THE EVOLUTION OF MULTIPLANAR DIAGNOSTIC IMAGING: PREDICTABLE TRANSFER OF PREOPERATIVE ANALYSIS TO THE SURGICAL SITE

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KEY WORDS

Helical CT
Stereolithography
Imaging software
Surgical guide

Presurgical planning and communication between the prosthodontist and the surgeon is essential to achieve optimal placement of functional implants. Besides the basic clinical examination and the use of mounted study casts, radiographic imaging is an essential adjunctive aid in treatment planning. In the past decade, multiplanar reformatted computerized tomography (CT) has become the most comprehensive and accurate aid for implant treatment planning. Available software programs allow precise assessment of the 3-dimensional architecture and internal anatomy of the jaws. The programs enable accurate preoperative evaluation for planning implant placement with a maximum use of bone. However, the accurate transfer of the implant analysis from 2- and 3-dimensional computer reconstruction to the surgical site was not predictable until recently. As advancements occurred in technology with the advent of the helical CT scanner and rapid prototype 3-dimensional model production by stereolithography, a CAD-CAM program was developed to create an accurate transfer from the image to the surgical site. Detailed preoperative analyses of the quantity and quality of bone as well as the ideal positioning of implant fixtures may be established with the aid of a surgical guide that is placed directly on the bone for precise implant insertion.

INTRODUCTION

During the past 15 years, there has been a significant evolution in the ability to use noninvasive technology to visualize human internal structures in their true form and shape. The discovery of X rays gave birth to radiology. The invention of computerized tomography (CT) and magnetic resonance (MRI) imaging has revolutionized radiology. Presently, 3-dimensional (3D) imaging and medical applications are allowing medical practitioners to not only visualize human organs but also to simulate reconstructive and invasive procedures.[1–4]

The irregularity and atrophy of the

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partially edentulous and fully edentulous mandible and maxillae and the ability to reconstruct them often perplex dental practitioners. Computer-assisted design, computer-assisted manufacturing (CAD-CAM), and multiplanar diagnostic imaging have allowed the practitioner to expand his or her horizons of clinical treatment.[5,6]

CT and MRI imaging have revolutionized analyses of the maxillofacial bones and their overlying soft tissue.[7] With these techniques, however, the surgeon must mentally integrate 2-dimensional (2D) data into 3 dimensions for clinical applications. Technology that generates 3D images from conventional computerized tomographic scans has advanced the analysis of human anatomy.[8]

A patient's slice data from CT scan images is analyzed via automatic contouring algorithms to provide a representation of the surface of the studied structures.[3,4,9] These structures can be displayed on the screen, compared against normative references for surgical planning, and modified to represent a simulated surgical operation.[3] Implant design and bony augmentation can be simulated on-screen as well.

In 1986, Fellingham et al[9] first demonstrated the use of interactive graphics and 3D modeling for surgical planning, prosthesis, and implant design. 3D images were transmitted to a computer-controlled milling machine for reproduction of the anatomical structure. This technology was used to reproduce atrophic mandibular and maxillary jawbones for full arch subperiosteal implants. Cranin et al[10] performed an in vitro study comparing the accuracy of bone models made from direct bone impressions and generated by CT/CAD-CAM technology using maxillae and mandibles harvested from cadavers. This study revealed that the CAD-CAM method yielded adequate castings in 5 of 7 cases. However, the authors reported desiccation of the specimens, micromovement, and a low sample size for the maxillae that may have contributed to the discrepancy in 2 of the cases.

Harris et al[6] concluded that ''all subperiosteal implants constructed on the CT model were well fitted and clinically acceptable when surgically inserted.'' Harris et al,[6] James,[11] Golec,[12] and Benjamin[13] in clinical reports demonstrated accuracy of implant fit and accurate reproduction of bony anatomy when CT scan and multiplanar diagnostic imaging were used. Thus the physical model permitted a more accurate contour and volume analysis in a more easily interpreted format than 2D data.[14,15]

Research and development have allowed the endosseous dental implant to become an acceptable treatment modality to be used as a prosthetic support. However, diagnosis and proper implant planning remains the key to success in implant dentistry.[14] In the past decade, multiplanar reformatted CT has become the most comprehensive and accurate aid for endosseous implant treatment planning.[15–17]

Advancements in diagnostic technology, namely helical (spiral) CT and stereolithography, have allowed for the development of a CAD-CAM processed surgical guide to be placed directly on the bony site. The surgical guide facilitates the predictable transfer of the analysis of the bony morphology and accurate positioning of the endosseous implant.

CT SCAN

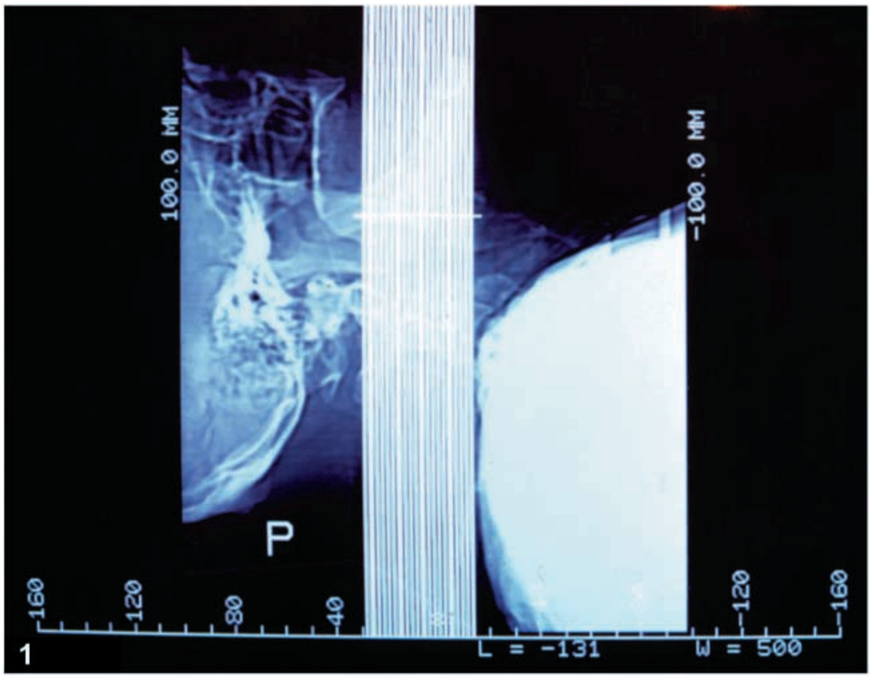
The input data for all CAD-CAM multiplanar diagnostic imaging is retrieved from CT technology. Since its introduction, helical (spiral) CT has dramatically changed the performance of CT scans.[7,18] The elimination of respiratory misregistration artifacts, the minimization of motion artifacts, and the production of overlapping images without additional radiation exposure are the most important technical advantages of helical CT. Such advantages have improved existing CT applications and have led to new applications involving multidimensional imaging.[19] Multiple transaxial images can be retrospectively reviewed from a single helical CT scan data set with various degrees of overlap. Thus 2D and 3D reformations may be generated with a maximum degree of longitudinal resolution optimizing image quality.[20] In addition, the rapid acquisition of a helical scan data set (less than 30 seconds) in a single breath-hold eliminates discontinuities in the reconstructions because of variations caused by respirations.[21]

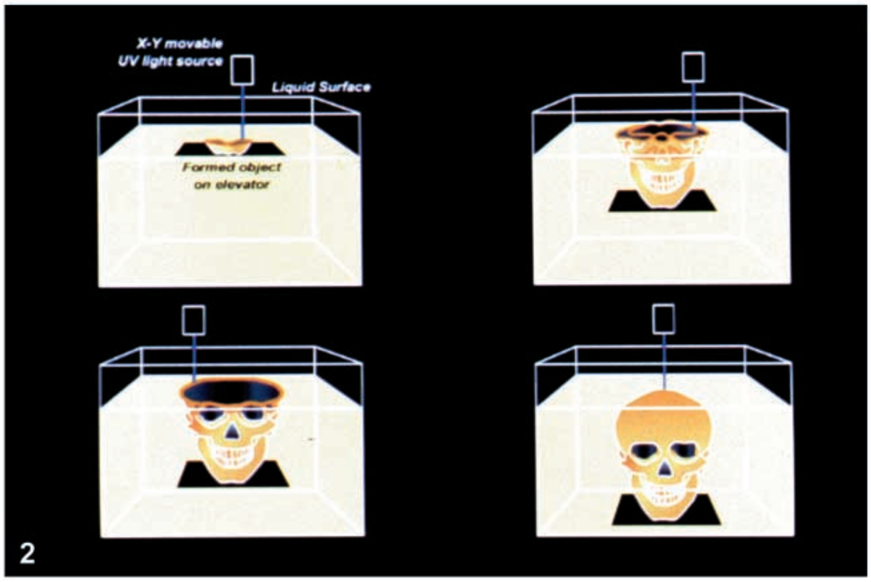
Whereas conventional CT scanning involves alternating patient translation and X-ray exposure, helical CT scanning involves simultaneous patient translation and X-ray exposure.[7,18] The technique is so named because the X-ray can be thought of as tracing a helix or spiral curve on the patient's surface. With conventional CT scanning, each rotation of the X-ray tube generates data from which corresponding transaxial images are constructed. With helical CT, each rotation of the X-ray tube generates data specific to an angled plane of section. This allows reconstruction of the transaxial image retrospectively and at very small increments, resulting in highly overlapping images. The retrospective reconstructive capability of helical CT scans permits substantial improvement in longitudinal resolution at small intervals without an increase in X-ray dose.[18,22]

Using a helical CT scan, the mandible or maxillae is scanned in a 14-cm field of view (FOV), 512 matrix, 1-mm slice thickness using a standard algorithm with the gantry tilt set to 0. The study is performed without the use of contrast material. Once the scan prosthesis is placed in the patient's oral cavity, the patient's head is positioned so the residual ridge is parallel to the scanning plane (Figure 1).

CONVERSION OF IMAGE DATA

CT scan image data from a study is placed on an optical disk, CD-ROM, floppy disk, or magnetic tape. The CT scan image data must be produced according to a specific scan protocol so





FIGURES 1–2. FIGURE 1. Axial images programmed on the computerized tomography (CT) scanner in lateral scout view. FIGURE 2. HeCd laser polymerizing an epoxy resin to produce a rapid prototype model.

the data are compatible with the imaging software. The imaging software (Mimics, Materialise/Columbia Scientific, Glen Burnie, Md) converts slice image data into 2D and 3D computer models for analyses.

CT scanners routinely obtain slices in a transverse plane. The imaging software performs 2D image processing by reformatting the data along planes and/or curves. The simplest reformatting is the construction of images that show slices oriented orthogonally to the original plane of section. These are called planar reconstructions: sagittal if they pass through the midline and are oriented front to rear; coronal if they pass through the midline and are oriented left to right; parasagittal or pericoronal if they are parallel to the sagittal or coronal plane and do not pass through the midline; and paraxial if they are obliquely oriented.[2,23]

Reformatted images are performed by reading in all the slices that are in the region to be viewed and selecting those pixels (a single element in a rectangular array of elements that form an image) that fall on the plane. Anywhere that there is no original pixel that corresponds to that location, the imaging software interpolates a pixel. Interpolation is a form of averaging, where pixels in the immediate neighborhood are weighted differently and added together to calculate the density at some location that does not exactly correspond to an original pixel.[3,4,9]

In order to make 3D images of the anatomy, a 3D coordinate system must be established. Each slice of data has a location relative to the other slices given by the amount the table indexed between acquisitions. The distance between slices establishes the third dimension, the other 2 dimensions being right/left and up/down on each slice.[4]

The imaging software can interpret the sequence of slices as a ''volume'' of data taking into account the overlap of slices. In order to create a 3D image of bone, for example, the slices are individually processed to extract only the tissue of bone density range. Where necessary, slices are interpolated between the original slices to give a more realistic 3D image. The edges (or contours) of the anatomy of interest, in this case bone, are stored for the entire set of slices (including the interpolated ones) as a ''contour file.'' It is this contour file that is processed to create the 3D images.[23,24]

The 3D images are created by rotating the contour file in space and then computing what the visible surface of that tissue looks like. If multiple contours are used to create a single 3D image, 1 of the objects can be translucent. The imaging software computes the appearance of the tissue by using ''lighting'' models to simulate the effect of light shining on the tissue.

In addition, the imaging software provides the capability to alter (edit) the contour files themselves. This is useful for editing out obvious metal artifacts, doing disarticulation, or for designing implants. Since the contour file itself is being modified, subsequent 3D images generated from that file will show the results of the editing operation.[4,24]

STEREOLITHOGRAPHY

In 1986 Dev et al[9] developed a computer-controlled, indirect milling machine for reproduction of an anatomical structure. Although accuracy was demonstrated, 3D imaging has evolved into a discipline of its own dealing with the various forms of visualization, manipulation, and analyses of multidimensional medical structures.

Further development resulted in the rapid prototyping technology of stereolithography. Once CT scan data have been segmented, the software interpolates the data on all 3 planes to form a smooth 3D model. A computer file of this model is transferred to stereolithography equipment where a physical model of the patients bone structure is created.

Stereolithography is a computer-driven process that creates precise models using lasers and epoxy resin. A computer-controlled HeCd laser generates an ultraviolet beam, which travels across the surface of a vat of photocurable liquid polymer. The laser draws each cross section of the anatomy 1 layer at a time. The photovoltaic energy from the laser polymerizes the epoxy immediately. The cured cross-sectional layer is lowered into the vat of resin and the next layer is processed. Successive layers of the anatomy are built in 0.15-mm increments until the model is completed (Figure 2).[25,26]

BONE AND IMPLANT SURGERY DESIGN

Prior to the CT scan, a scan prosthesis that plays several critical roles in obtaining accurate input data is developed.[27] The scan prosthesis stabilizes the opposing jawbones to prevent jaw movement during the CT scan. Although motion is minimized with the helical CT, even slight jaw movement needs to be prevented. Second, occlusion and future tooth set-up can be simulated and represented in 2D and 3D reconstructions.

The base of the scan prosthesis should be constructed to represent a radiolucent appearance on the transaxial images. Porous maxillary bone and knife-edge ridges on the mandibular bone must be distinguished from the CT scan prosthesis. Prosthetic teeth are represented as radio-opaque images clearly distinguishable in form and figure. Simulation of the prosthetic tooth position can be accomplished using porcelain denture teeth, coating acrylic teeth with 10% barium sulfate, or using gutta percha markers or a similar radio-opaque material.

The CT scan prosthesis facilitates proper angulation of the jawbone to be scanned. By scanning either the mandible or maxillae parallel to the residual ridge, the number of slices needed to cover the bony morphology required for the study are minimized. In addition, perpendicular oblique images to the axial images are more accurately represented.

Positioning and angulation of the individual jawbone becomes critical when metal restorations are present. Pure titanium is the only metal that does not produce a flash artifact (scatter) when the X-ray beam passes through it.[18]

Due to the resorption pattern of alveolar bone once natural teeth are lost, the edentulous residual ridges will be at either an inferior level on the mandible or a superior level on the maxillae to the natural teeth. Axial images are programmed either 2 mm above the residual occlusal ridge to the inferior border of the mandible or 2 mm below the residual occlusal ridge to the zygomatic arch of the maxillae in order to alleviate the scatter effect from metal restorations in natural teeth.

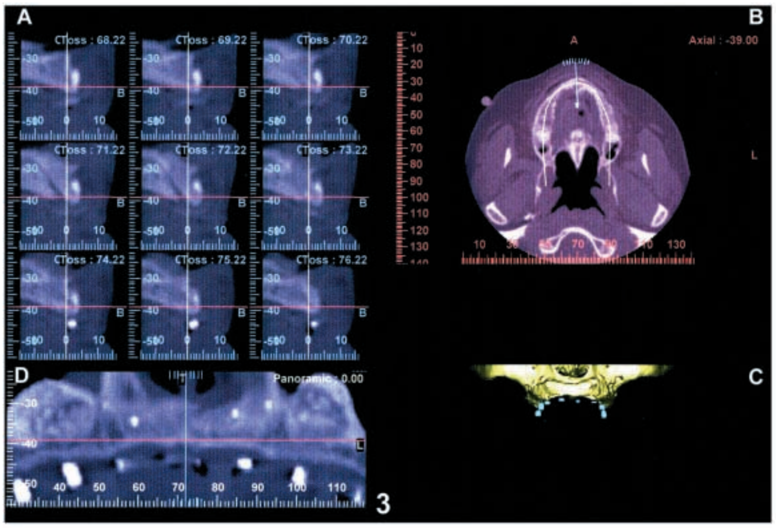
Software programs have been developed (SIM/Plant, Materialise) for enhancing implant surgery planning in order to obtain exact morphological measurements of the bone and simulation of the final prosthesis. The objective of the software program is to determine the quantity and quality of bone and relate implant placement to proper prosthetic requirements.[28,29]

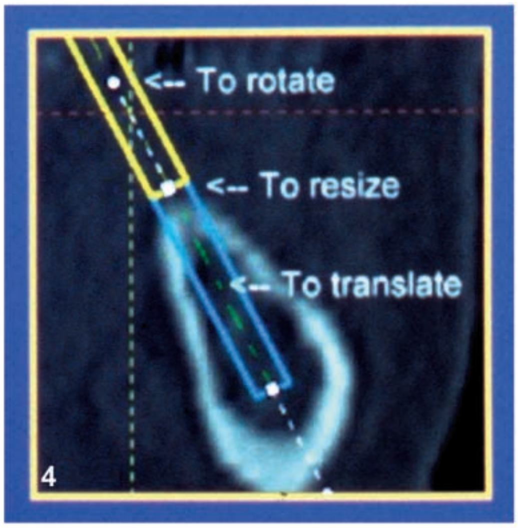
Reformatting a data set begins analysis of the bony morphology and internal structures. By drawing a panoramic curve on an axial image, a panoramic image and cross sections are created. For a mandible, the panoramic curve is normally drawn on the axial image at a level at which the mental foramen is evident. The floor of the maxillary sinus represents a good anatomical landmark for a panoramic curve of the maxillae. However, based on unusual anatomical situations, the panoramic curve may be positioned either superior or inferior to these landmarks.

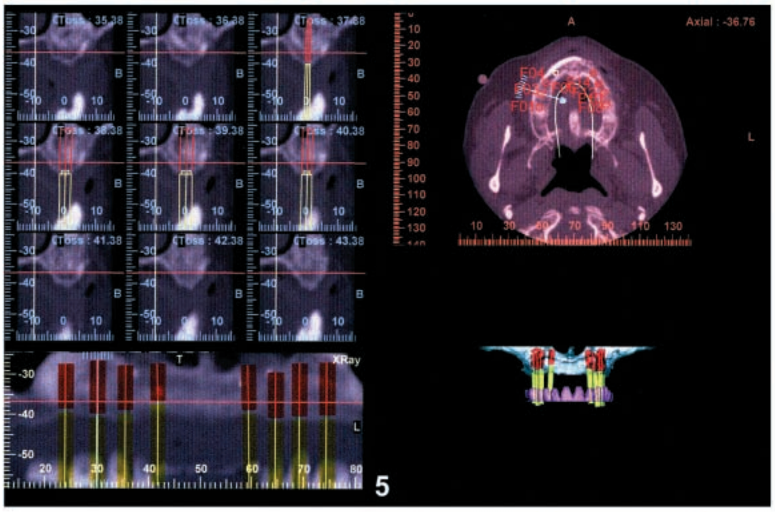
The panoramic image is the cross-section orthogonal to the axial image and follows the panoramic curve. The boundaries of this image are defined by the lowest and highest axial slices. There are 2 visualization models for the panoramic image: normal and X-ray.

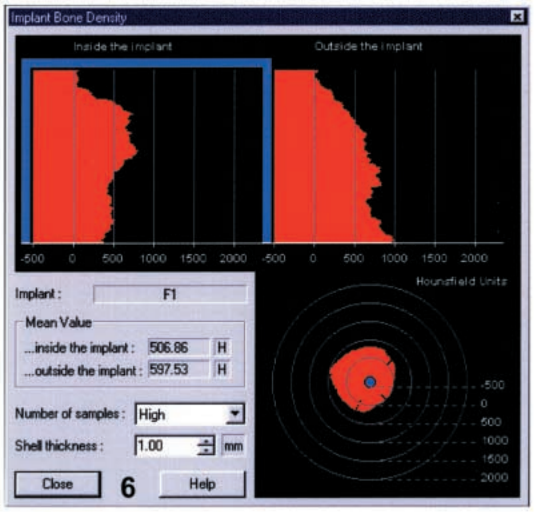
The software provides 4 interactive windows from the reformatted CT data. The axial image in which the panoramic curve is drawn is represented in the upper right quadrant (Figure 3b). The software allows the practitioner to view the entire study of axial images by scrolling through this window. The panoramic view of the axial image represented in the upper right quadrant window appears in the lower left quadrant window (Figure 3d). Cross-sectional images in a 3 × 3 format are represented in the upper left quadrant window (Figure 3a). The 3D reformat is represented in the lower right quadrant window (Figure 3c).

The software program is fully interactive. In other words, as the cursor on the panoramic curve is moved from anterior to posterior, the corresponding cross-sectional reformat is repre-









Implant : F1

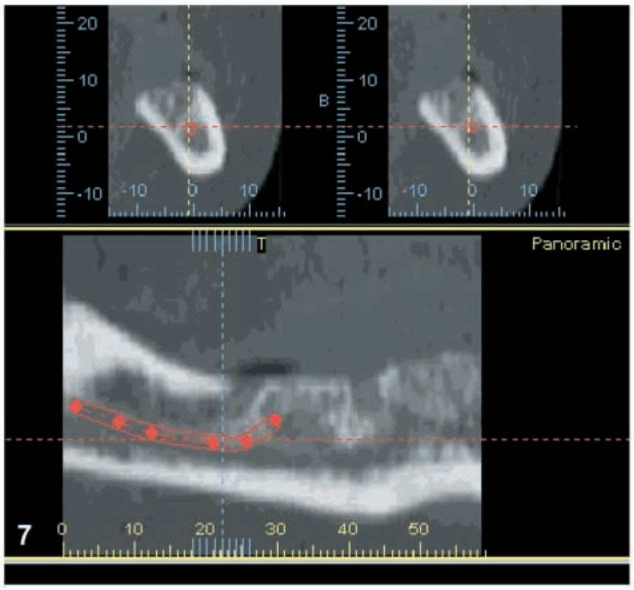
Mean Value

...inside the implant : 506.86 H

...outside the implant : 597.53 H

Number of samples : High

Shell thickness : 1.00 mm



FIGURES 3–4. FIGURE 3. Gutta percha markers are used on a scan prothesis. The following reformatted images are displayed: (a) cross-sectional images, (b) axial image-panoramic curve, (c) 3-dimensional image, and (d) panoramic image. FIGURE 4. Implant planning is demonstrated on a 1 × 1 cross-sectional image.

sented. The 3D image can be viewed anywhere on a 360° rotation.

Figure 3 represents a fully edentulous maxillary reformat. The subject had a bilateral sinus augmentation and allogenic bone onlay grafts 6 months prior to the CT scan. Gutta percha markers represent desired positions of endosseous implants.

In this example, the cursor is placed on the midline, and the corresponding cross-sectional images and position on the panoramic window (blue line) are represented. Bony morphology and the prosthetic tooth position determine implant placement. The preferential setting for the represented cross-sectional images are 1 mm apart. The buccal-lingual contour and the vertical dimension of available bone are well represented in the cross-sectional images. By placing the cursor within the medullary bone, the status bar will reflect the x, y, and z coordinates at that particular point as well as the Hounsfield reading.[30] A Hounsfield reading is a relative density value where water is a 0 Hounsfield unit. A sinus cavity or void has a negative Hounsfield value, whereas a cortical plate is found to be well over 1000 Hounsfield units. Medullary bone generally falls within 300–800 Hounsfield units. Therefore, the quantity and quality of bone can be evaluated across the entire circumference of the panoramic curve.

Prosthetic tooth position is generally determined from the 3D reformat. When the cursor is placed on the 3D reformatted image, the corresponding cross-sectional view of the bony site appears. The software has the ability to change the cross-sectional images from a 3 × 3 format to a 1 × 1 format by using the zoom function on the toolbar. An implant is planned in this 1 × 1 cross-sectional format (Figure 4).

The software allows the practitioner to manipulate the length, diameter, and position of the implant body. The software provides a database of all major implant manufacturers with the individual implant specifications as well as generic specifications. Once an implant is placed, the position can be checked in the other images and in the 3D view. The position of an implant can be changed from any view.

Figure 5 represents a planned implant case. The panoramic reformatted image is in the X-ray mode. The cursor is placed on the right first molar implant. The corresponding cross-sectional image is represented as well as the position on the axial image. The horizontal redline on the panoramic and cross-sectional images represent the axial image shown. The 3D image can be rotated to determine implant placement relative to simulated, anticipated prosthetic tooth position.

The software allows the practitioner to view a longitudinal and a concentric graph of bone density value around each individual implant (Figure 6). Should the practitioner feel inadequate density of bone exists, then repositioning of the particular implant may be required or bone augmentation indicated.

The software provides for 3 main mouse modes. The navigation and implant selection mode, the panoramic curve mode, and the nerve mode. The software provides the nerve mode to clearly represent the inferior alveolar nerve canal in the panoramic and the cross-sectional views (Figure 7). Using this information, irregularities in and misinterpretation of the position of the inferior alveolar nerve canal are avoided when planning mandibular implant reconstructions.

By viewing the planned implant reconstruction in the 3D window, the practitioner is permitted to check implant positions relative to planned prosthetic design. If the planned final prosthesis was represented in the CT scan prosthesis, the simulated reconstruction can be viewed relative to implant placement positions. The software demonstrates the position of the fixture, abutment, and restorative space. It also allows analysis of the planned implant reconstruction by allowing rotation of the image in different planes as well as making certain components of the reconstruction translucent. If the practitioner has decided to incorporate bone augmentation in conjunction with implant placement, then the augmentation and volume analysis can be performed on the 3D image (Figure 8).

The implant position in relation to the bony morphology is demonstrated in Figure 9. The implant size (length and diameter) based on analysis of quantity and quality of bone from the reformatted 2D and 3D images are summarized (Figure 9). If the practitioner desires to position all implant bodies 1 mm below the level of the residual ridge, the 1-mm measurement needs to be added to the length of the individual implants.

The implant plan as well as the diameters of the drilling sequence for the surgical osteotomies are exported to a CAD-CAM computer. These are used for the manufacture of the surgical guide.

SURGICAL GUIDE

The advent of the surgical guide represents the culmination of 15 years of research and development using CAD-CAM multiplanar diagnostic imaging for dental implants. Verstreken et al[31] wrote about a true 3D approach for planning oral implants, as well as simultaneous visualization of 2D and 3D reformatted images that outperformed the manual planning practice based on

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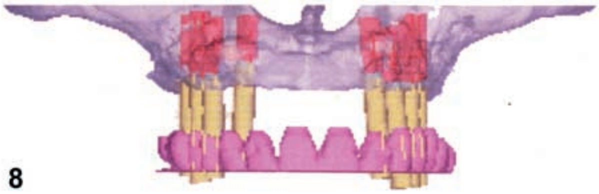
FIGURES 5–7. FIGURE 5. Porcelain teeth are used on a scan prosthesis. A completed planned implant case is demonstrated. FIGURE 6. Bone density values are graphically represented longitudinally and concentrically of an individual implant. FIGURE 7. The inferior alveolar nerve is represented in the cross-sectional and the panoramic reformats.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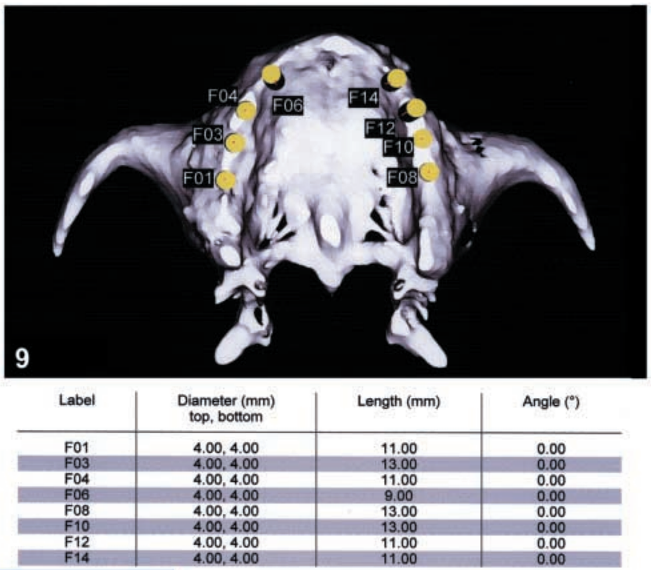

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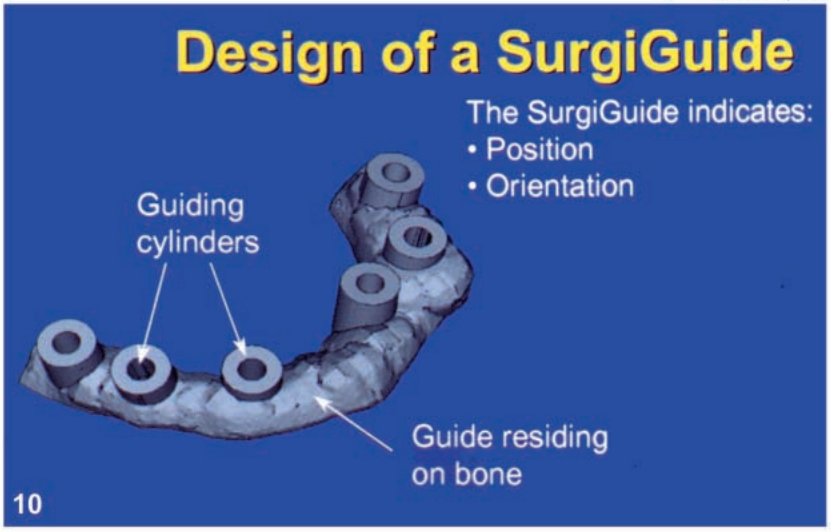
Label	Diameter (mm) top, bottom	Length (mm)	Angle (°)
F01	4.00, 4.00	11.00	0.00
F03	4.00, 4.00	13.00	0.00
F04	4.00, 4.00	11.00	0.00
F06	4.00, 4.00	9.00	0.00
F08	4.00, 4.00	13.00	0.00
F10	4.00, 4.00	13.00	0.00
F12	4.00, 4.00	11.00	0.00
F14	4.00, 4.00	11.00	0.00


Design of a SurgiGuide

The SurgiGuide indicates:
- Position
- Orientation

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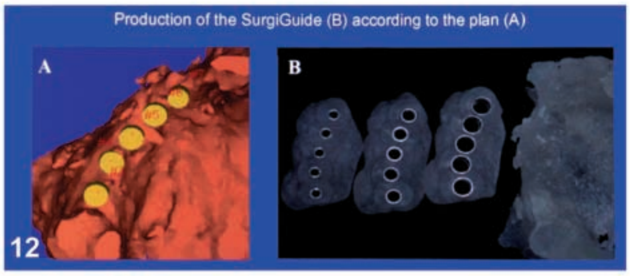
Production of the SurgiGuide (B) according to the plan (A)

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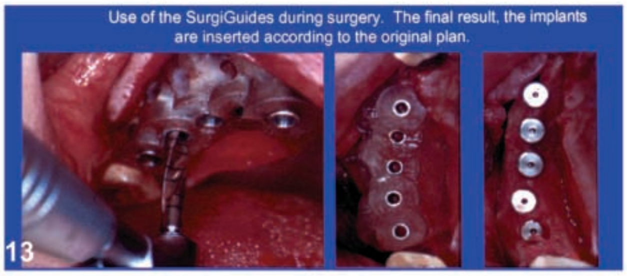
Use of the SurgiGuides during surgery. The final result, the implants are inserted according to the original plan.

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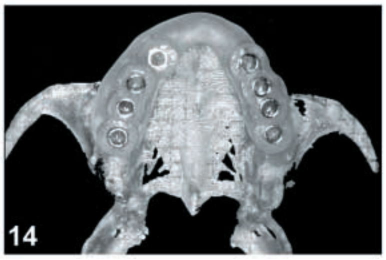
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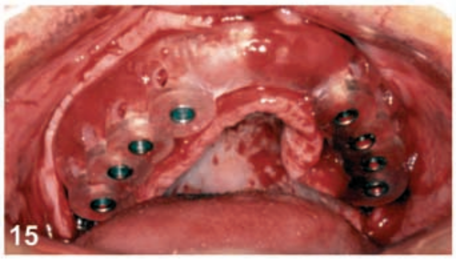
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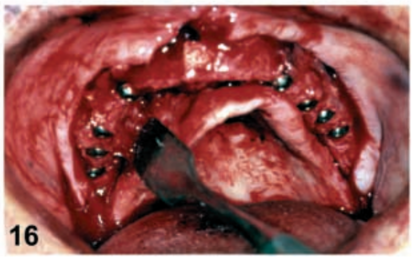
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FIGURES 8–9. FIGURE 8. A 3-dimensional (3D) image demonstrating the implant, abutment, and restorative space. FIGURE 9. The final implant position represented 3-dimensionally and the implants diameters and lengths illustrated as the plan.

2D dental CT images printed or on film.

In the past decade, efforts have been made to use tissue-borne templates and scan prostheses to transfer implant analysis data.[32,33] However, the demands for the predictable and accurate transfer of preoperative diagnostic analyses and implant planning has led to the clinical application of the surgical guide (SurgiGuide, Materialise). A CAD-CAM program to accurately transfer the simulated implant placement to the surgical site is designed to produce the surgical guide.

The surgical guide is processed by stereolithography in acrylic resin (USP class VI approved by the Food and Drug Administration). The guiding cylinders are made of stainless steel, which are positioned to extend 5 mm above the residual ridge. The diameters of the cylinders are 0.2 mm greater than the diameter of the specified drill. As a result of this technology, the surgical guide permits accurate and consistent position and orientation of the implants (Figure 10).

Surgical guides are produced in a series of 3, which correspond to the diameters of the pilot drill, the intermediate spade, and the final spade drills. Since the diameters of the drills used for progressive osteotomies are specific for each implant system being utilized, the surgical guide takes cognizance of this (Figure 11).

Figure 12 represents the stereolithography production of the surgical guide according to the bony analysis and plan for a partially edentulous case. The surgical guide shows 7 mm extensions buccally and 5 mm palatally from the midcrestal bone. Stability is achieved by its accuracy of fit.

Figure 13 demonstrates an osteotomy being performed with a final spade drill through the guiding cylinder of the surgical guide. The implant fixtures are inserted following the bone surgery.

The ultimate success of an implant case is based on the modern concepts of bone physiology, metabolism, and biomechanics. The surgical placement of a dental implant elicits an osteogenic response that is driven by specific physiologic factors.[34,35] Adequate vascularization at a particular site is required for the osteogenic process.

The bone density analysis is critical for implant positioning. Open marrow spaces or zones of unorganized fibrous tissue offer fewer areas of contact with the body of the implant. When comparing different types of bone and their density differences in contact with the implant surface, the percentage of bone contact is significantly greater in cortical bone than in trabecular bone.[36] Regeneration of bone from allogenic bone grafts and autogenous bone grafts and their ability to maintain the biomechanical stresses require preoperative assessment. Maximizing the amount of bone in contact with the implant and maximizing the ability for bone regeneration to support the stresses of function may require increasing the number of implants in a particular arch.[36]

One of the most challenging cases confronting the implant surgeon is the fully edentulous jawbone when fixed prosthetics are planned. As bony irregularities occur and resorption of alveolar bone progresses, internal anatomical structures become more prominent. As the demands of clinical practice become more challenging, the application of noninvasive diagnostic tools and technological advances in surgical techniques become more imperative to the practitioner (Figures 14–16).

CONCLUSIONS

Just as advances in noninvasive diagnostic techniques and interventional surgery have revolutionized medical treatment, implant dentistry has advanced far beyond its original expectations. There is an urgent need for improved and speedy access to information, which delineates the techniques and technologies required to support the application of modern implant dentistry.[29] Accuracy of preoperative diagnostic information has been established,[17] and more recently the predictable transfer of endosseous implant analysis to the surgical site has been made available.

Erickson et al[37] wrote about surgeons using CAD-CAM multiplanar imaging and 3D stereolithography models as being beneficial for diagnosis, treatment planning, reference during surgery, and in surgical devices that afforded surgical solutions previously not available. Patients were believed to have received better care because the surgeons had more knowledge of their unique anatomy before surgery. The researchers noted that patients experienced shorter surgical procedures with more predictable results. Bill et al[38] also noted that using multiplanar diagnostic imaging and SLA modeling provided accurate planning, improved postoperative results, decreased risks, and shortened treatment time.

Korves et al[39] listed the advantages of model and image-based surgical planning:

- A better understanding of the anatomical relationships.

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FIGURES 10–16. FIGURE 10. The design of the surgical guide with the stainless steel guiding cylinders within the acrylic resin base. FIGURE 11. The 3 surgical guides have guiding cylinders with progressive diameters according to the requirements of the implant system used. FIGURE 12. The production of a partially edentulous surgical guide (b) according to the plan (a). FIGURE 13. The osteotomy is performed through the guiding cylinder. FIGURE 14. A surgical guide is placed on a fully edentulous maxillary stereolithography model. FIGURE 15. The surgical guide pictured in Figure 14 is placed on the maxillary bone, thus providing the position and orientation of the implants. FIGURE 16. Eight implants have been accurately transferred to the surgical site.

- The feasibility of presurgical simulation of the prevailing procedure.
- An improved intraoperative localization accuracy.
- Prosthesis fabrication in reconstruction procedures with an approach to more accuracy.
- Permanent recordings for future requirements or reconstructions.

The present use of CAD-CAM multiplanar diagnostic imaging, stereolithography, and the advent of the surgical guide for implant dentistry provide a high degree of reliability in morphologic diagnosis, determining the surgical procedure, and establishing the subsequent prognosis.

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