise than freehand placement because it overcomes the inherent inaccuracy of human vision. Crucially, the dynamic approach to implant

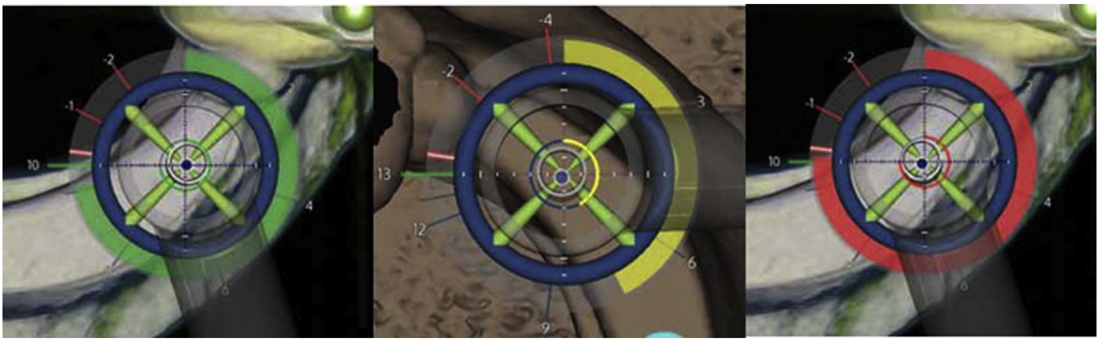

Fig. 10. As implant drilling occurs, the depth indicator changes in color from green to yellow when the drill is 0.5 mm from the targeted depth. The yellow turns to red, indicating when to stop the depth of the osteotomy. (*Courtesy of* X-Nav Technologies, Lansdale, Pennsylvania.)

placement has implant failure rates similar to those of static and traditional approaches.

Ergonomically, DN allows the surgeon to look at the screen more so than inside the mouth, decreasing the need to bend the back or neck for a prolonged period. DN also allows the surgeon to perform the osteotomy and place the implant with limited direct visualization in the mouth in patients with limited mouth opening or in cases of posterior implant placement with difficult visualization. It also allows for guidance of implant placement when interdental spaces prohibit appropriate guidance tubes with static guides, such as in the mandibular incisor region.

DYNAMIC NAVIGATION DISADVANTAGES

The implementation of DN requires significant investment for the dental implant surgeon. In addition to a CBCT and an IOS, there is the capital cost of the DN system. There is also per-case cost of fiducial clips, markers, and plates. Those surgeons with limited experience with technology and virtual image processing may find it difficult to transition to a different modality of practice. There is also a learning curve with the application of a new technology for all levels of technological comfort. The learning curve for one DN system was evaluated. The surgeon become statistically equivalent, proficient, after 10 to 20 implants placed with the system.[15] In addition, restorative dentist will require training to be comfortable with the workflow implemented by the implant surgeon.

Another downside is that the current FDA approved systems for edentulous patients require the additional surgery of the placement of fiducial screws and tracking plates. This obstacle will soon be replaced with a fiducial free method. The patient's anatomy will take the place of the screws. The doctor will select specific points on the CBCT during planning. After the patient tracker is placed the patient will be registered by toughing those points with the calibrated probe. Both dentate and edentulous patient must have also a potentially cumbersome tracking arms attached to their mouth. As the DN systems hardware and software mature these disadvantage will diminish.

SUMMARY

The natural progression from analog 2-D imaging and diagnostics to digital 3-D imaging and diagnostics has led to increased understanding of the complex nature of implant surgery and prosthetics. The increased utilization of these digital 3-D diagnostic and therapeutic modalities allows the surgical team to see the limitations of freehand surgery. CAS allows the implant team to overcome the limitations of human stereo vision and increase the accuracy and precision of implant placement. DN allows the surgeon to implement digital implant treatment plans in an efficient fashion. This efficiency and flexibility allow the team to utilize CAS on every implant in every patient. High-level statistical evidence clearly illustrates the improved accuracy and precision of CAS over freehand surgery.

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