ISSN: 2581-5989
PubMed - National Library of Medicine - ID: 101738774

International Journal of Dental Science and Innovative Research (IJDSIR)
IJDSIR : Dental Publication Service
Available Online at:www.ijdsir.com
Volume – 8, Issue – 4, August – 2025, Page No. : 192 - 199

From Scan to Surgery: A Review of Computer-Assisted Imaging in Dental Implant Planning

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Citation of this Article: Dr. Sireesha Anumula, Dr.Vidya Sagar Sisinty, Dr. Suryakanth Malgikar, Dr. Rohit Gampala, "From Scan to Surgery: A Review of Computer-Assisted Imaging in Dental Implant Planning", IJDSIR- August – 2025, Volume – 8, Issue – 4, P. No. 192 – 199.

Type of Publication: Review Article

Conflicts of Interest: Nil

Abstract

Computer-assisted imaging has become integral to modern implant dentistry, enhancing precision, safety, and predictability in surgical outcomes. Central to this digital workflow are Cone Beam Computed Tomography (CBCT) and Standard Tessellation Language (STL) files, which provide complementary datasets for comprehensive treatment planning. CBCT offers detailed three-dimensional visualization of hard tissues, enabling accurate assessment of bone volume, anatomical landmarks, and proximity to vital structures. STL files, derived from intraoral or desktop scanners, represent the surface morphology of teeth and soft tissues with high resolution. In static navigation systems, these datasets are merged to design and fabricate surgical guides using computer-aided design/computer-aided manufacturing (CAD/CAM) technology. These guides facilitate precise osteotomy preparation and implant placement based on a pre-defined virtual plan. On the other hand, dynamic navigation systems utilize real-time tracking technologies, integrating CBCT-derived anatomical data with STL surface scans to allow intraoperative adjustments and visual guidance without the need for a physical guide. The integration of CBCT and STL data thus bridges diagnostic accuracy with operational precision, enabling minimally invasive procedures and

improving both aesthetic and functional outcomes. As the field continues to evolve with innovations such as artificial intelligence and robotics, mastering the use of these digital tools is essential for clinicians seeking to deliver evidence-based, patient-centered care.

Keywords: Digital Workflow, Computer-Aided Design, Surgical Guide, Dynamic Navigation System.

Introduction

Acquiring reliable data from the patient is fundamental for accomplishing a correct diagnosis and treatment plan; for that, the clinician needs to obtain two types of data: a surface scan from the patient's oral cavity and medical imaging from underlying structures like bone. The knowledge of bone architecture is necessary when planning surgery; thus, medical instrumentation and technology have evolved to provide detailed imaging for precise diagnosis, for which a universal language has been established to visualize these images, known as DICOM files. They can come from X-rays, CBCT, and MRI. However, medical images are typically obtained using cone-beam computed tomography (CBCT), which produces high-resolution, three-dimensional images of the craniofacial skeleton. The resulting files are stored in the standardized DICOM (Digital Imaging and Communications in Medicine) format, ensuring compatibility with advanced diagnostic and treatment planning software. While CBCT offers invaluable information about internal structures, such as bone volume, sinus cavities, and neurovascular bundles, it often lacks the surface detail necessary to visualize the teeth and soft tissues with high fidelity, especially in the presence of metallic restorations that may cause imaging artifacts. To address this limitation, intraoral scanning technologies are employed to capture surface topography in the form of STL (stereolithography) files. These files provide a highly accurate digital representation of the patient's dental arches, enabling clinicians to assess occlusion, soft tissue contours, and prosthetic space requirements. On the other side, the implant should be fully driven by the prosthetic plan. Digital imaging from the patient's dental arches is needed for implant planning and template or surgical guide fabrication.

A. Surface Scans (STL Files)

Jaw replicas are needed for the fabrication of prosthetic restorations, a surgical template to fit into the oral cavity, registration of the area of interest and its relation with opposite jaws, neighboring teeth, and surrounding tissues is mandatory to develop a prosthetic plan to guide surgical protocols and fabrication of templates for precise placement of implants in the oral cavity. Earlier, a stone cast has been used to create a virtual model for implant placement; later, a surface geometry of a 3-dimensional object has been introduced, known as STL files.[1]

The STL format, which stands for either "Standard Tessellation Language" or "Standard Triangle Language." It is used to represent the shape of the object. The original STL files were created for stereolithography CAD software by 3D Systems® to enhance data processing for 3D printing and computer-aided manufacturing. Nowadays, STL files are supported by many software programmes that have become a universal CAD language.

There are 2 methods for digitizing patient dental arches: intraoral scanning and extraoral scanning.

Extraoral scanners

Mostly used by dental technicians to digitize the stone casts or conventional impressions.

Extraoral scanners are subdivided into 2 types: contact and non-contact or optical scanners. Initially, non-contact or mechanical scanners use a probe to go across the object surface to detect its morphology, whereas contact scanners are widely used; most of them have a laser to illuminate the object to collect the information using the STL principle. The light projected onto the object is reflected and captured by the receptor unit. The sensor measures the angle of reflected light and calculates the 3D data by means of the triangulation principle. This offers the advantage of greater interposition accuracy of the components within the model.[2] They are mostly preferred in extended edentulous patients and full arch reconstruction.

Intraoral scanners: (ISO) enhance digital workflow, provide fluency and precision. They reduce the operative and treatment time and improve communication with the lab.

Optical non-contact intraoral scanners are devices like portable cameras used to record the oral topography. There are different technologies available for ISO, such as confocal imaging, which focuses light at different depths inside the mouth. It captures many sharp images at different layers (depths), and a computer combines them into one detailed 3D image. Optical coherence tomography, a light-based scanning method that can see under the surface, like X-rays, but using light. It bounces low-energy light into tissues and measures how it reflects. This shows both surface and subsurface details. Active wave front sampling is a dynamic imaging method that captures data from different angles using a moving lens. It changes the focus dynamically while recording how light reflects from the surface of teeth. It usually requires a light coating of powder, such as titanium or magnesium dioxide powder, for better visibility.[3] The latest IOS are designed with powder-free to improve scanning.

The use of retractors and moisture control, switching of the chair light to avoid the lightning interference, is necessary for better image quality.[4] Built-in heating element to reduce fogging of the glass surface. If multiple teeth are missing, soft tissue mobility can interfere with scanner recognition; in that case, conventional impression and extraoral scanners are recommended.

The popular intraoral scanners[5] available for purchase are listed below. (Table 1)

Table 1: Commercially available intraoral scanners

Sn.	Scanner Name	Manufacturer	Country	Technology Used
1.	TRIOS Series TRIOS3, TRIOS 4	3 Shape	Denmark	Ultra-fast Optical Sectioning (based on confocal and video capture)
2.	Medit i700 /i600 / i500	Medit	South Korea	Structured Light Scanning
3	3MTrue Definition	3M ESPE	USA	Active Wavefront Sampling
4.	Planmeca Emerald S	Planmeca	Finland	Active triangulation with blue laser
5.	CS 3600 / CS 3700	Carestream Dental	Germany	Active Triangulation
6.	Dentsply Sirona Prime scan	Dentsply Sirona	Germany	High-frequency optical scanning
7.	E4D Dentist / Plan Scan	Planmeca (formerly E4D Technologies)	USA	Optical Coherence Tomography
8.	Aoral scan 3	Shining 3D	China	Structured Light Scanning
9.	Virtuo Vivo	Dental Wings	Canada	3D Video Scanning

CBCT Images (DICOM Files)

DICOM (Digital Imaging and Communications in Medicine) is considered the standard for sharing medical imaging information and related data. Once the image is acquired, the technician evaluates the outcome and assess the visibility of related anatomic structures, then file containing the slices is processed by software to determine jaw horizontal, panoramic curves, axial slices, together with implant measurements, recognition of never canal and other relevant information is exported as printable format such as JPG or PNG files and delivered to patient. DICOM files can often be found in a folder named images or data inside the CD, and these files can be sent by mail. DICOM files can be stored in 3 different formats.

1. DICOM (single frame), every slice scanned by CBCT equipment is saved in an independent file, resulting in multiple small-sized files. Software puts all those together to reconstruct the three-dimensional image; however, due to multiple files, it increases the storage process.
2. DICOM (multi-frame) This format reduces the file size, storage by combining all the slices into a single DICOM file.
3. DICOMDIR is a special file that serves as a directory to collect DICOM files. Format is similar to a ZIP/RAR file, and can store multiple studies. Most of the hospitals use DICOM directory, which helps to display information stored in DICOM files.

General Considerations for Justified Imaging Prescription:

Any radiation exposure entails risk to the patient; every radiographic examination must benefit the patient.[6]

Use of imaging modalities for pre-surgical dental implant planning should support three goals: to establish bone volume and quality, determine the orientation of bone concerning the prosthetic plan, and identify any anatomical or pathological defect.[7]

According to the SEDENTEXCT project, radiation doses[8] from CBCT are usually higher than conventional radiographs. But lower than multislice computer tomography (MSCT), overall CBCT has better image quality than MSCT.[9]

One of the main reasons for prescribing CBCT is to visualize the structures, such as the mandibular nerve and maxillary sinus. Although it would be difficult to trace the benefits of CBCT over conventional imaging, it should be noted that guided surgery relies only on virtual planning and data collected pre-operatively. In traditional planning, whenever there is an intraoperative situation that does not meet the expectations, osteotomies can be modified to solve the problem, such as changing the implant position, angulation, implant type, its length, or diameter. But in a clinical situation of virtual planning that does not meet the planning protocol, it can be replaced by a free-hand protocol; thus, it is mandatory to have a accurate information of underlying structures to prepare the guide, hence CBCT is always needed to perform virtual planning.

The optimization of radiation dose should follow the ALARA principle postulated by the International Commission on Radiology Protection (ICRP), which states that radiation dose should be kept as low; therefore, the clinician should prescribe the CBCT based on patient history, examination, and specify the exposure and image quality parameters to achieve proper diagnosis.[10]

Harries *et al.*,[6] EAO guidelines for prescribing CBCT based on patient physical characteristics, FoV selection, dental-related factors, and whether the image database is to be exported to implant planning software (Figure 1).

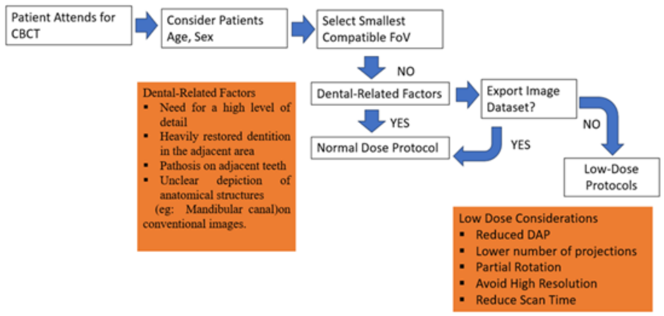

Figure 1: Dose optimization strategy flow chart for CBCT when used in implant dentistry

Techniques to improve CBCT imaging

Although prescribing CBCT is routine practice in implant dentistry, some specifications help the technician to deliver high quality image with proper communication between the clinician and technician is mandatory.

1. Inter-arch distance: CBCT is performed while the patient is in occlusion, and the chin rests on the mental support provided by the device. This allows the patient to remain still and avoid deformation, but due to no space, the upper and lower arch occlusal surfaces and cusps cannot be distinguished properly. In order to merge STL files with CBCT, tooth anatomy is the best reference, because that means separation between the jaws allows CBCT to give a neat image on incisal edges, occlusal surfaces, which also helps in virtual planning of prosthesis and surgical template preparation. At least 10 mm separation using cotton rolls can serve as an occlusal stop to establish inter-arch space.
2. Soft tissue separation: lips and cheeks contact with jaw structures will not provide accurate visualisation, so displacement of lips and cheeks can improve tooth, crestal bone, and gingival contour visualisation. This can be done using cotton rolls, lip retractors. Januario *et al.*,[11] developed a novel technique based on CBCT (STCBCT) to visualise and precisely measure the distance corresponding to hard and soft tissue of periodontium and dento-alveolar attachment apparatus. Soft tissue (STCBCT) to improve buccal tissue visualisation to measure the dental structures and avoid invasive techniques like bone sounding or transgingival probing.
3. Field of view: The field of view (FoV) refers to the area of the patient that will be irradiated. Different FoV sizes can be used depending on dental treatment indications; they are divided into small, medium, and large.

- Small FoV: it covers around 6 in diameter and allows proper visualisation of 5 anterior or 3 posterior teeth. It delivers high-quality images together with low 3D distortion. But it requires multiple scans to capture a complete arch, so more radiation to the patient.
- Medium FoV: it covers around 9 inches in diameter, which can visualize the entire arch, TMJ alterations. But shows less in terms of volume accuracy and image resolution than a small FoV.
- Large FoV: it covers around 12 inches in diameter, capable of delivering an image of the whole craniofacial area. Mostly useful in case of orthognathic surgery and pathologies, and trauma cases. Also, visualise the maxillary sinus.

Implant planning can be done in every FoV; however, major volume alterations are seen in large FoV. Although these alterations will not affect the conventional implant placement, but may interfere with virtual implant placement as it demands accuracy. Static guided surgery does not allow osteotomy modification if the bone morphology does not resemble the CBCT image.

4. Voxel size: voxel is the same as pixel in an image. The smaller the voxel higher the quality of the image/CBCT. As a rule, smaller FoV use smaller voxel size to obtain information from small

structures. Thus, FoV indications come along with voxel size.

5. Segmentation and 3D reconstruction: Segmentation is the process used by a tomography software to separate one specific anatomic structure from the rest of the volume. This is the fundamental aspect of CBCT as a virtual reconstruction. Automatic segmentation is the most commonly used method. However, it can even be done manually in most software.

Selection criteria for using CBCT[12] as a diagnostic task are listed below in Table 2

Table 2: Implant Imaging Recommendations Based on Diagnostic Task

Diagnostic task	Recommendation
Preliminary assessment of the edentulous site	Panoramic radiography alone or with periapical radiographs. CBCT is not recommended for the initial assessment of edentulous sites.
Radiographic evaluation of a potential implant site.	Cross-section (CBCT) imaging focused on areas of interest. In the absence of CBCT, CT should be considered as an alternative with proper dose-reduction protocols.
Implant site development or planning for alveolar bone augmentation /sinus grafting	CBCT should be considered**.**
Postoperative assessment of an augmentation or grafting procedure.	CBCT should be considered
Periodic implant evaluation in the absence of clinical signs or symptoms	IOPA or OPG CBCT is not recommended for routine implant follow-up.
Implant evaluation immediately after surgery	CBCT is recommended if there are clinical signs of implant mobility or neurological disturbances. (especially in the mandible)
Implant evaluation in cases of complications, exposure, presence of osseous defects around the implant, mobility, or implant failure.	CBCT is recommended
Implant retrieval	CBCT should be considered if implant retrieval is anticipated because defect characterization is required for possible future implant site development.

Table 3: Commercially available imaging software

Sn.	Software	Company (Country)	Purpose	Key Imaging Features
1	Blue Sky Plan® (Imaging Module)	Blue Sky Bio (USA)	Imaging + guided surgery	Free CBCT viewer, supports multiplanar reconstruction (MPR)

2	Tx Studio	i-CAT (USA)	CBCT viewing, implant planning	Nerve tracing, airway analysis, and real-time implant positioning
3	In vivo™	Anatomage (USA)	3D imaging and diagnostics	High-resolution rendering, surgical simulation, and implant visualization
4	Romexis®	Planmeca (Finland)	Comprehensive imaging suite	CBCT, panoramic imaging, prosthetic, and surgical planning
5	Carestream CS 3D Imaging	Carestream Dental (USA)	CBCT viewing and planning	Full-featured implant planning, intuitive nerve canal tracing
6	RadiAnt DICOM Viewer	Medixant (Poland)	DICOM file visualization	Lightweight, fast, supports implant simulation with STL overlay
7	DTX Studio™ Imaging	Nobel Biocare / Envista (Switzerland/USA	Diagnostic imaging and planning	Unified platform for implant, prosthetic, and radiologic workflows
8	Sidexis 4	Dentsply Sirona (Germany)	Imaging platform for Sirona devices	CBCT viewer integrates with Galileo's Implant software

After visualization of CBCT images clinician makes the implant planning and design a surgical template. CAD (computer-assisted design) requires software to read the STL and DICOM files from CBCT to perform prosthetic device and template fabrication for guided implant surgery. DICOM files are uploaded in implant software, and the clinician will be able to navigate the study by measuring the distance or placement of the virtual implant. Many commercially available software programs[13] are listed in (Table 3). Some of them are free versions, and most of them are full versions of programs, with purchase help from planning to template preparation using 3D printing for guided implant surgery.

In case of a dynamic navigation system, it allows the surgeon to make changes both during planning and surgery, it allows real-time visualization and verification of surgical treatment. It is computer-guided free-hand technology that eliminates static templates. In a dynamic navigation workflow, a stent is fixed in the residual teeth, a CBCT scan is obtained with this stent, then DICOM files from CBCT are imported to navigational software, followed by STL files from the virtual restorative plan. The surgeon starts with the surgery, in dynamic navigation with trace and place protocol, and there is no need for stent preparation. A CBCT scan is done, and trace registration utilizes high contrast landmarks that are visible in the CBCT image or STL files. Once the tracing is complete, the software allows clinicians to accurately check the screen to verify the measurements that are close to the true value to ensure the accuracy and to perform implant placement carefully.

Conclusion

CBCT plays an integral part in implant imaging and planning, which represents a shift in precision-driven dental implantology. STL files obtained from intraoral scanners offer high-resolution surface data crucial for prosthetically guided planning. Merging of STL files and CBCT supports both static and dynamic navigation systems, enhancing surgical accuracy, minimizing complications, and improving esthetics and final outcome. As digital workflows continue to evolve with advancements in software, artificial intelligence, and robotic assistance, the reliance on CBCT and STL files will remain foundational to safe, efficient, and patient-specific implant placement.

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