Three-Dimensional Navigation in Oral Implantology: A Preliminary Investigation

Peter Randelzhofer, DDS, Dr Med Dent*
Jose Moctezuma de la Barrera, PhD**
Martin Spielberg, DDS, Dr Med Dent*
Claudia Kurtz, MD, Dr Med***
Jörg R. Strub, DDS, Dr Med Dent, PhD****

With the help of new support technology, oral implants can be planned and carried out in altogether new dimensions. The clinician is no longer restricted to his or her experience and the use of two-dimensional image-based procedures. The Stryker Leibinger navigation system now enables surgical planning based on three-dimensional models that can be endlessly manipulated; it produces an intraoperative view of the surgical field (online in real time). The aim of this study was to test a new surgical procedure with the use of a modified system that promises to be safer, more finely controlled, less complicated, and more valid in terms of predictive success than conventional procedures. In this preliminary investigation, the comprehensive system specifications are presented and a critical assessment of the procedural performance and potential is made. (Int J Periodontics Restorative Dent 2001;21:617–626.)

The recent advancements in software and computer technology in the area of image-guided surgery have led to dramatic general improvements in surgical practice.1–3 Computer navigation allows the surgeon accurate intraoperative access to preplanned locations in the patient's body. The planning is based on computed tomographic (CT) data and allows a greatly enhanced view of the surgical field.4 An outstanding advantage of this new technology is the safety with which surgical procedures can be carried out, certainly a value-added bonus arising from refinements in the planning, simulation, and real-world execution of the procedure.5–7

Today's image-guided surgery techniques make use mainly of optical tracking systems based on infrared light for the transmission of the instrument's and patient's position to the computer. Aside from the tracking system, the navigation unit consists of a data-processing computer and a monitor. The computer remains in continuous contact with the instruments used in the surgical field via the infrared camera, giving

*Assistant Professor, Department of Prosthodontics, School of Dentistry, Albert Ludwigs University, Freiburg, Germany.
**Manager, Therapy Technologies, Stryker Leibinger, Freiburg, Germany.
***Assistant Professor, Department of Diagnostic Radiology, Albert Ludwigs University, Freiburg, Germany.
****Dean and Chair, Department of Prosthodontics, School of Dentistry, Albert Ludwigs University, Freiburg, Germany.

Reprint requests: Dr Peter Randelzhofer, Academic Center of Oral Implantology, Theemf 154, 1186.KK, Amstelveen, The Netherlands. e-mail: peter.randelzhofer@web.de
the surgeon continuous updates regarding the exact position of the instruments relative to the patient.6,8,9

The technique described here has been used primarily in neurosurgery and orthopedic and maxillofacial surgery.1,10,11 In the 1980s, Vannier et al12 worked on the visualization of skull anatomy and pathology with the use of computer graphics. The CT data obtained were used to support planning and carry out craniofacial surgery. It took almost another 10 years before navigation and localization techniques were introduced in the form of simulated operations involving the use of anatomic representations of the structures to be treated.13–17 In 1993, Altobelli et al17 presented a computer system for the planning of intracranial surgery in which the bone representations derived from standard anatomy. Keeve et al18 based their surgical planning on the manipulation of representations of soft tissue structures to achieve a simulated postoperative image of the patient before the actual surgery.

Even though it is very likely that the experience drawn from these investigations will find broad application in various areas of dentistry, the intraoperative deployment of a computer-assisted system in the area of oral implantology promises the highest outcome improvements. The implants used in image-guided dentistry include titanium roots placed in the jawbone for teeth replacement to reestablish function, comfort, phonetics, and esthetics.19,20 The surgical procedure itself is limited by parameters such as available bone volume, bone quality, and the need to avoid damage to neighboring nerves and blood vessels.

Every oral implant procedure aims to make the best possible use of the available bone volume in surgical and prosthetic terms.21–24 Implantologic success depends first on the primary stability of the anchors, a factor that is directly related to implant sizing.25,26 The strategy in cases involving too little available bone volume (<8 mm) or other limiting anatomic factors has been augmentative or nerve-displacing procedures. Such procedures are technically difficult, time consuming, and expensive. Their overall success is also only somewhat predictable because of tissue resorption processes that are difficult to influence.27–29 In the long run, the use of a navigation system in oral implantology promises minimized collateral damage to neighboring structures, optimal use of available bone volume, and, with the use of a diagnostic splint, guaranteed prosthetically driven implant placement. Furthermore, this technology could increase the array of treatment capabilities involving dental implants and make elaborate supplemental surgical procedures unnecessary.

**System requirements**

The navigation procedure was modified to the task of dental implant placement. The existing software module (a Stryker Leibinger prototype) for orthopedics could be used without modifications, since it already features the sufficiently analogous navigated placement of osteosynthetic screws in the spinal column. The ability for both screw sizing and spatial orientation correspond to the requirements for the planning of dental implant procedures. The hardware and software prototypes of the Stryker Leibinger navigation system fulfill all the basic requirements for the surgical procedure, and they were exclusively used in the treatments described (Fig 1). The data used in the planning and surgical procedure were obtained using conventional spiral CT. A high-definition protocol was used (1-mm slice thickness, 1-mm table feed, and a gantry tilt of 0) to achieve optimal image quality (pixel size of around 0.5 mm).

The navigation computer requires a form of orientation assistance, or registration, so that the spatial relation between the surgical field and the stored planning data can be continuously evaluated throughout the surgical procedure. This assistance is provided by the use of fiducial markers in the form of four small beads (diameter of approximately 0.5 mm), which show up with high contrast in the CT images because of their dense molecular structures. One special difficulty in establishing adequate orientation involves the
positioning of the fiducial markers on the patient. While fixing them to the bone with screws gives precise and stable positioning, it necessitates an invasive preoperative procedure. Furthermore, since the fiducial markers cannot be removed between the time of the CT examination and the surgery—they must remain in the exact same position during this time—this too would mean added discomfort for the patient. Attaching the fiducial markers to the facial skin with adhesive bands also had to be ruled out because it would offer too little stability.

The integration of the fiducial markers in a drilling template emerged as the most promising method, since it permits a safe, stable, and reproducible registration of the patient. To construct the template, a waxup of the replacement teeth is first made according to prosthetic guidelines. Working from the waxup, a 2-mm-thick template is constructed. This thickness is advantageous because it ensures adequate stability; the template must retain its exact position throughout the operative procedure. The replacement tooth is then formed with a synthetic polymer. The prosthetically required implant location and desired axial disposition are marked with a radiopaque gutta percha marker that is afterward polymerized to the template. The marked implant position must be unambiguously identifiable on the CT. In the case of prosthetically complex cases, it is advisable to test the constructed template before the planned radiographic diagnosis to allow any necessary corrections. A further advantage of the overall setup is that it obviates the need to immobilize the patient’s head with a Mayfield clamp (Stryker Leibinger) because the tracking system automatically signals the patient’s movements to the computer for instantaneous assessment. This is achieved by rigidly attaching a tracking device to the template throughout the registration and surgical procedure. To achieve a high level of predictive precision, the markers were positioned in divergent axial planes. This ensures coverage of the greatest possible area in a nonplanar fashion, thus augmenting the achievable registration accuracy of the navigation apparatus.

The data are processed with various Stryker Leibinger software modules. First, a 3-D image is produced depicting the layered jaw area at any given plane and as a total reconstruction. In this multiplanar view, the exact image according to the anatomic disposition can be selected. This, as well as all of the other image-processing capabilities provided, permits a very intuitive and comprehensive processing of the data. The most important functions include adjustments of contrast (gray-shade fine tuning in the bone and soft tissue windows), object size (detail magnification up to 400%), and color (particular structures can be color coded). The screw planning program enables exact implant selection (length, width, diameter) and positioning (location in relation to neighboring teeth) according to the anatomic and prosthetic circumstances (Fig 2).

The connection between patient and computer is established by the infrared signals of the patient tracker (the dynamic reference frame) and the infrared camera (Stryker Leibinger). The dynamic reference frame must be fixed to the template and remain in position throughout the surgical procedure. Simultaneously, infrared signals from the navigation instruments (pointer and contra-angle drill, Stryker Leibinger) are picked up and processed along with all available data. A precondition for a safe procedure is a landmark test, which involves checking the instrument location at the surgical site against the position of the instrument shown on the computer. The landmark test must establish that real-world oral location and location on the monitor correlate exactly and that the internal referencing precision does not exceed a maximum deviation of 0.7 mm. Once the length of the drill body has been selected, the computer-assisted operation can begin. The clinician is afforded an exact view of every plane of the surgical site. The computer issues the planned objective, and the movement of the drill body is transmitted online (Fig 3).
Case presentation

The planning of the implant dimensions and position avoided intrusion into nerves and blood vessels. The results from laboratory trials and the specially designed devices were to be tested under clinical circumstances in a way that would also permit inspection of a mobile mandible. Therefore, a newly designed moveable system was examined and clinically used for the first time.

A healthy, middle-aged man with two short-span fixed partial dentures was treated with a navigated oral implant in the area of the mandibular right first molar (Fig 4).

At the first appointment, the medical and dental histories, clinical recordings, and impressions and panoramic radiographs of both jaws were taken. The study casts were mounted in a semiadjustable articulator using a facebow transfer and check bites. On the basis of the results, prosthetic treatment
planning was carried out and a particular restorative therapy established. The investigations revealed no contraindications to implantation. The dental panoramic (Ortho Oralix FD 5, Gendex) showed sufficient available bone volume. Since the precise selection of the implant dimensions was to be made only after the more comprehensive 3-D CT images were available, the dental panoramic was employed only to establish the possibility of direct implant treatment.

A waxup of the missing first molar was fabricated by the dental technician. This served as a guide for the construction of the 3-D radiographic template, which was then transferred to a drilling guide (3-D navigation template). The replacement tooth was to be reconstructed so that it matched the arch and opposite arch esthetically and functionally. The drilling template supported by the teeth was produced with a thickness of 2 mm to achieve adequate stability. The waxed tooth was formed with a silicone wrench (Moldasil, Heraeus Kulzer) and later transposed in transparent polymere (Pro Base, Ivoclar). With the aim of being able to identify the implant position on the axial overview of the CT image, a radiopaque gutta percha (Roeko) marker of approximately 3 mm in length was inserted into the replacement tooth. The gutta percha marker, whose purpose is to indicate the desired implant position, should be of an adequate length so that it can be located on the axial CT slices that run in spatial increments of 1 mm. The fiducial markers necessary for registration prior to navigation were arranged on various axial planes and polymerized to the template with a clear synthetic (Pro Base) after being fixed with quick-bonding glue. After double checking the fit of the template, the patient was sent to the radiology department for CT scanning. Proper template fit and stability is important because the positioning during the CT (Somatom Plus 4, Siemens) examination must be identical to that during the subsequent surgical procedure. The radiographic examination is carried out with a closed bite to ensure greater template stability.

The CT images were stored on a magnetic optical disk and downloaded to the navigation computer for evaluation. The jaw to be treated was comprehensively imaged and reconstructed in a multiplanar view (Fig 5). The mandibular reconstructions could be imaged at any given plane, beginning from the base planes (axial, sagittal, and coronal). In addition, a complete 3-D reconstruction of the jaw was produced and the various base planes displayed next to one another. Afterward, the navigation system's most contrast-rich gray value distribution was selected in the bone window to facilitate a better assessment of the bone and soft tissue. Detail areas were evaluated at a magnification of up to 400%. This enabled optimal ascertainment of the inferior alveolar nerve canal. The nerve structure was color coded in several horizontal slices.

The final implant treatment planning was carried out with the screw planning program, in which the imaging of the various planes resembles that of a multiplanar view and a simulated implant can be positioned in any given plane and dimension in relation to neighboring teeth and opposite arch (Fig 6). The exact location for the subsequent implant was determined in accordance with prosthetic planning and was double checked using a distance measurement program. The color-coded representation of the inferior alveolar nerve facilitated determination of the maximum implant length. The implant diameter was determined via the representation of sagittal slices. The correct choice of implant dimensions can be checked by inspecting the axial slices. At any given slice, the implant must be surrounded by at least 2 mm of bone or maintain a distance of at least 2 mm from the inferior alveolar nerve canal (Fig 7).
The final implant selection in terms of implant number and dimensions was undertaken only after concluding all of the described measures. One implant for the mandibular right first molar (width 3.75 mm, length 13 mm; Brånemark Mark 2, Nobel Biocare) was selected. The time required for this elaborate planning was 10 minutes.

Afterward, the dynamic reference frame, responsible for signaling the disposition of the mandible to the infrared camera via light diodes, was polymerized to the drilling template with Pattern Resin (GC). The pointer (necessary for the registration procedure) and the surgical handpiece (Kavo) were then verified to ensure that their physical shapes matched the stored geometry in the navigation system (Fig 8). This procedure follows the calibration of the instruments with the navigation system and requires approximately 0.5 minute. Both instruments are outfitted with several infrared light diodes whose function is to communicate with the computer via the infrared camera for the purpose of disposition recording. All instruments fitted with light diodes must remain in continuous contact with the infrared camera. If line of sight does not exist for at least three diodes, the navigation function is interrupted and a message is displayed on the computer monitor.

Local infiltration anesthesia (buccal and lingual) was used for the implantation. The flap was begun as a sulcus incision, followed by an incision on top of the alveolar ridge. The circumcised papillae were carefully detached with a papilla scalpel (CKN 1/2, Hu-Friedy) before the flap could be moved beyond the mucogingival border. The navigation template could be brought into alignment each time without obstructing the full-thickness flaps. After the repositioning of the template, the registration accuracy was checked by referencing the fiducial markers via the calibrated pointer. The limit for registration inaccuracy was set to 0.7 mm. To achieve good results, the markers must be approached as gently as possible. The interaction with the software was done by a
member of the surgical team via remote control.

Before the actual implant treatment began, a landmark test was carried out. This involved setting the drill bit to anatomically prominent points in the patient’s mouth and seeing if the monitor represented the position of the drill bit exactly. The approach of all drill bodies (from spiral drilling to implant placement) to their targets in the bone was followed online (Fig 9). The position established as optimal at all planes during treatment planning was impeccably followed by the drilling instruments, making it easy for the surgeon to achieve proper implant placement.

After successful implant placement and setting of the cover screw, the surgical site was rinsed with sterile saline and closed (leaving an eye to reduce pressure) with mattress and stabilizing single-head sutures (Gore-Tex CV-5, 3i/WL Gore). Postoperative radiographs revealed a correlation with the preimplantologic planning. The distances between all structures taken into account during planning were precisely reproduced (Fig 10).

Discussion

The improvements in quality and the minimization of risk associated with navigation-assisted surgical techniques are no longer questioned. The achievable average precision for operative navigation is currently approximately 2 mm. While this level of precision may be of great help in the work of maxillofacial surgeons and neurosurgeons, it is not yet adequate for dental implantation.

Aside from the matter of precision, the foremost problem remains the system’s limited flexibility. Hope in this regard centers on enhanced referencing systems and ergonomically improved tools. The most recent publications concerning navigation-assisted implant placement are restricted to procedures involving the maxilla, which is relatively easy to immobilize. Millesi et al see the future of image-guided surgery in the (remote) interactive cooperation
of several specialists, with the possibility of joint onscreen planning and real-time evaluation of results.

The navigated implantation procedures we conducted demonstrated some progress in relation to other current contributions to the literature. The extra time required for the implant treatment planning was reasonable, especially considering the fact that shorter times could be achieved using software designed especially for oral implantology. The extra time for implant treatment planning is on the order of 15 minutes for less elaborate cases and up to 45 minutes for more elaborate cases. In light of the increased procedural simplification, the extra time required during surgery is insignificant.

The special software measuring system in the screw planning program enabled a precise estimate of the required minimum distances between tooth and implant. The number of implants and their length and width can also be determined exactly. Additionally, a prosthetically perfect implant inclination can be presented via the 3-D anatomic representations, especially those of adjacent teeth. A further advantage results from the CT imaging itself, as this sort of preimplantologic diagnosis shows a distortion-free representation. The possibility of representation from any given level offers the practitioner access to far more varied information than is available via conventional radiographic diagnostics.

A definite drawback to this method is the radiation exposure during the CT examination, as it exceeds that of conventional dental radiographs by an average factor of 10. In the interest of optimal preimplantologic diagnoses, it is certainly desirable to be able to fall back on conventional dental radiographs. As CT examination is an indispensable part of interactive implant navigation, it seems best to select from the available treatments on a case-by-case basis. Current studies whose aim is to replace CT examinations with MRIs constitute a promising development.

The metallic materials used in restorative dentistry create star formations on the axial planes of the reconstruction. Since the CT images are based on a density measure of the tissue types, optimizing their evaluation requires referring back to slices lying above or below these levels. Although this can be problematic in connection with metal cores reaching into the bone, the problem did not arise in the cases we examined. The extent to which artifacts from metal cores have a bearing on navigation planning remains to be investigated. The artifacts stemming from the bead-shaped fiducial markers do not limit the view of the reconstructions. On the contrary, these are easily recognizable and targetable. The markers caused difficulty only in connection with the metallic reconstructions, since an identification of the points required precise analysis. Titanium materials do not produce artifacts.

The use of the equipment in an average-sized operatory was unproblematic, although more space-saving equipment would be advantageous. Also unproblematic was the use of the surgical instruments, although smaller ones in the sense of improved ergonomics would be advantageous. A redesign of the dynamic reference frame is especially necessary, as it exerts considerable strain on the template because of its size (diameter of 12 cm). While a space-saving version had already been developed at the time the study took place, it was not yet ready for use.

Continual communication between the light diodes attached to the surgical instruments and dynamic reference frame and the infrared camera is especially important. Although this was not a problem, it is easy to imagine that it might be difficult to avoid interrupting signal flow given an inconvenient implant localization. The achieved registration accuracy was 0.52 mm, indicating that intraoperative manual precision adjustment in 3-D navigation within the space defined by the fiducial markers is not a viable option; a means to more accurately position the navigated surgical instruments would considerably reduce trial positioning time. An inaccurate image can be problematic, especially when an attempt is made to circumnavigate the inferior alveolar nerve during implant treatment. A distance of 2 mm appears to be sufficient, especially considering that the borders of the structures represented in the CT image are rendered as quadratic pixels.

It is clear that navigation offers a simplification of the entire surgical procedure owing to the possibility of
viewing the surgical field and carrying out continual procedural checks. It enables the less experienced clinician to proceed safely and predictably with difficult implant cases. In the future, a programmable, partially or fully automatic system could present additional improvements.

There remains a discrepancy between the measured distance from the implant to the inferior alveolar nerve as seen on the CT image and panoramic radiograph. The discrepancy is so pronounced that when compared to the CT, the dental panoramic suggests a larger vertical bone volume. As the literature attests to an almost absolute correlation with real-world anatomy in the case of the CT, we are inclined to suspect the dental panoramic of transmission distortions. The other possibility lies in the representation of the nerve in the navigation system’s software program. It is conceivable that loose bone spongiosa above the nerve presents a density similar to that of the nerve and so is difficult to distinguish from the nerve. The latest developments aim at representing the nerve structure via automatic, continuous density measurement. This would make it possible to mark the nerve by clicking the cursor on two sagittal slices lying at a distance from one another and so obviate the identification of the nerve via individual axial slices. The computer would then automatically check the area between these two slices for the exact density of the nerve tissue and so also document the nerve canal in its exact extension.

Lastly, the navigation system is prohibitively expensive (approximately US$150,000) and lies well beyond the means of the average dental practice. The high price, however, is directly related to the number of units manufactured and sold. Increased sales would likely reduce the purchase cost considerably.

References


