DIGITAL IMPLANT PLANNING AND GUIDED IMPLANT SURGERY

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Written by

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LIST OF ABBREVIATIONS

Abbreviation	Full Form
3D	Three-Dimensional
3Y-TZP	3 mol% Yttria-Stabilized Tetragonal Zirconia Polycrystal
5Y-PSZ	5 mol% Yttria-Stabilized Partially Stabilized Zirconia
AAOMR	American Academy of Oral and Maxillofacial Radiology
AD	Angular Deviation
AGD	Apical Global Deviation
AI	Artificial Intelligence
ALADA	As Low as Diagnostically Acceptable
ALARA	As Low as Reasonably Achievable
AAOMR	American Academy of Oral and Maxillofacial Radiology
AM	Additive Manufacturing
AP	Anterior–Posterior
AR	Augmented Reality
CAI	Computer-Assisted Imaging
CAIM	Computer-Aided Impression Making
CAIPP	Computer-Assisted Implant Planning and Placement
CAIS	Computer-Aided Implant Surgery
CAD	Computer-Assisted Design
CAM	Computer-Assisted Manufacturing
CBCT	Cone Beam Computed Tomography
CGD	Coronal Global Deviation

CNC	Computer Numerical Control
Co-Cr	Cobalt-Chromium
CT	Computed Tomography
D1–D4	Bone Density Classification (Lekholm & Zarb classification: D1 = dense cortical bone → D4 = very soft trabecular bone)
DCM	Dental Communications Model (specific file format used by 3Shape®)
DICOM	Digital Imaging and Communications in Medicine
DLP	Digital Light Processing
DT	Dual Tomography
DWOS	Dental Wings Open Software
EADMFR	European Academy of Dento Maxillo- Facial Radiology
FDA	Food and Drug Administration
FDM	Fused Deposition Modelling
FEA	Finite Element Analysis
FFF	Fused Filament Fabrication
FoV	Field of View
FGM	Functionally Graded Materials
GIS	Guided Implant Surgery
GPS	Global Positioning System (used as an analogy for navigation)
GPT-9	Glossary of Prosthodontic Terms-9
HU	Hounsfield Unit
ICRP	International Commission on Radiological Protection
IOS	Intraoral Scanner / Intraoral Optical Scanner
IPA	Isopropyl Alcohol

JPG	Joint Photographic Experts Group
LCD	Liquid Crystal Display
LED	Light-Emitting Diode
ML	Machine Learning
MRI	Magnetic Resonance Imaging
MSCT	Multi-Slice Computed Tomography
MT	Model-Based Tomography
OBJ	Object file format
PEEK	Polyetheretherketone
PES	Pink Esthetic Score
PLY	Polygon File Format
PMMA	Polymethylmethacrylate
PNG	Portable Network Graphics
PREs	Patient-Reported Experiences
PROs	Patient-Reported Outcomes
PVS	Polyvinyl Siloxane
RCT	Randomized Controlled Trial
rCAIS	Robot-Assisted Computer-Assisted Implant Surgery
SLA	Stereolithography
sCAIS	Static Computer-Assisted Implant Surgery
SG	Surgical Guide
sGIS	Static Guided Implant Surgery
SLS	Selective Laser Sintering
STL	Standard Tessellation Language / Standard Triangle Language

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INTRODUCTION

Tooth loss may result from poor oral hygiene, neglect, or failed restorations and results in significant physical, emotional, and psychological challenges, including impaired mastication, reduced aesthetics, and diminished self-esteem. Varied prosthetic options are available in the dentist's armamentarium to bridge this gap, ranging from the more traditional ones like complete dentures, removable partial dentures, fixed bridges, to the more recent ones like dental implants. However, Implants have shown to offer superior stability, comfort, and long-term outcomes. [1]

Traditionally, implant placement was guided by clinical judgment, study casts, and two-dimensional radiographic evaluations like periapical and panoramic radiographs.[2] While these tools provided fundamental insights, they lacked precision—particularly in visualizing the complex three-dimensional maxillofacial anatomy, often resulting in inaccuracies. Moreover, Implant placement was based primarily on the available bone volume, often overlooking the prosthetic demands of the case. These limitations often led to suboptimal implant positioning, jeopardizing prosthetic design, aesthetics, hygiene maintenance, or even damage to vital anatomical structures like nerves or sinus cavities and biomechanical stability.[3,4] In complex cases, such as edentulous arches or severely resorbed ridges, the absence of natural landmarks further complicates the process.[5]

However, Computer-assisted/-guided/-aided implantology has been founded to overcome the errors encountered during implant osteotomies and to position the implants more precisely.[6] The introduction of Computed Tomography (CT) and later Cone-Beam Computed Tomography (CBCT) also revolutionized implant diagnostics by allowing high-resolution, distortion-free, 3D imaging. CT technology overcame challenges that plagued conventional radiographic methods.[6,7] Furthermore, Computer-aided implant surgery (CAIS) represents a further advancement in this digital shift. By enabling the precise placement of implants at preplanned locations, CAIS allows for faster, more accurate, and minimally invasive surgical procedures.[8] Computer-guided approaches can significantly reduce postoperative discomfort, morbidity, and healing time, thereby enhancing patient satisfaction during the early recovery period.[9] Particularly in flapless surgical techniques, where direct visualization is limited, digital planning becomes essential to avoid critical anatomical structures and ensure the ideal depth and orientation of the implant.[10]

Additionally, the digital workflow in implant dentistry is not limited to planning and surgical execution. It extends to the prosthetic phase as well, encompassing digital impressions, virtual prosthesis design, and CAD/CAM fabrication of the final restorations. Collectively, these stages comprise what is now referred to as "digital implantology," a comprehensive, technology-driven approach that enhances the precision and efficiency of implant treatment from start to finish.[3]

Thus, Digital implant planning and Guided implant surgery has ushered in a new era in dental implantology. This Library dissertation aims to explore the principles, applications, and clinical benefits of digital implant planning, highlighting its transformative impact on modern dental practice.

HISTORICAL PERSPECTIVE

Between 1600 and 1800, surgical innovation emerged in dental practice. In the 1700s, Dr. John Hunter experimented with tooth transplantation, even embedding a human tooth into a rooster's comb—remarkably, blood vessels grew into the pulp, hinting at biological integration.[11]

In 1809, J. Maggiolo attempted implanting a gold tube to support a porcelain crown, but inflammation limited success.[12] The first notable long-term success came in 1913 with the Greenfield implant, an iridio-platinum "crib" with a gold crown that showed signs of early osseointegration.[13]

Progress accelerated in the 1930s–1940s. Drs. Alvin and Moses Strock introduced Vitallium screws for endosteal use. In 1938, P.B. Adams patented a threaded implant with a healing cap. Formiggini and Zepponi later developed spiral stainless-steel designs to stimulate bone growth. Simultaneously, Bothe, Beaton, and Davenport noted in 1940 that bone fused closely to titanium screws—a pivotal observation marking the early concept of osseointegration.[14]

By 1951, Gottlieb Leventhal successfully implanted titanium rods in rabbits, concluding titanium as the ideal surgical material. Meanwhile, subperiosteal implants, resting atop bone, were promoted by Gershkoff and Goldberg.[15]

A transformative breakthrough occurred in 1965, when Dr. Per-Ingvar Brånemark introduced the first two-stage titanium root-form implant. These implants directly bonded with bone and proved extraordinarily durable. Brånemark's design evolved from cylindrical to tapered, and Swiss researchers Schroeder and Straumann refined implant materials for dental use.[14]

The 1980s brought widespread innovation. Dr. Niznick's Core-Vent, Screw-Vent, and Bio-Vent systems improved mechanical design. The IMZ system by Dr. Kirsch mimicked natural tooth mobility. In 1985, the Straumann ITI system introduced one-stage implants with plasma-sprayed surfaces.[12]

Meanwhile, digital tools entered dentistry. The 1970s saw the rise of CT scanning, enabling internal imaging of jaws and improving surgical planning.[16] In 1971, Dr. Robert Ledley introduced a computer-controlled dental drill.[17] By the 1980s, CAD/CAM systems allowed digital design and milling of restorations, eliminating the need for manual lab work.[18]

Standardization took hold between 1980 and 2000, with the 1982 Toronto Conference defining implant success.[11] New implant designs emerged: zygomatic implants (developed by Brånemark in 1988, released in 1998) enabled implant placement in patients with severe bone loss, avoiding grafts.[19] Pterygoid implants, introduced by Tulasne in 1989, offered a graft-free anchorage method via the pterygoid plate.[20]

In 1993, Dr. Paulo Malo introduced the All-on-4 concept—placing two anterior and two angled posterior implants to support a full-arch prosthesis. The All-on-6 variant added further posterior implants for enhanced support. Also in 1993, Dr. David Scharf demonstrated that sterile conditions in dental offices, rather than hospitals, sufficed for successful implant placement—changing clinical standards. [11]

The late 1990s ushered in 3D printing, initially for dental models and later for crowns, bridges, and surgical guides. CEREC (Sirona) revolutionized same-day restorations by integrating digital scanning with CAD/CAM milling. [21]

Cone Beam Computed Tomography (CBCT), introduced in the mid-2000s, marked another leap. It provided three-dimensional imaging across planes, allowing precise visualization of bone, sinuses, and nerves. CBCT became essential for treatment planning and surgical accuracy. [16]

Between 2000 and 2015, implants became the gold standard for tooth loss. Tools like Finite Element Analysis (FEA) and CAD/CAM simulations allowed better implant design and stress distribution. Mehrali et al. introduced functionally graded materials (FGMs)—implants tailored to mimic bone's porous nature. Materials like zirconia enhanced aesthetics and biocompatibility, while advanced thread designs optimized load management. [11]

From 2015 to 2020, image-guided surgery emerged with two dominant methods: Real-time navigation systems using optical/electromagnetic tracking for intraoperative drill guidance and Stereolithographic surgical guides, prefabricated based on 3D planning to ensure precise angulation and depth. These technologies improved safety, avoiding structures like sinuses and nerves.[22]

Simultaneously, Augmented Reality (AR) began assisting in implant positioning, surgical education, and patient communication. Patients could visualize predicted outcomes, enhancing treatment acceptance.[23] Additionally, The COVID-19 pandemic spurred the growth of tele dentistry, enabling remote consultations and monitoring using digital imaging and cloud-based tools, particularly benefiting underserved regions. [24]

Most transformative has been the rise of Artificial Intelligence (AI) and Machine Learning (ML). These technologies process vast datasets to aid in diagnosis, treatment planning, and personalized care.[25] AI-assisted robotic systems can now perform procedures with micrometre-level accuracy, reducing surgical errors. Since 2001, research into robotic-assisted implant placement has steadily grown, extending even to complex cases like zygomatic implants. Robotic arms now perform implant osteotomies with remarkable precision. [26]

Looking to the future, implantology stands at the cusp of a digital revolution. AI, robotics, nanotechnology, bioinformatics, and regenerative medicine are converging to define the next phase of care. Future systems may include self-learning diagnostic platforms, fully automated robotic surgeries, smart implants with embedded sensors, and tissue engineering protocols integrated with digital planning.

FUNDAMENTALS OF DIGITAL IMPLANT PLANNING

DENTAL IMPLANT

Definition: Dental implant is a prosthetic device made of alloplastic material(s) implanted into the oral tissues beneath the mucosal and/or periosteal layer and on or within the bone to provide retention and support for a fixed or removable dental prosthesis; a substance that is placed into and/or on the jawbone to support a fixed or removable dental prosthesis.[27] (GPT-9)

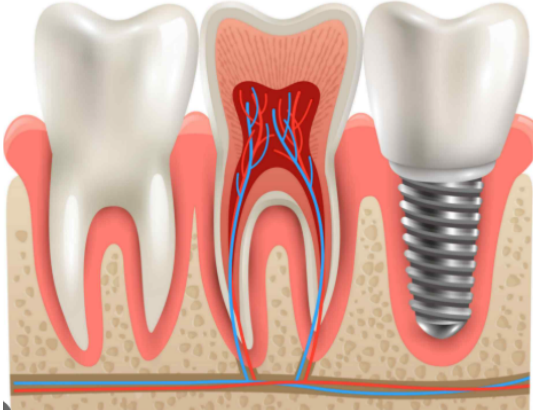


Figure-1: Dental Implant

DIGITAL IMPLANT PLANNING

Digital implant planning is a computer-based process that enables precise virtual placement of dental implants using advanced imaging and modelling. [28]This approach integrates volumetric data from cone-beam computed tomography (CBCT) with surface data from intraoral or model scans. [29] The result is a three-dimensional digital representation of the patient's oral anatomy, allowing virtual placement of implants in an ideal position.[29] Using specialized software, Implant is positioned considering bone quality and quantity, the location of vital anatomical structures such as the maxillary sinus and inferior alveolar nerve, and the final prosthetic outcome. This method—

known as prosthetically driven planning—ensures that the implant is positioned to optimize both function and aesthetics while minimizing surgical and restorative complications.[6]

Digital implant planning involves a multi-step process:[2]

1. Data Acquisition: Using CBCT for volumetric imaging of bone and intraoral scanners for capturing soft tissue and tooth morphology.
2. Image Fusion and Planning: The data sets are imported into specialized software (e.g., SimPlant®, NobelClinician®, coDiagnostiX®), which allows clinicians to virtually place implants in the 3D reconstructed anatomy.
3. Virtual Implant Simulation: The software permits real-time visualization and manipulation of implant placement, allowing accurate angulation, depth, and positional planning with respect to vital structures (e.g., inferior alveolar nerve, maxillary sinus).
4. Surgical Guide Fabrication: Once the virtual plan is finalized, CAD/CAM or 3D-printed surgical guides are fabricated, ensuring precise translation of the plan to the operative site.

Parameter	Traditional Workflow	Digital Workflow
Imaging	2D radiographs	3D CBCT (DICOM)
Impressions	Physical (alginate, PVS)	Digital (Intraoral/Extraoral scan)
Planning	Manual estimation	Software-based simulation
Guide Fabrication	Manual stent	3D printed surgical guide
Accuracy	Operator-dependent	High (guided surgery)
Turnaround Time	Longer	Faster

Table 1- Comparison of Traditional vs. Digital Implant Planning

COMPUTER-ASSISTED IMAGING (CAI)

Computer-Assisted Imaging is the initial step in digital implant planning. It involves acquiring high-quality digital data from both hard and soft tissues. [29]

Two types of files are central to this process:

1. DICOM Files

Digital Imaging and Communications in Medicine (DICOM) files are derived from CBCT scans and contain detailed volumetric information about the internal structures of the jaw, including bone morphology and the spatial relationship to critical anatomical landmarks. It helps to evaluate bone density, shape, and proximity to vital structures.[30]

2. STL Files

STL (Standard Tessellation Language) files, on the other hand, are created through intraoral scanning and provide accurate surface geometry of the dental arches and soft tissues. These files are essential for virtual wax-ups, surgical guide design, soft tissue mapping and prosthetic planning.[31]

Integration and Workflow

The integration of DICOM and STL files forms the backbone of digital implant planning. It allows clinicians to virtually align and overlay the patient's external anatomy with internal structures using specialized software. These are then aligned using AI-based tools or manual landmark identification. Once aligned, virtual implant placement is performed, allowing the clinician to adjust implant size, depth, angulation, and position to accommodate both bone availability and prosthetic design. Following the finalized digital plan, a surgical guide is designed and fabricated, usually via 3D printing (in-office or lab-based). This guide enables precise, minimally invasive placement of implants during surgery. [30]

Advantages [2]

- High placement accuracy (up to 95%)
- Predictable prosthetic outcomes
- Reduced risk of complications (nerve/sinus injury)
- Time efficiency and potential for immediate loading
- Ability to assess and quantify bone density

Limitations[29]

- Radiation exposure from CBCT (though modern units are low dose)
- Cost and access to technology and training
- Static surgical guides have limited intraoperative flexibility
- Artifacts from restorations may reduce image quality
- Edentulous patients pose difficulty for image matching

ROLE OF CBCT IN DIGITAL IMPLANT PLANNING

The evolution of radiographic imaging in dentistry has significantly advanced since the discovery of X-rays by Wilhelm Roentgen in the late 19th century. While early imaging allowed for non-invasive observation of internal structures, it was limited to two-dimensional (2D) visualization. The advent of computed tomography (CT), pioneered by Sir Godfrey Hounsfield and Allan Cormack, marked a pivotal transition to three-dimensional (3D) imaging, enabling greater diagnostic precision and anatomical interpretation. [32]

In dentistry, Cone Beam Computed Tomography (CBCT), introduced by Mozzo et al. in 1998 and FDA-approved by 2001, has revolutionized implant planning by providing detailed 3D representations of craniofacial structures with lower radiation exposure compared to traditional medical CT. [33]

Mechanism:

CBCT units function by directing a collimated, cone-shaped X-ray beam of constant width through the patient's head onto a flat panel or image intensifier detector. During the scan, the equipment rotates around the object—typically the maxillofacial region—capturing a series of two-dimensional projections at each angle. This rotation occurs along a fixed focal plane in either a partial or full arc. [34]

The collected 2D images are then reconstructed by computer algorithms to generate a 3D volumetric data set that accurately represents the scanned area. This volumetric imaging enables multiple interrelated projections of the maxillofacial structures, allowing for comprehensive three-dimensional evaluation. Subsequently, orthogonal (sagittal, coronal and axial) sectioning can be done, and the anatomic structures are visualised.

Some anatomic structures which cannot be visualised in orthogonal sections can be viewed in non-orthogonal planes with the help of multiplanar reformatting process. [34] Both CT and CBCT images are stored in the standardized Digital Imaging and Communications in Medicine (DICOM) format, facilitating their integration with various diagnostic and treatment planning software systems.[35]

Clinical Applications of CBCT in Implantology:

High-Resolution 3D Imaging: CBCT enables clinicians to evaluate the quantity and quality of alveolar bone, angulation, and density with high accuracy. It is instrumental in assessing anatomical landmarks such as the mandibular canal, mental foramen, maxillary sinus, and nasopalatine canal, thereby avoiding critical structure encroachment. [34,35]

Integration with Digital Workflows and Virtual Planning: CBCT data is exported in DICOM format, which can be imported into implant planning software (e.g., Blue Sky Plan, coDiagnostiX, Simplant, NobelClinician).[36] These programs allow Overlay of Standard Triangulation Language (STL) files (intraoral scans or scanned models) with CBCT data to visualize both hard and soft tissue structures aligning the implant with the planned restoration and adjustment of implant angulation, depth, and diameter in real time on the 3D model. [37] This fusion supports accurate virtual planning that considers both hard tissue and occlusal morphology, which CBCT alone may inadequately represent due to metal artifacts and poor surface definition. [38]

Advantages:[35,36,39]

1. Fabrication of Precise Surgical Guides: CBCT-based planning enables fabrication of Surgical guides which are generated from virtual plans and printed using CAD/CAM or stereolithography. These guides translate the virtual implant position directly to the patient's mouth during surgery.
2. Assessment of Bone Grafting Needs: CBCT is valuable in evaluating bone graft requirements and monitoring graft success, especially in cases of atrophic ridges or maxillary sinus pneumatization.
3. Minimization of Complications and Surgical Risks: By accurately mapping out bone and anatomical structures, CBCT reduces the likelihood of: Perforation of cortical plates, Nerve injury, Sinus penetration, Malpositioned implants. Proper planning ensures that the implant is placed in a prosthetically and biologically ideal location, reducing the risk of peri-implantitis and implant failure.
4. Radiation Efficiency and Accessibility: Compared to multislice CT (MSCT), CBCT offers significantly reduced radiation exposure (typically measured in microsieverts), making it more suitable for dental applications. It also provides easier accessibility and cost-efficiency for routine clinical use.

Limitations:[40]

1. Artifacts from metallic restorations can distort images.
2. Soft tissue resolution is poor compared to MRI or MSCT.
3. Accuracy can be affected by patient movement, improper calibration, or registration errors during image alignment.
4. Manual segmentation may be required to accurately define structures when automated tools are insufficient.

TECHNIQUES TO IMPROVE CBCT IMAGING

While prescribing CBCT scans is routine, specifying details are required to deliver high-quality, clinically useful images.

1. Interarch Distance[41]

Proper separation between the jaws is crucial. CBCT is typically taken with the patient in occlusion, chin resting on the device support. This stabilizes the head but causes the upper and lower teeth to overlap, obscuring occlusal surfaces.

For merging CBCT images with surface scans, tooth anatomy serves as the primary reference. Separation between jaws provides clear visualization of incisal edges and occlusal surfaces, improving accuracy for prosthodontic planning, wax-ups, and surgical guides.

- Methods: Cotton rolls (often more than one) or pre-fabricated bite splints can create a ~10 mm gap.
- Caution: Check radiopacity of bite registration materials as they may distort the scan.

2. Soft Tissue Separation[42]

Lips and cheeks normally rest against the jaws during CBCT, obscuring the gingival margin and bone contours. Similarly, the tongue often covers the palate and lingual surfaces.

- Solution: Lip retractors (preferred) or cotton rolls displace soft tissues, allowing visualization of gingival contours, crestal bone, and phenotypic features.
- Benefit: Clearer tissue outlines aid diagnosis and improve accuracy when merging surface scans and DICOM files.

- Reference: Januário et al. developed a method using lip retractors for non-invasive measurement of gingival thickness.

3. Field Of View (FOV)[43]

FoV determines the area irradiated and visible in the scan. Selection depends on diagnostic needs and equipment capacity:

- Small FoV (~6 in):
    - Visualizes 5 anterior or 3 posterior teeth.
    - Used for endodontics, root fractures, periapical lesions.
    - Produces high-resolution images with minimal distortion and low radiation.
    - Fixed small FoV machines require multiple scans for full arches, increasing exposure .
- Medium FoV (~9 in):
    - Covers an entire arch with apical extension .
    - Can display antagonists up to the bone crest.
    - Ideal for implant planning and TMJ evaluation, balancing image resolution with radiation.
- Large FoV (~12 in):
    - Captures the whole craniofacial area, useful in orthognathic surgery, trauma, and extensive pathology.
    - May introduce slight volume distortion—not ideal for precise guided implant surgery.
    - Involves higher radiation; use only when clinically justified .

4. Voxel Size[44, 45]

A voxel (3D pixel) determines CBCT resolution:

- Smaller voxels → sharper images, higher radiation, longer scan time.
- Larger voxels → lower resolution, faster scans (better for patients who struggle to stay still).

Voxel size typically correlates with FoV: smaller FoVs use smaller voxels for detail (e.g., periodontal ligament), while implant planning balances voxel size with radiation dose.

5. Segmentation & 3d Reconstruction[46]

Segmentation isolates specific anatomical structures, eliminating visual interference from surrounding tissues. Combined with 3D reconstruction, it generates clear, manipulable renderings for planning.

- Methods:
    - Automatic segmentation (most common) using:
        - Hounsfield Unit (HU) thresholds—each tissue type has a typical HU range.
        - Preset rendering modes built into the software.
    - Custom segmentation allows isolation of targeted structures (e.g., a mandibular section).

Accurate segmentation is critical for precise implant planning and integration of CBCT data with surface scans.[46]

Benefits of CBCT in precision, safety, and efficiency make it indispensable in modern implantology. Cone Beam Computed Tomography (CBCT) has become an essential diagnostic tool in digital implantology due to its ability to generate three-dimensional, high-resolution images of dental and maxillofacial structures. It bridges the gap between diagnostic imaging and computer-assisted surgery, providing a reliable foundation for virtual implant planning and guided placement.[47]

ALARA PRINCIPLE AND IMAGING GUIDELINES

Radiation safety is crucial in CBCT use. The ALARA (As Low As Reasonably Achievable) principle mandates:[48 ,49, 50]

- Justification: Use CBCT only when clinically necessary.
- Optimization: Choose the smallest FOV, lowest resolution, and minimal exposure time appropriate for the diagnostic need. (Pauwels et al., 2012)
- Protection: Employ shielding (lead aprons, thyroid collars) especially in children and pregnant patients.

Professional Guidelines:[51,52,53]

- American Academy of Oral and Maxillofacial Radiology (AAOMR)2013: Use CBCT only when conventional imaging is inadequate.
- European Academy of Dento Maxillo Facial Radiology (EADMFR) Guidelines 2012: Justify and document CBCT use with the lowest exposure protocols.
- International Commission on Radiological Protection (ICRP, 2015): The ICRP sets the global framework for radiation protection, emphasizing the three fundamental principles: justification, optimization, and dose limitation.

Quality Assurance and Patient Consent (Jaju & Jaju, 2015): emphasize that CBCT use should be guided by justification, optimization, and dose minimization, moving from ALARA (As Low As Reasonably Achievable) to ALADA (As Low As Diagnostically Acceptable).[54]

- Regular calibration and maintenance are essential.
- Operators must be trained in machine use, dose optimization, and image interpretation.
- Obtain informed consent with an explanation of benefits, risks, and alternatives. (Bornstein et al., 2014)

Emerging Trends[55,56,57]

- AI-enhanced Imaging: Predictive algorithms for optimized dose settings.
- Iterative Reconstruction: Maintains image quality at reduced exposure.
- Real-time Dosimetry: Embedded dose monitoring during scanning.

CBCT has become a cornerstone in digital implantology by offering unparalleled 3D visualization, integration with digital planning tools, and the ability to produce highly accurate surgical guides. Its role spans from diagnosis and planning to execution and postoperative assessment, making it indispensable for safe, predictable, and efficient implant therapy.[58]

STL FILES

STL (Standard Tessellation Language or Stereolithography) is a digital file format used to represent the surface geometry of 3D objects. It is widely used in digital dentistry for modelling anatomical structures, designing restorations, and fabricating surgical guides. STL files are typically generated from intraoral or extraoral scanning devices and serve as digital replicas of the patient's oral anatomy.[31]

In digital implantology, STL files complement DICOM data by providing surface detail of the oral cavity, allowing for a complete understanding of both hard and soft tissue structures when merged. This superimposition is crucial for prosthetically-driven implant planning and the design of patient-specific surgical guides.[59]

In digital implant planning, STL files are essential for the following applications:[60,61,62]

1. Merging with DICOM Data: STL files of the patient’s soft tissue and dental surfaces are superimposed onto DICOM data to create a comprehensive 3D model that includes both hard and soft tissues.
2. Virtual Wax-Ups: Digital simulations of the final prosthesis are created using STL files, allowing clinicians to plan implant positions based on ideal restorative outcomes.
3. Surgical Guide Fabrication: Once the virtual implant position is finalized, STL data is used to design a surgical guide, which is then 3D printed.
4. Prosthetic Design: Using STL data, clinicians and dental technicians can design crowns, bridges, abutments, and full-arch prostheses virtually before implant placement.
5. Treatment Simulation: STL files can be imported into planning software to simulate occlusion, assess interarch space, and visualize restorative contours.

STL Generation and Accuracy

STL files are derived from two primary scanning methods:[31]

- Intraoral Scanning: Direct capture of the patient’s oral anatomy using optical scanners.
- Extraoral or Laboratory Scanning: Digitization of conventional impressions or stone models.

Accuracy of STL data is paramount. Errors in scanning or file processing can lead to mismatches during the merging with DICOM files, resulting in compromised implant placement or prosthetic fit. High-resolution STL files (with small triangle mesh sizes) offer more detail but require greater computing power and storage.[63]

Merging STL with DICOM

STL and DICOM integration is performed using landmark-based or surface-matching algorithms in planning software. The precision of this step determines the alignment of soft tissue contours (from STL) with underlying bone and anatomical structures (from DICOM). Misalignment can cause:[59]

- Improper implant axis orientation
- Inaccurate emergence profiles
- Compromised surgical guide seating

Most modern software platforms provide automatic and manual tools for optimizing STL-DICOM alignment. Verification steps are crucial before proceeding to surgical guide design.

Advantages of STL Files[31]

- Highly detailed representation of surface anatomy
- Compatibility with a wide range of CAD/CAM platforms
- Ease of storage, sharing, and manipulation
- Enable remote collaboration between clinicians and labs

Limitations[31]

- STL format lacks internal structure data (e.g., bone density or volume)
- Sensitive to scanning artifacts or reflective materials (e.g., metal restorations)
- File sizes can be large and cumbersome to process
- Errors in scan body capture can lead to inaccurate implant analog positioning

INTRAORAL SCANNERS

The concept of digital impressions began with Dr. François Duret in 1973. In 1977, Youn Altschuler developed a complex and costly intraoral surface mapping system. In the 1980s, Dr. W Mörmann, a Swiss dentist, and Marco Brandest an Italian electrical engineer, invented the first using the open standard tessellation language.[64]

Intraoral scanners (IOS) are handheld digital devices used by dentists to create 3D images of the mouth, including teeth and gums. IOS have become common in many dental fields due to their ease of use and precision. They replace messy traditional impressions such as alginate or polyvinyl siloxane (PVS) with a faster, more comfortable, and accurate digital method. In implant dentistry, digital scans are used to design surgical guides and custom parts, ensuring the implants are placed in the best position. This reduces errors, improves appearance, and increases the success of the implant.[65]

IOS create digital files known as Standard Triangulation Language (STL files) that can be combined with DICOM files from CBCT scans, this enables precise planning of implant placement, guide design, and flapless surgeries, improving outcomes, minimizing complications and achieve both functional and aesthetic results. [33]

Figure-2: Intraoral dental scanner

Mechanism of Intraoral Scanners:[65,66]

The working principle of IOS devices involves several technological components that collaborate to record and process accurate digital impressions.

1. Optical Components and Imaging Sensors: Intraoral scanners utilize high-resolution lenses, mirrors, and imaging sensors to capture the topography of intraoral structures. These optics ensure that even minute details such as pits, fissures, and gingival contours are recorded accurately.
2. Light Projection and Scanning Technology: Most modern IOS systems employ structured light, laser beams, or confocal microscopy to scan the oral cavity. These techniques involve projecting a known pattern of light onto the surfaces and analyzing how it deforms. This deformation is interpreted through triangulation or image stitching to generate a 3D model.
3. Real-time Image Feedback and Guidance: As the scanner tip moves within the mouth, the captured data is simultaneously displayed on a monitor. This real-time feedback ensures the operator can detect missed areas instantly and scan them again, leading to comprehensive and error-free impressions.
4. Multi-axis Tip Movement: IOS devices are ergonomically designed with rotatable scanning tips to allow easy access to posterior teeth and difficult anatomical areas, reducing the need for patient repositioning.
5. Software Algorithms: Advanced processing software assembles captured frames into a cohesive Standard Tessellation Language (STL) file. These algorithms remove redundancies, correct motion blur, and ensure surface continuity.
6. Data Stitching: To create a complete model, the software stitches together multiple images taken from different angles. Algorithms identify overlapping areas in the images

and merge them to form a seamless digital model. This stitching process is crucial for maintaining accuracy and continuity in the final 3D representation.

Over the years, technology has rapidly advanced, giving rise to various commercial systems: [67,68,69]

- Lava C.O.S (2006): Introduced wave-front sampling for improved accuracy and smaller scanner tips.
- iTero (2007): Employed red laser and parallel confocal imaging for real-time scanning.
- PlanScan (2008): Used laser video-streaming with blue light and featured a powder-free system.
- E4D and CEREC Bluecam (2008-2009): Integrated optical coherence tomography with co-focal microscopy. CEREC required contrast powders.
- TRIOS (2010): Revolutionized IOS with ultra-fast scanning, powder-free technology, real-time image correction, and automatic removal of artifacts.
- CEREC Omnicam (2012): Created full-color digital casts with advanced video streaming and open STL export capability.
- CS 3500 and True Definition (2013-2016): Click-point systems using blue LED, requiring powder coating for image clarity.
- Virtuo Vivo (2017): Included five integrated scanning technologies for difficult areas and DWOS CAD software.
- Medit i500 and WOW (2018-2019): Used video photogrammetry and open workflows to generate hyper-realistic digital models.
- CEREC Primascan (2019): Improved processing power and touch-screen interface for user-friendly design.

Clinical Applications in Implantology[70,71,72]

1. Digital Impressions for Edentulous and Partially Edentulous Arches: Intraoral scanners are particularly beneficial for capturing soft tissue contours and mucosal details around implant sites.
2. Scan Bodies: In implant workflows, scan bodies are attached to the implant or abutment to digitally register their exact position and orientation.
3. Prosthesis Design: Scans can be used to design temporaries, custom abutments, and final restorations.
4. Occlusal Analysis: Accurate capture of opposing arch and occlusal relationships facilitates functional prosthetic design.
5. Postoperative Monitoring: Intraoral scans can document soft tissue healing and track changes in gingival contour over time.

Clinical Protocol[73]

1. Dry and isolate the area to minimize reflectivity and soft tissue movement.
2. Capture full arches including occlusal and buccal bite registrations.
3. Use high-resolution scan mode for implant sites and soft tissue contours.
4. Verify scans using inbuilt software validation tools.
5. Export STL files and merge with DICOM in planning software.

Advantages of Intraoral Scanners[66]

- High Accuracy and Reproducibility: They minimize errors like air bubbles and dimensional distortions found in traditional materials.
- Enhanced Patient Comfort: The elimination of impression trays and materials reduces anxiety and discomfort, particularly in paediatric and geriatric patients.

- Faster Workflow: Immediate data capture and transmission enable faster turnaround times for prosthetic delivery.
- Digital Integration: Cloud-based data transfer, Seamless export of STL files into CAD/CAM and 3D printing systems enhances communication with dental labs.
- Environmentally Friendly: Reduces the need for impression materials, gypsum models, and storage space.
- Portability and Wireless Connectivity: Many latest IOS models are wireless and lightweight, increasing manoeuvrability and reducing operator fatigue.

Limitations of Intraoral Scanners[74]

- High Initial Cost: The equipment and required software represent a significant financial investment for smaller practices.
- Moisture and Reflective Surface Sensitivity: The presence of saliva, blood, or shiny materials like metal restorations can interfere with image capture.
- Edentulous Scanning Challenges: Absence of teeth leads to fewer landmarks, making accurate scanning difficult in fully edentulous cases.
- Learning Curve and Training: New users require proper training and adaptation to maximize the effectiveness of the technology.
- Data Management and Security: The use of cloud storage and digital transfers necessitates stringent data protection and compliance with privacy laws.

Intraoral scanners have become indispensable tools in modern dentistry. By providing precise, rapid, and comfortable digital impressions, IOS enhances patient care and clinical efficiency. Their integration with CAD/CAM systems allows for streamlined prosthetic workflows, virtual treatment planning, and minimally invasive surgical procedures. Although some limitations persist, ongoing technological advancements and increased accessibility are steadily overcoming these barriers, promising a future where digital dentistry becomes universally adopted across all dental disciplines.[75]

EXTRAORAL SCANNING

Extraoral scanning is a complementary digital tool in implantology used primarily to digitize physical models, impressions, or prosthetic components in clinical and laboratory settings. It plays a vital role when intraoral scanning is not feasible or when existing analog data must be incorporated into a digital workflow.[76]

Extraoral scanners (EOS) can be subdivided into two types: contact or contactless. While the first refers to former digitalizing methods (i.e., Procera®, Nobel Biocare), non-contact or optical scanners are widely used today.[77]

Figure-3: Former contact scanners. Procera® by Nobel Biocare[78]

Figure-4: Extraoral optical (non-contact) scanner. Autodesk® by Shining 3D[41]

Technology and Workflow

Extraoral scanners, also referred to as desktop or laboratory scanners, utilize technologies such as structured light projection or laser triangulation to capture surface data of plaster models, wax-ups, or prosthetic appliances. The scanning process involves[79]

1. Placing the object (e.g., stone cast or denture) on a turntable.
2. Sequential imaging from multiple angles.
3. Software reconstruction of the captured data into a three-dimensional STL file.

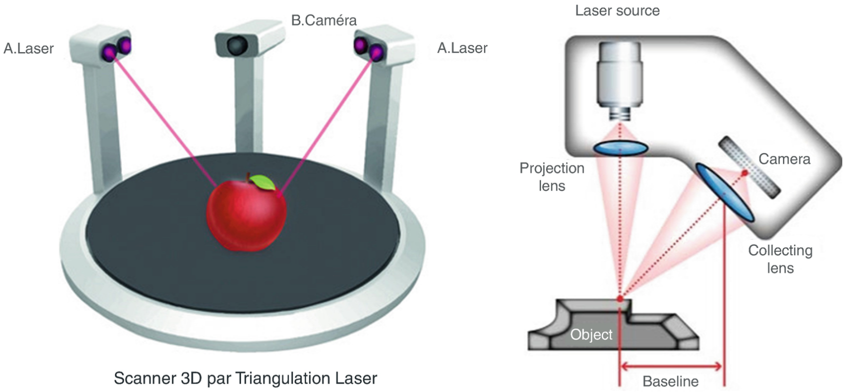


Figure-5: Triangulation principle. A light is projected over an object and the reflection is captured by a camera. The angle of reflection is measured to determine the surface of the scanned object [80]

Modern scanners, such as 3Shape E-series, Medit T-series, or Dental Wings scanners, offer high precision (typically <10 microns) and can capture detailed occlusal anatomy, undercuts, and margin lines.[79]

Applications in Digital Implant Planning[79]

1. Digitization of Conventional Impressions: When intraoral scanning is not possible (e.g., due to bleeding, restricted access, or extensive edentulous spans), conventional impressions are poured into stone models and digitized.
2. Scanning of Existing Prostheses: Extraoral scanning allows the digitization of removable prostheses such as complete dentures, which can be used for planning implant-supported overdentures.
3. Digitization of Wax-Ups: Diagnostic wax-ups and occlusal rims can be scanned and used to simulate the final prosthetic outcome in planning software.
4. Integration with CBCT: Digitized models are matched with CBCT data to simulate implant placement within the context of soft and hard tissue anatomy.
5. Custom Tray and Guide Design: Scanned models can be used to design custom impression trays and surgical guides.

Advantages[80,81]

- High Accuracy: Extraoral scanners offer excellent accuracy in capturing fine surface details (Mangano et al., 2017).
- Material Versatility: Able to scan various materials including gypsum, wax, resin, and metal.
- Non-Invasive: Does not rely on patient cooperation or intraoral accessibility.
- Restoration Archiving: Scanned prostheses can be stored digitally and reproduced if needed.
- Restorative Design: Used extensively in CAD workflows for designing crowns, bridges, and implant abutments.

Limitations[82]

- Additional Step: Requires physical impressions or models to be made before digitization.
- Time-Consuming: Model preparation, scanning, and post-processing take more time than direct intraoral scanning.
- Dependency on Physical Accuracy: Errors in impression taking or model pouring are preserved in the digital file.
- Limited Soft Tissue Detail: Unlike intraoral scans, mucosal dynamics are not accurately represented.

Clinical Indications[83]

Extraoral scanning is particularly useful in cases involving:

- Edentulous arches
- Reproduction of existing dentures
- Reverse engineering of prostheses
- Laboratory-based workflows with physical wax-ups

Integration with Digital Planning Software[72]

STL files from extraoral scans are imported into planning platforms and superimposed onto CBCT volumes using reference points or fiducial markers. In full-arch cases, the denture scan is aligned with a radiographic scan (obtained with the denture in place during CBCT acquisition) to ensure proper spatial registration.

Future Prospects[84,85,86]

- Automated Model Recognition: AI-assisted tools for automatic detection of occlusal and margin lines.
- Increased Automation: Auto-matching of scan data to DICOM volumes.
- Improved Soft Tissue Simulation: Research into surface texture and color acquisition for complete prosthetic simulation.

Extraoral scanning has shown accuracy levels comparable to intraoral scanning when properly calibrate. It is also a preferred method for archiving and replicating existing dentures. Its integration with CBCT allows a holistic view of both prosthetic and surgical parameters.[72]

COMPUTER-ASSISTED DESIGNING (CAD)

Implant dentistry has undergone a remarkable transformation over the past two decades, driven by the convergence of advanced imaging technologies, digital workflows, and innovations in medical informatics. Among these advancements, Computer-Assisted Designing (CAD), often combined with Computer-Assisted Manufacturing (CAM), has emerged as a cornerstone of modern implantology. CAD enables clinicians to create a detailed, prosthetically driven treatment plan by integrating diagnostic images, anatomical data, and restorative objectives into a single digital workflow.[86]

This paradigm shift represents a move away from traditional freehand implant placement, where implant positioning relied heavily on the clinician’s experience and intraoperative judgment. Instead, CAD-based implant planning allows clinicians to simulate the ideal implant position virtually, fabricate highly accurate surgical guides, and perform implant placement with unprecedented precision.[87]

By incorporating CAD, implantology has evolved into a predictable, minimally invasive, and patient-centered specialty, where the surgical and restorative phases are seamlessly integrated to ensure functional and esthetic outcomes.[88]

The Role of CAD in Implantology

CAD has redefined implant planning by enabling a prosthetically driven approach, in which the final restoration dictates implant placement, rather than simply adapting the prosthesis to surgically placed implants.[89]

Key functions of CAD in implant planning include:[87,90]

- Three-Dimensional Visualization: CAD software merges radiographic and surface scan data to create a virtual 3D model of the patient’s anatomy, enabling clinicians to examine bone volume, density, and proximity to vital structures such as the inferior alveolar nerve, mental foramen, or maxillary sinus.
- Precision Planning: Implant type, size, position, depth, and angulation are digitally simulated to achieve optimal prosthetic and functional outcomes while avoiding critical anatomical structures.
- Prosthetic Integration: By incorporating digital wax-ups and virtual mock-ups, CAD ensures implants are placed to support the final prosthetic design, enhancing esthetics, occlusion, and longevity.
- Guide Design and Fabrication: CAD software allows the design of surgical templates, which are fabricated using 3D printing or milling. These templates translate the digital plan into the surgical field with high accuracy.
- Collaborative Communication: CAD fosters better communication between implant surgeons, prosthodontists, dental laboratories, and patients, as all parties can visualize and contribute to the virtual plan before treatment begins.

Data Acquisition and File Management in CAD Workflows[91,92]

A successful CAD-based workflow begins with comprehensive digital data collection, which forms the foundation for virtual planning. The process typically involves three core data streams:

1. DICOM Files (Digital Imaging and Communications in Medicine):

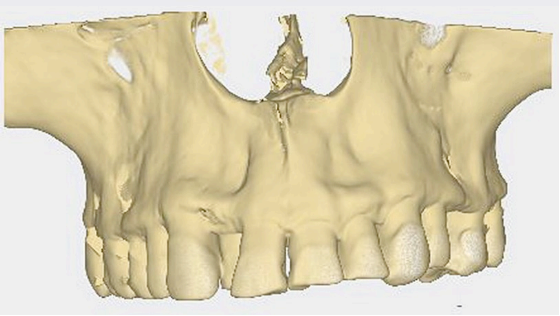


Figure-6: DICOM file from patient CBCT[41]

- Generated from Cone Beam Computed Tomography (CBCT) scans.
- Provide radiographic information about bone morphology, density, sinus anatomy, and nerve pathways.
- Essential for mapping vital structures and assessing the suitability of implant placement sites.

2. STL Files (Standard Tessellation Language):

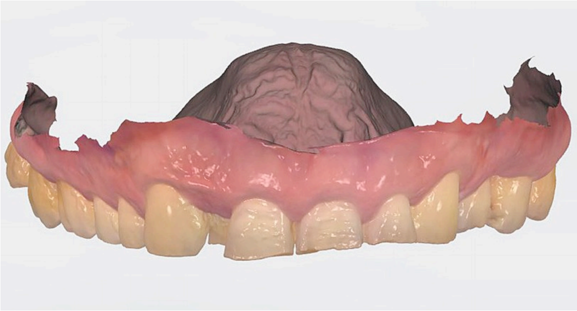


Figure-7: Surface scan from patient oral situation[41]

- Created using intraoral scanners or laboratory-based optical scanners.
- Capture surface anatomy, including teeth, gingival contours, and occlusion.
- Provide the basis for designing prosthetic elements, fabricate a template for guided surgery and aligning the prosthetic plan with the underlying anatomy. Thus, if only a DICOM file is uploaded in an implant planning

software, clinician will be able to navigate the study, measure distances or place a virtual implant, but won't be able to determine a precise prosthetic plan (digital wax-up and future crown position) or even deliver a surgical template.[41]

3. Integration of DICOM and STL Data:[92]
    - CAD software merges radiographic and surface data to create a comprehensive 3D model.
    - This merged model serves as the foundation for prosthetically driven implant planning, ensuring the restorative design dictates implant positioning rather than the other way around.

Types of CAD Software in Digital Implant Planning[34]

CAD software platforms used in digital implantology can be broadly categorized based on their primary function and capabilities:

- Prosthetic Planning Software:
    - Primarily used by dental laboratories to design prosthetic components such as crowns, bridges, abutments, and hybrid restorations.
    - Ensures the final prosthetic design informs the surgical plan.
- Implant Planning Software:
    - Used by clinicians for 3D visualization, implant simulation, and surgical guide design.
    - Allows for virtual implant placement, assessment of anatomical considerations, and planning of surgical access.

Popular Software Examples:[33,41]

- Basic *Tomography* Viewers: CBCT-linked programs (e.g., Romexis®) – Allow clinicians to visualize anatomy but have limited or no guide-design functionality.
- Open-Source Programs: *BlueSkyPlan*® – Affordable solutions with flexible features, though exporting files for guide fabrication may incur minimal costs.
- Premium Platforms: *3Shape Implant Studio®, CoDiagnostix®, Exoplan*® – Offer comprehensive workflows, large implant libraries, and seamless integration with dental labs.

Interoperability and File Formats[78]

Although STL is a universal format, proprietary file types (e.g., DCM by 3Shape) are sometimes used to store additional metadata such as tooth shade, occlusal schemes, or planning markers.

- When exporting STL files between software platforms, minor misalignments can occur, requiring manual correction within CAD programs.
- Understanding file compatibility is essential for maintaining data integrity and planning accuracy when moving between software systems.

CAD Workflow in Implant Planning[28,93]

The CAD workflow for implant planning involves several systematic stages, ensuring a seamless transition from diagnosis to surgical execution:

1. Treatment Goal Definition:
    - Establish the clinical and prosthetic objectives (e.g., single-tooth restoration, full-arch rehabilitation).
    - Outline aesthetic, functional, and biomechanical requirements.
2. Data Acquisition:
    - Obtain CBCT scans for bone assessment (DICOM files).
    - Capture digital impressions or laboratory scans for surface anatomy (STL files).
3. Model Optimization:
    - Crop extraneous structures (e.g., lips or tongue) to streamline processing and visualization.
4. Anatomical Mapping:
    - Identify critical landmarks such as the mandibular canal, sinus floor, or nasal cavity.
5. Virtual Wax-Up:
    - Create a digital mock-up of the proposed prosthesis, which serves as the blueprint for implant positioning.
6. Data Merging:
    - Align DICOM and STL data into a unified 3D model.
    - Perform fine-tuning if automatic alignment is slightly off.
7. Virtual Implant Placement:
    - Select implant size, type, and angulation virtually.

  - Position implants to support the prosthetic plan while respecting anatomical constraints.

8. Guide Design:
    - Design a surgical template (tooth-, mucosa-, or bone-supported) with planned drill sleeve positions.
9. Fabrication:
    - Export the digital guide for 3D printing or milling.
    - Verify and sterilize the guide before clinical use.
10. Surgical Execution:
    - Place the guide intraoperatively and follow the planned drilling sequence, transferring the digital plan into reality.

Image Merging Techniques in CAD Workflows

Merging CBCT and surface scan data is one of the most critical steps in CAD-based implant planning:

- Three-Point Recognition (Automatic Alignment): Software identifies three or more reference points (e.g., cusp tips, incisal edges) for automatic alignment. When natural dental structures are preserved, anatomic crowns serve as reliable reference points for aligning surface scans with CBCT 3D reconstructions. The software displays both datasets in a double window—one showing the surface model (STL) and the other the CBCT rendering. Three points, spaced as far apart as possible, are selected in both views to establish correspondence. Advanced programs may automatically align the datasets if images are clear and tooth structures are intact; however, manual point selection often refines accuracy. [28,41]

Several factors enhance this matching process. Tissue density adjustment is key modifying the Hounsfield Unit (HU) threshold ensures enamel, dentin, and bone are visible while soft tissues are excluded. Soft tissue separation during CBCT acquisition further improves clarity. Magnification and orientation help in precise point placement; both images should be scaled and angled similarly for consistency. [28,41]

When choosing points, buccal cusp tips are preferred as they are distinct and visible in both datasets. Cervical areas and proximal surfaces are less reliable due to limited visibility or overlapping enamel. Natural teeth are superior to restorations for reference, while metal objects should be avoided because tomography artifacts can distort their image. Accurate alignment ensures surgical guides and implant plans match clinical reality. [28,41]

- Manual Adjustments: Clinicians refine alignment using zoom and density tools when necessary. After merging the selected alignment points, the result should be inspected for accuracy. Some software provides a color scale, using a Boolean difference process, to highlight matching quality and identify mismatches. If the merge is unsatisfactory, additional points can be selected, or the surface scan can be moved and rotated for better fit. Radiopaque markers can improve accuracy in cases with limited tooth structures or large edentulous areas. Without markers, the palate and firm mucosa can guide adjustments. Soft tissue separation in CBCT enhances gingival contour visibility. Manual adjustments should be the last resort when automated alignment fails. [28,41]

- Radiopaque Markers: In edentulous cases, barium sulfate-coated markers or gutta-percha dots are added to assist alignment. Large edentulous spaces, such as a missing posterior quadrant, can hinder image merging. In such cases, a tomographic template with radiopaque spots can provide alignment points. These markers must appear in both the surface scan and CBCT, so scanning should be done with the template in place. Creating a notch before adding radiopaque material ensures correspondence between STL and DICOM data, improving merging accuracy.[87,94]

Special Protocols for Edentulous Patients:

- Double Scan Technique: If the patients existing dentures are found to be satisfactory in aesthetics and function, then it can be converted into a radiographic template by placing fiducial markers on the duplicate dentures. Sometimes a laboratory fabricated radiographic template is also used. First data set is obtained by CBCT imaging of the patient with the radiographic template/duplicate dentures with radiopaque markers in mouth. The second set data is obtained by CBCT imaging the radiographic template alone. The radiographic template which is devoid of any metallic restoration, and implants will prevent the development of artefact. Thus, the clean occlusal surface obtained from the radiographic template can be merged to the first data set with the help of fiducial markers and sent to the laboratory for the fabrication of surgical stent. [34]

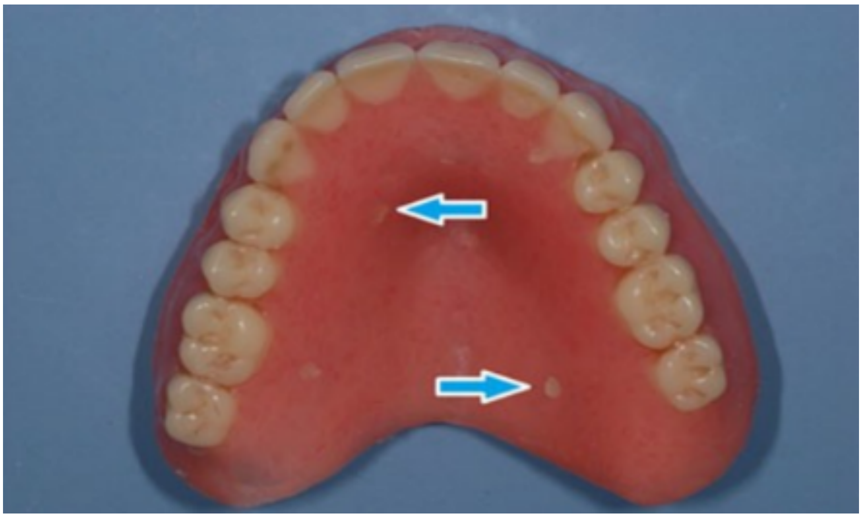


Figure-8: Duplicate dentures with radiopaque markers[95]

Figure-9: Radiographic template with radiopaque teeth[95]

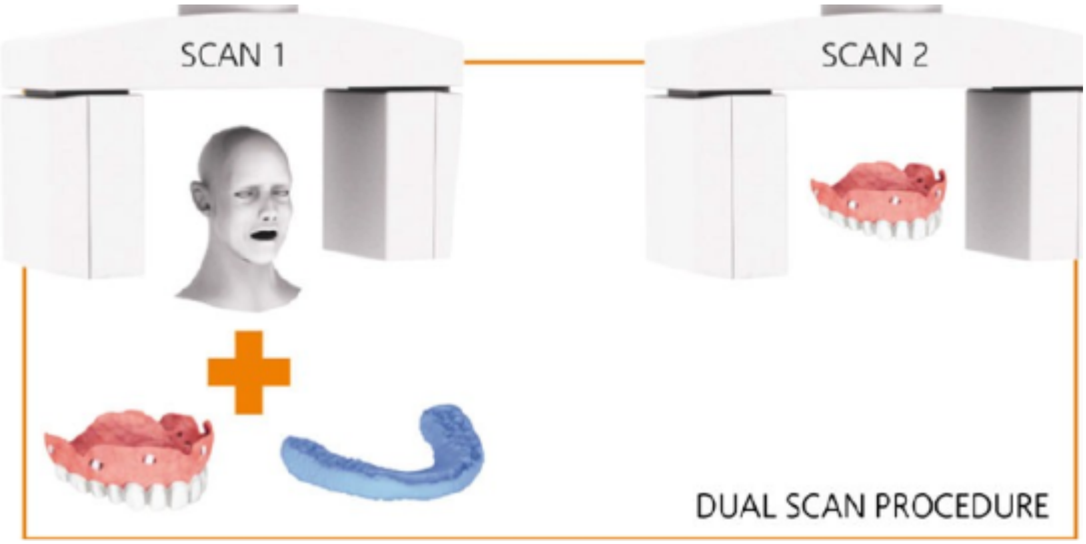


Figure-10: picture depicting dual scan protocol[96]

CBCT scan of the patient wearing a radiographic guide is combined with a separate scan of the guide alone. Based on the spherical markers visible in both scans, the scans are superimposed onto each other, resulting in a 3D bone model of the patient together with a 3D model of the radiographic guide. Using the data from dual scan procedure, surgical stents are fabricated with the help of stereolithography.[34]

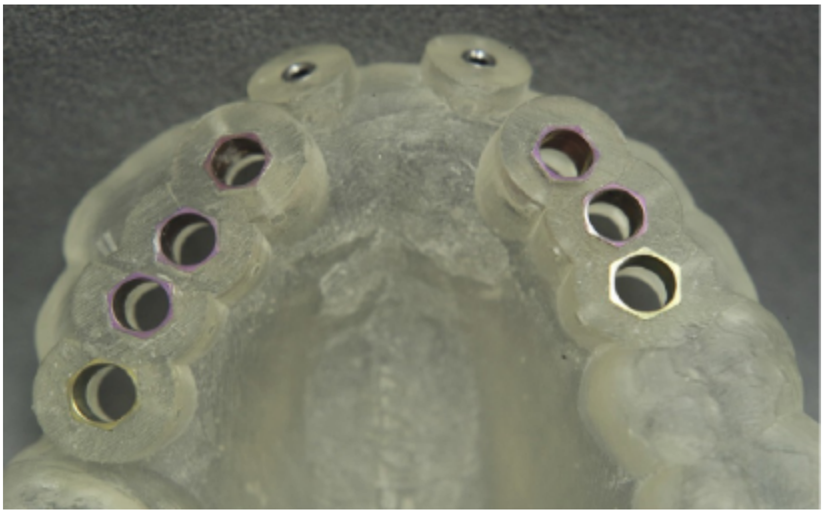


Figure-11: Surgical stent fabricated using stereolithography[41]

Some drill guidance allows only for the usage of pilot drill. Multiple surgical guides with varying diameter of drill guides can also be fabricated to precisely place the implants. In, sleeve-in-sleeve concept, a single surgical guide with multiple sleeves with varying diameter is also fabricated.

- Triple Scan Method: Includes scans of the guide, the guide on a model, and the patient wearing the guide, capturing all relevant data for precise alignment. When double CBCT imaging produces a low-quality prosthesis render, an alternative approach can improve accuracy. This method records the prosthesis’s outer surface (tooth distribution), inner surface (mucosal base), and radiopaque notches. First, a stone model of the edentulous area is prepared to hold the prosthesis in the correct position—ideally made from the prosthesis itself. Reference marks are placed on the model base, away from the prosthetic area, and notches are made in the prosthesis. A scanner is then used to capture two datasets: one of the bare model to record the mucosa, and a second with the prosthesis seated but empty notches. The notches are then filled with radiopaque material, and a single CBCT is taken with the prosthesis in place. Merging involves superimposing the scans using the base reference marks, aligning the STL notch image to the radiopaque dots in CBCT. This links all three datasets—CBCT for bone and prosthetic positioning, the outer surface scan for tooth distribution, and the inner surface scan for mucosal support. The result is an accurate, muco-supported surgical template and a precise implant plan, even in challenging cases where direct prosthesis CBCT visualization is poor.[41,97]

Digital Wax-Up and Prosthetic Simulation

The digital wax-up is a critical step in CAD implant planning, providing a visual representation of the final prosthetic outcome.

- Direct Wax-Up: Designed within implant software. Implant planning software allows clinicians to position a virtual crown within surface scans or CBCT data, with advanced programs enabling adjustments of emergence profile, cusp height, and occlusal anatomy, while basic ones only permit size and position changes. Even if a provisional crown is not fabricated, the wax-up remains a necessary step, since surgical planning software cannot deliver the final prosthesis. After completing surgical planning, the data must be exported into a prosthetic CAD program to design abutments and restorations by defining margin lines, material thickness, cement space, and other features, all guided by the initial wax-up. Importantly, both software platforms must be compatible to ensure seamless data transfer.[91,98]

- Indirect Wax-Up: Created externally (e.g., in Exocad) and imported into implant planning software. An indirect wax-up is used when implant planning software alone cannot handle complex restorative designs, particularly in multi-unit cases where tooth anatomy or distribution must be modified. In such situations, a wax-up is first created in a prosthetic CAD program and clinically verified with a try-in to confirm new esthetic and functional parameters before continuing with implant planning. This workflow ensures greater accuracy and predictability, since implant planning software and prosthetic design software must be compatible to allow seamless data exchange.[41,91]

This wax-up helps clinicians and patients visualize the final result and ensures implant placement aligns with functional and esthetic goals.

Technical Protocol for CAD-Guided Surgery[93]

A precise technical protocol is followed to translate the digital plan into the surgical setting:

1. Design Prosthetic Prototype:
    - Establish the end goal for esthetics, occlusion, and function.
2. Fabricate Radiographic Template:
    - Duplicate the prosthesis or denture, embedding radiopaque markers for scan alignment.
3. Perform CBCT Scans:
    - Capture scans of the patient wearing the guide and the guide alone using identical scan parameters.

4. Virtual Planning:
    - Merge scans, digitally position implants, and confirm the prosthetic alignment.
5. Guide Fabrication:
    - Design and print the surgical guide using stereolithography or other 3D printing technologies.
6. Surgical Execution:
    - Seat and stabilize the guide.
    - Follow the guided drilling protocol to ensure precise implant placement.

Advantages of CAD in Digital Implant Planning[22,99,100]

The integration of CAD into implantology offers numerous benefits:

- Exceptional Accuracy: Digital planning ensures implants are positioned exactly as designed.
- Minimally Invasive Surgery: Enables flapless procedures, reducing trauma, bleeding, and postoperative discomfort.
- Enhanced Safety: Protects vital structures such as nerves, vessels, and sinuses.
- Improved Efficiency: Reduces surgical time and chairside adjustments.
- Immediate Loading: Allows presurgical fabrication of temporary or definitive restorations.
- Interdisciplinary Communication: Facilitates collaboration between surgeons, prosthodontists, and laboratories.
- Predictability: Creates highly consistent and reproducible surgical outcomes.

Limitations of CAD in Digital Implant Planning[93,101]

Despite its transformative potential, CAD-based implant planning has certain constraints:

- Technical Inaccuracies: Errors may occur during scanning, merging, or guide fabrication, causing slight deviations.
- Guide-Related Complications: Guides can fracture or dislodge during surgery, compromising accuracy.
- Reduced Irrigation: Flapless, guided procedures may limit access for external irrigation, increasing thermal injury risk during drilling.
- Cost and Infrastructure: Software licenses, 3D printers, scanners, and training demand significant investment.
- Learning Curve: Clinicians and staff require training to master the workflow.
- Limited Flexibility in Static Systems: Once fabricated, static guides do not allow for intraoperative modifications; unexpected anatomical findings may require abandoning the guide mid-surgery.

Computer-Assisted Designing (CAD) has revolutionized implant dentistry, shifting the discipline toward prosthetically driven, digitally guided workflows. By integrating radiographic imaging, surface scanning, prosthetic design, and surgical execution, CAD allows for highly accurate, minimally invasive, and predictable implant placement.

The workflow—from digital wax-up and image merging to guide fabrication and guided surgery—ensures that every implant is placed in harmony with the patient's anatomy and restorative needs.[101]

While cost, technical limitations, and the need for training remain challenges, the benefits of CAD-based implant planning—accuracy, safety, efficiency, and patient satisfaction—far outweigh its drawbacks. As CAD technology continues to evolve, it is poised to become the universal standard for implant planning and execution, transforming implant dentistry into an increasingly precise and patient-centered field.[101]

COMPUTER-ASSISTED MANUFACTURING (CAM)

Computer-Assisted Manufacturing (CAM) in implantology refers to the use of digitally controlled machinery and systems to produce dental components based on CAD data. CAM enables the efficient and reproducible fabrication of surgical guides, implant frameworks, custom abutments, and prosthetic structures with high precision. The incorporation of CAM into implant dentistry enhances treatment accuracy, reduces manual errors, and allows for reproducible, high-quality results.[102]

Surgical Template: Glossary of Prosthodontic terms (GPT) defines surgical template as a guide used to assist in proper surgical placement and angulation of dental implants.[103] It enables prediction and minimal invasive surgery. The main objective of surgical template is to direct the implant drilling system and provide an accurate placement of the implant according to the surgical treatment plan. Customized conventional radiographic or computer image guided surgical templates have become a treatment of choice.[104]

A surgical guide consists of two components: The guiding cylinders and the contact surface. The contact surface fits either on an element of a patient's gums or on the patient's jaw (i.e., the bone, the teeth). Cylinders within the drill guides helps in transferring the drill in the exact location and orientation. The implant must be placed such that firstly the bottom and sides are covered fully by bone or bone-replacement material. Care should be taken of not damaging any neighbouring anatomic structures. These are in particular the mandibular nerve in case of mandible and the schneiderian membrane of the maxillary sinus in maxilla and also the roots of adjacent teeth. Thirdly, position of the implant has to be compatible with the intended final prosthodontic restoration. [104]

CLASSIFICATION OF SURGICAL GUIDES

One of the remarkable strengths of guided implant surgery (GIS) is its adaptability. Far from being a one-size-fits-all approach, surgical guides come in several forms, tailored to patient anatomy, prosthetic requirements, and clinical complexity. Classifying these guides helps to understand their strengths, weaknesses, and appropriate indications. Surgical guides are classified by their support mechanism and level of guidance:[104,105]

A). Based on Support Mechanism: [106]

the anatomical differences among teeth, bone and mucosa may lead to different accuracy of guides with different support types.

1. Tooth-Supported Guides:[106] These are anchored on the remaining teeth, typically used in partially edentulous cases. They are considered the most accurate due to their stable support and minimal tissue movement during surgery. Studies reported higher implant placement accuracy and reduced angular deviation in these guides compared to other types (Vercruyssen et al., 2014).

Advantages: Highest accuracy due to immovable support base. Reported angular deviations as low as 2–3°.

Limitations: Require at least 3–4 periodontally stable teeth in the arch. Cannot be used in fully edentulous cases.

Clinical use: Best for partially edentulous patients with sufficient teeth for stability.

2. Mucosa-Supported Guides:[107] Designed for fully edentulous patients, these rest on the soft tissues of the alveolar ridge. Since soft tissue is compressible, mucosa-supported guides require fixation pins to ensure stability during surgery. They are commonly used with full-arch implant placements and All-on-4 protocols (Schnutenhaus et al., 2021).

Advantages: Allow flapless surgery, reducing operative time and morbidity.

Limitations: Accuracy compromised due to mucosal resiliency. Must be stabilized with multiple fixation pins. Deviation increases with mucosa thickness (>3.5 mm).

Clinical use: Full-arch implant rehabilitation, especially in elderly patients seeking minimally invasive solutions.

3. Bone-Supported Guides:[108] These rest directly on the alveolar bone and are used in cases of severe ridge resorption or when teeth and mucosa do not provide reliable support. A full-thickness flap is required to seat the guide, which may increase surgical time and invasiveness (Widmann & Bale, 2006).

Advantages: Provide direct visualization of the surgical field and precise depth control. Useful in cases of limited dentition.

Limitations: More invasive, associated with postoperative discomfort, risk of impaired vascularization. Reported deviations are higher than mucosa- or tooth-supported guides.

Clinical use: Historically the first type of guides for edentulous arches; now used selectively in complex reconstructions.

4. Hybrid Guides (Bone + Tooth Support)[30]

These innovative designs combine remaining teeth for anterior stability with bone support in distal extension edentulous regions.

Advantages: Improved stability compared to mucosa-supported designs; reduce guide bending in long-span edentulous cases. Especially useful for hemi-maxillectomy or zygomatic/pterygoid implant cases.

Limitations: Require flap elevation for bone contact, increasing invasiveness. Need advanced CAD design skills to merge datasets accurately.

Clinical use: Distal extension arches with very few teeth remaining, or unilateral dentition cases.

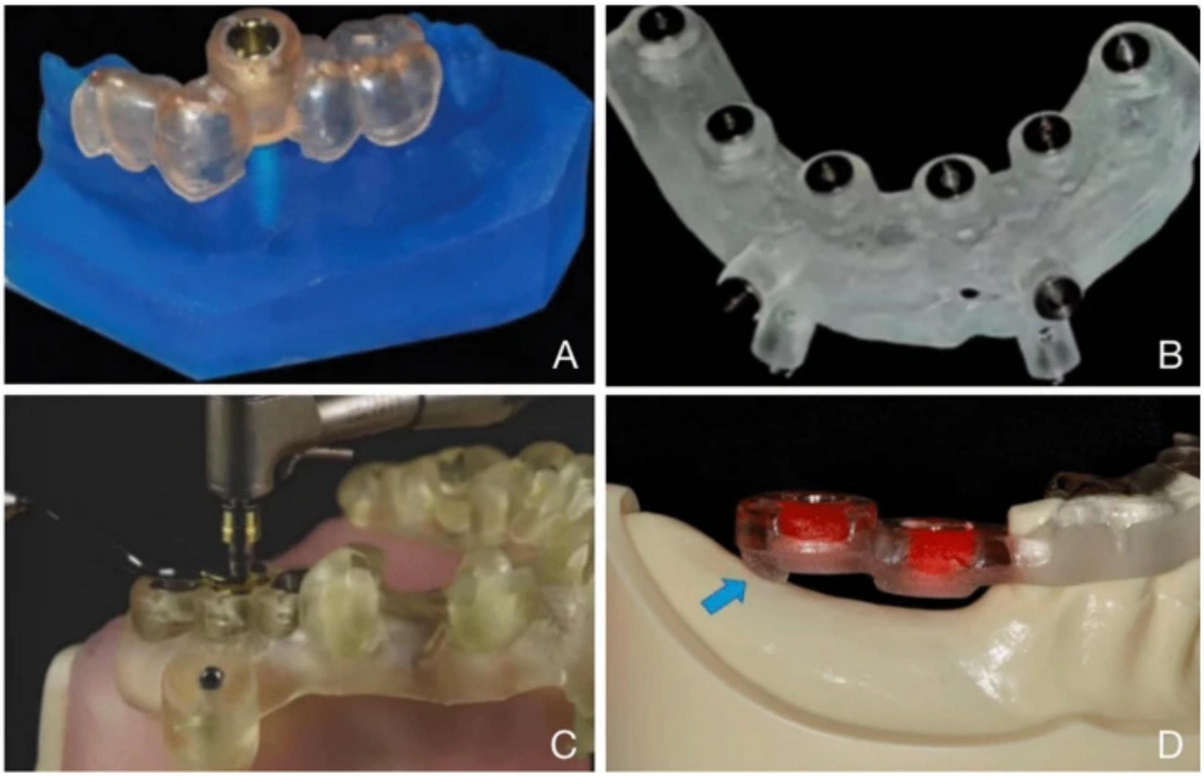


Figure-12: Different support types of implanting guides: A bilateral tooth-supported; B mucosa-supported; C mixed tooth-/mucosa-supported: D mixed tooth-/bone-supported[109]

B). Based on Guidance Mechanism:[110,111]

1. Pilot Drill Guides: These assist only with the initial osteotomy, guiding the angulation and entry point for the first drill. Once the initial trajectory is set, the remaining steps are done freehand. They offer partial control and are typically used when surgical flexibility is desired.[110]

Advantages: Simple, less expensive, allows surgeon flexibility during deeper drilling.

Limitations: Less accurate overall since subsequent steps are not guided. Accuracy depends heavily on the surgeon’s hand stability.

Clinical use: Useful in cases where full guidance is not feasible (e.g., limited mouth opening, posterior sites with access issues).

2. Partial-Depth Guides: These provide drilling guidance up to a predefined depth but do not control implant insertion. They are suitable for clinicians who want a balance between guidance and manual control.[111]

Advantages: Better accuracy than pilot-only guides, some operator flexibility, reduced cost compared to full systems.

Limitations: Accuracy compromised at final seating stage since implant insertion is unguided.

Clinical use: Appropriate for moderate cases where angulation is critical but cost constraints exist.

3. Fully Guided Guides: These control all drilling steps and implant placement, including angulation, depth, and position. They often incorporate metal sleeves to stabilize drills. Fully guided systems are ideal for high-precision cases, such as immediate loading and esthetic zone placement.[110,111]

Advantages: Highest precision, minimal operator variability, fully prosthetically driven.

Limitations: Requires specialized drill kits, limited flexibility if intraoperative changes are needed. More expensive.

Clinical use: Ideal for complex prosthetically driven cases, immediate loading protocols, and when avoiding critical anatomical structures is paramount.

Design of fixation screws[105]

For bone- and mucosa-supported guides, fixation screws can be further introduced to fix the surgical guide and avoid displacement. The accuracy of implantation is reported to be improved by the application of fixation screws and influenced by its distribution. For mucosa-supported guides used in edentulous patients, the use of fixation screws provide larger surface support and reduce the intraoperative displacement, efficiently reduce the angular deviation, depth deviation and horizontal deviation. Therefore, in cases demanding a high depth precision and avoiding injury to the mandibular nerve, application of fixation screws contribute to better implant results.

For mixed tooth-/mucosa-supported guide in free-end dental implantation, application of fixation screws also results in a significant improvement in the accuracy regarding horizontal apical and depth deviation (direction considered). Apart from mucosa-supported and mixed tooth-/mucosa-supported guides, fixation screws can also be introduced into tooth-supported guides to achieve improved stability in both maxillary and mandibular anterior implantation.

Design of sleeve[105]

The guidance of drill hole, implant direction, depth, and angle are realized via design of sleeves, which can also reduce surgical time. Sleeves can be classified as open or closed. Open sleeves with C-shaped buccally opening are applied in posterior areas where mouth opening and interarch space are limited or insufficient. To ensure implant accuracy, the drill should be in the center and parallel to the inner wall of sleeves during hole preparation. [105]

Implant accuracy is affected by the design of height, drilling distance, and sleeve–bone distance, but the sleeve–implant distance and the sleeve axis angle do not affect the accuracy of digital implant guides. By using shorter sleeve heights or shorter implants, decreasing the drilling distance below the guided sleeve can significantly increase the implant accuracy and reduce lateral movement of the drill. However, sleeve heights ≤ 5 mm lead to implant placement deviation and decrease of the accuracy. The increased drilling distance beyond the guiding sleeve results in a significant global and angular deviation at both the implant crest and apex. Decreased sleeve–bone distance results in higher accuracy of the implant surgical guide. With the sleeve–bone distance of 2 or 4 mm, the implant accuracy of closed and open sleeve is similar; whereas with the sleeve–bone distance of 6 mm, lower accuracy is shown in both open and closed sleeves, and open sleeves exhibited a more significant trend. [105]

In addition, material of the sleeve also affects implant accuracy. Metal sleeves are common in early surgery guides, and with the development of material science and technology, it is reported that plastic sleeves endow lower angle deviation, depth deviation, placement deviation than metal ones, as well as ensure a faster and easier guided surgery workflow. [105]

GUIDE FABRICATION METHODS (3D PRINTING AND MILLING)

Three techniques commonly used for preparing the guide holes and fabricating the radiographic and surgical implant guide are conventional free-hand, milling, and computer-aided design/computer-assisted manufacture (CAD-CAM) technology. After planning in CAD software, surgical guides can be fabricated using either additive or subtractive manufacturing techniques.[105]

A. SUBTRACTIVE MANUFACTURING (CAD/CAM MILLING)

Subtractive manufacturing refers to the process of removing material from a solid block to create a dental component using CNC (Computer Numerical Control) milling machines. In order to manufacture an object by a subtractive method, a machine has to mill a block using specific burs and rotating axes. This machine is usually the same that the one used to mill dental restorations. [112]

Types Of Milling Machines

Computer numerical controlled (CNC) machines are in charge of producing objects by a subtractive method. In dental lab devices, milling process involves a spinning bur that moves in different directions to cut a block that is attached to a baseplate. In contrast, industrial lathes represent a different type of CNC machines; in which the material (usually a cylinder) spins at high speed and the cutting tools do not rotate. This latest method is commonly used to fabricate implants, abutments, and screws, but is not suitable for customized requirements.[112]

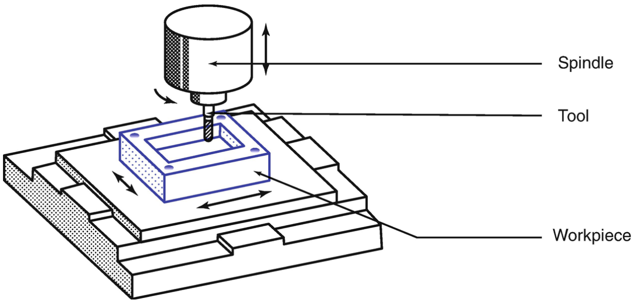


Figure-13: Milling machine concept. A spinning bur cuts a block that is hold still in a baseplate [41]

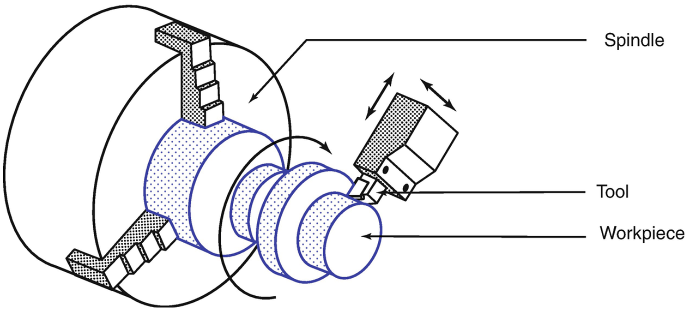


Figure-14: Lathe concept. The material is hold into a spindle and the cutting tool moves without spinning [41]

Within the milling machine, two types of devices can be distinguished: 3-axes or multi-axes. The level of detail and complexity that can be achieved depends on the number of axes of the machine:[112]

- 3-axis: Basic movement in X, Y, and Z directions; machines allow movement only in the handpiece, suitable for simple restorations. The simplicity and reduced time for calculation and milling are what characterized the 3- axis machines. Large and complex prostheses are not typically produced using 3-axis machines. Examples of such machines include the first introduced machines from in Lab (Sirona), Lava (3M ESPE), and Cercon brain (Degu Dent)[112]
- 4-axis: Adds rotational movement for angled surfaces. it allows movement both in the handpiece containing the bur and the plate holding the material. This feature is particularly useful for shaping larger blanks and creating extensive frameworks. The Planmeca Plan Mill 35, and the last introduced Primemill from Sirona, are examples of a 4-axis chairside machine [20]. Typical and widely used 4-axis laboratory milling machines are Zenotec mini (Wieland-Imes), CEREC inlab MC XL.[112]

- 5-axis: Enables full-range motion for complex geometries and undercuts. The transition to 5-axis milling machines includes adding rotating movements in two different directions of either the milling tool or the blank. This includes X-, Y-, and Z-axis translation, along with A- and C-axis rotation , enabling the creation of complex geometries and smoother external surfaces. Some of the modern examples include Zenotec select and T1 from Wieland, DWX-50, Everest Engine (KaVo), and HSC Milling Device (etkon).[112]

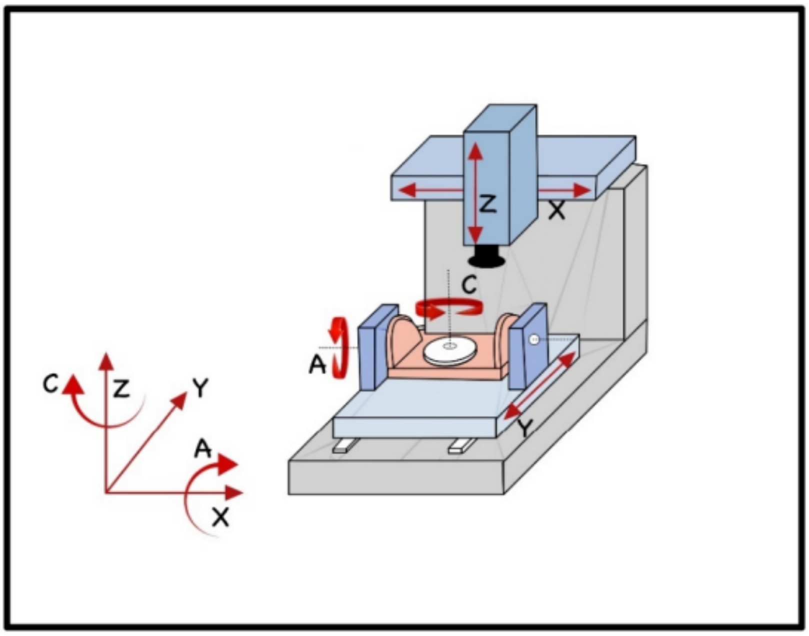


Figure-15: The common movement of the milling machines, characterized mainly by the transitional movement of the spindle and the base, besides the rotational movements of the base[112]

Classifications According to the Mode of Milling

The majority of milling machines offer one of two options: wet milling or dry milling, such as VHF milling machines

- Soft Milling / Dry Milling: Soft milling is suited for low-hardness or dry-milled materials like presintered zirconia, Co-Cr alloys, and wax. It offers speed, reduced cutting forces, longer tool life, and improved surface quality—e.g., chairside systems like Primemill can mill a zirconia crown in under 5 minutes. Post-milling sintering causes shrinkage (≈23% for zirconia, 0.2–0.3% for lithium disilicate), automatically compensated by the system. While efficient, soft milling may show greater dimensional discrepancies than hard milling. Wet-ground zirconia performs better mechanically than dry-milled, but water-impregnated grinding should be avoided to preserve translucency. Continuous advancements are improving shrinkage compensation accuracy.[112]

- Hard Milling / Wet Milling: Hard milling is used for tough materials like metals and densely sintered zirconia, requiring robust CNC systems to handle high cutting forces. Heat buildup—especially in titanium and zirconia—demands continuous cooling to prevent tool wear and material damage. Wet milling is preferred for ceramics, polymers, titanium, and fully sintered zirconia to avoid cracking, overheating, and dust. Co-Cr alloys can be milled wet or dry depending on the system. While wet processing extends tool life, hard milling is time-consuming and, in zirconia, may cause micro-cracks or phase changes, influenced by tool type and the material's properties.[112]

Milling Materials

- PMMA (Polymethylmethacrylate): Most common material used for provisional restorations and surgical guides is polymethyl methacrylate (PMMA) for its strength and low cost. This material comes in different shades but has a transparent option destined for guides or splints.[113]

- PEEK (Polyetheretherketone) /PEKK: High-performance polymers used in implant frameworks and long-term temporaries. This lightweight thermoplastic material has excellent mechanic properties, tolerates sterilization processes and is biocompatible; allowing it to stay in contact with blood or tissue indefinitely while mimicking the stiffness of the bone. Although suitable for templates, this material is usually preferred for implantation (guided bone regeneration), due to its properties. [114]

- Zirconia (3Y, 4Y, 5Y): Zirconia occurs in different solid phases, depending on the applied temperature. In this context, the tetragonal phase features favorable mechanical properties. For this reason, stabilizers such as CaO, MgO, or Y_2O_3 help stabilize zirconia in the tetragonal phase. First-generation zirconia (3Y-TZP) (3mol% yttria-stabilized tetragonal zirconia polycrystal) contains about 85% of the tetragonal phase, which results in high flexural strengths but low translucency (40%). Changes in the compositions of the different phases of zirconia have led to more translucent materials compared to 3rd generation zirconia (5Y-PSZ), which contains approximately 50% of both tetragonal and cubic phases and an yttria content of 5 mol% and therefore has improved optical appearance (translucency 49%) but lower flexural strengths. Used For definitive restorations with varying degrees of strength and translucency.[115]

- Cobalt-Chromium (Co-Cr): Ideal for metal frameworks with high strength requirements.[115]

Clinical Applications:

- Custom abutments and prosthetic bars
- Full-arch frameworks for screw-retained restorations
- Long-term temporary crowns and bridges
- Occlusal splints and guides

Advantages:

- Excellent mechanical properties
- Precise marginal and internal fit
- Strong and durable for long-term clinical use

Limitations:

- Material wastage during cutting
- High initial cost of milling units and maintenance
- Requires longer machining time for complex designs

Workflow:

1. Import STL file from CAD software
2. Choose material block and secure it in the mill
3. ConFig- milling parameters (tool path, bur selection, spindle speed)
4. Start automated milling
5. Post-process: remove supports, polish, and sterilize

B. ADDITIVE MANUFACTURING (3D PRINTING)

Additive CAM refers to the process of building an object layer by layer using various 3D printing technologies. It is especially suited for creating surgical guides, anatomical models, and even provisional prostheses. The machines in charge of said procedure are known as 3D printers and material used is usually a polymer.[116] The principles of this technology were established in the 1980s with the photopolymerization of polymer resin in a vat. While the initial idea and first reported work are attributable to Hideo Kodama, a Japanese researcher, the first two patents on this technology were French and American and were filed within a few days of each other in 1984.[117]

Opposite to CNC machining, 3D printers fabricate an object either by material deposition, material fusion or by hardening material layers from a resin deposited in a vat. Once an object is designed, it becomes a blueprint for the software to process it. This model is then sliced into sequential 2-dimensional layers to give the printer instructions to build the object; layer by layer. Additionally, 3D printers do not need “extra tools,” such as special burs, to obtain a desired model and both simple and complex forms can be equally achieved.[117]

Typical 3D printing includes stereo lithography appearance (SLA), PolyJet, MultiJet, fused filament fabrication (FFF), digital light processing (DLP), etc.[105]

Popular Additive Technologies:

1. SLA (Stereolithography) or VAT polymerization: [118]

SLA printers use a laser beam to cure photosensitive resin in a tank. The laser moves point by point, solidifying the resin layer-by-layer. This method offers excellent surface detail and is considered the gold standard for high-precision surgical guides. However, it is relatively slow and may require extensive post-processing.

SLA apparatus contain a resin tank with a transparent base where the liquid resin rests. A building platform moves vertically through an axis (or multiple axes) and allows the construction of the desired object, either in a normal or an inverted way. The platform moves to the bottom of the vat, leaving a space equal to the desired layer thickness, waits for that layer to be cured and moves to allow space for the next layer.

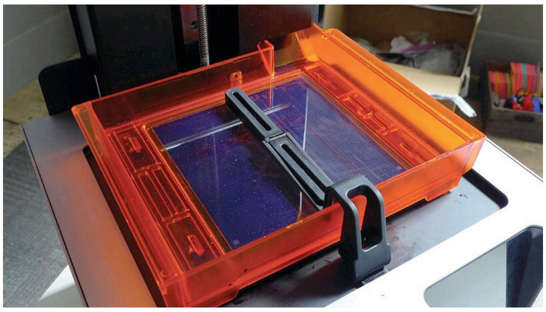


Figure-16: Resin tank for SLA printer[41]

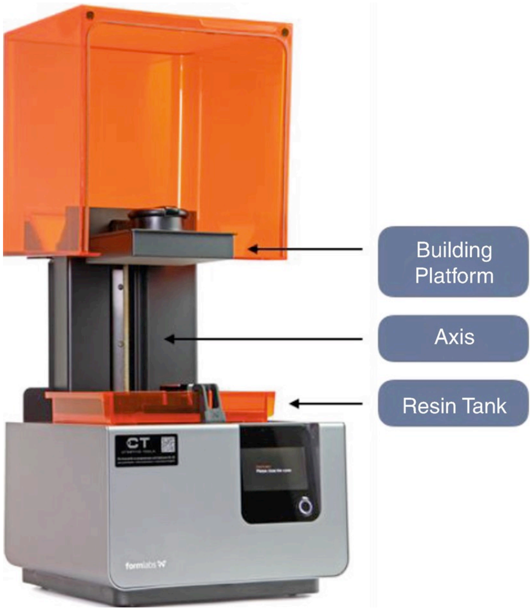


Figure-17: Formlabs Form2® SLA printer[41]

Layer thickness ranges between 25 and 100 µm. Reducing this parameter results in smoother surface (rounded shape objects) but increases printing time and costs. Desktop printers build the object facing upside down, as the light source comes from below and the platform arises on every increment. This helps to deliver an affordable equipment but decreases building size possibilities, as gravity force applied to the object being constructed can cause the print to fail. On the other hand, industrial SLA machines normally use a top-down system to allow massive production without risks of failing or losing accuracy. [118]

In stereolithography Apparatus (SLA) only 80% of the total polymerization is completed in the vat, whereas the remaining 20% can be completed in a conventional ultraviolet light curing unit.

The so produced surgical template is provided with surgical grade stainless steel tubes with sleeves that are 5 mm in height, 0.2 mm wider than osteotomy, and also with drill limiting angulation deviation to 5°. Buccal window is made so that it enhances retention during surgery. Usually, three 2 mm holes are placed into the buccal surface of each side of the denture.[104]

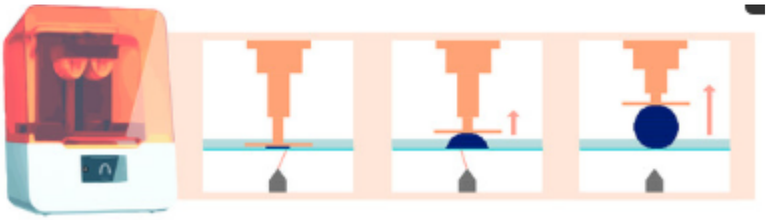


Figure-18: Operation of stereolithography (laser) printing technology. The orange arrow indicates that the platform lifts upward, while the element is being printed[117]

2. DLP (Digital Light Processing): indirect light projection[118]

DLP AM is very similar to SLA technology, as both fall under the category of AM according to the American Society for Testing and Materials (ASTM). The main difference between the SLA and DLP is the light source. DLP uses a digital projector to flash an entire image layer onto the resin at once, curing each layer simultaneously. Desktop DLP printers have a building platform which moves vertically and descends into a resin tank. The transparent bottom enables polymerization coming from a digital projector screen beneath, instead of a laser. The whole image of each layer is then projected to the vat using tiny mirrors. Each dot in each layer is cured at the same time; although instead of a dot, a square pixel is materialized. As the number of layers increment, the form delivered is made of small cubes (or voxels), different from the rounded micro-topography that is delivered by the laser projection in SLA printers. This makes it significantly faster than SLA. DLP systems are especially useful in offices with moderate production needs and balance speed with precision. Slight pixelation may occur depending on projector resolution.[118]

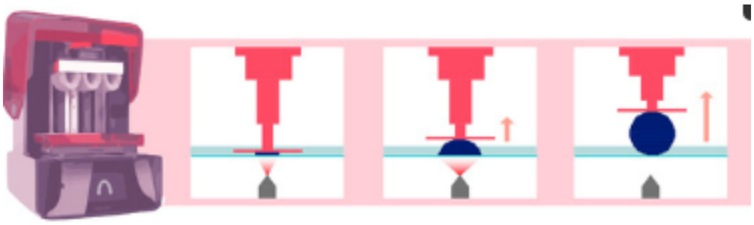


Figure-19: Operation of DLP printing technology. The pink arrow indicates that the platform lifts upward, while the element is being printed[117]

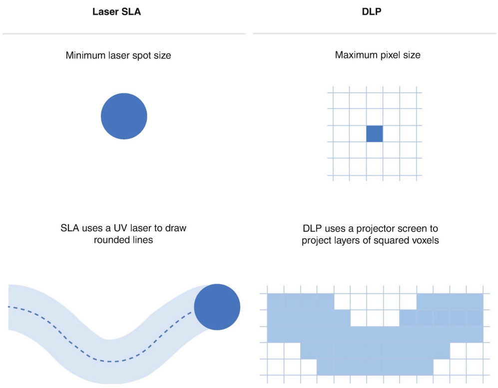


Figure-20: Laser dot (SLA) versus pixel (DLP)

The most common printers include the Sprintray Pro 55S and 95S (Sprintray, Los Angeles, CA, USA), the NextDent 5100 (3D System, Rock Hill, SC, USA), the Varseo XS (Bego, Bremen, Germany), and the CaraPrint 4.0 Pro (Kulzer, Hanau, Germany).

3. LCD Printing:[117,118]

Direct light projection using an LCD screen (LCD: liquid crystal display, also called mSLA: mask stereolithography apparatus).[117]

Similar to DLP, LCD printers use an LED light source and a liquid crystal display (LCD) panel to control light exposure. Instead of DLP chips, an LED projector is hidden behind an LCD screen placed near the printing tank. The projector emits monochromatic ultraviolet light, which is filtered by the LCD screen on the areas not to be printed in the tank. This approach enables higher printing resolutions, with theoretical LCD screen resolutions ranging from 4 to 12 K. Although still less common than SLA and DLP options, it offers the same main advantage of DLP: increased build speed when compared to SLA. Instead of a projector, this printer uses an array of LEDs as UV light source, shining through an LCD and flashing directly onto the build platform, following a parallel direction. Therefore, no mirror is required to direct the light and so, pixel distortion is enhanced.[118]

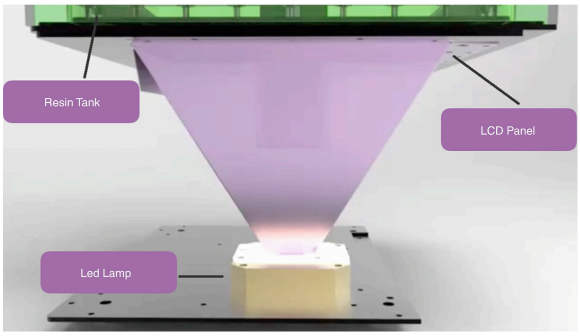


Figure-21: LED lamp as UV light source and LCD panel to select pixel visualization

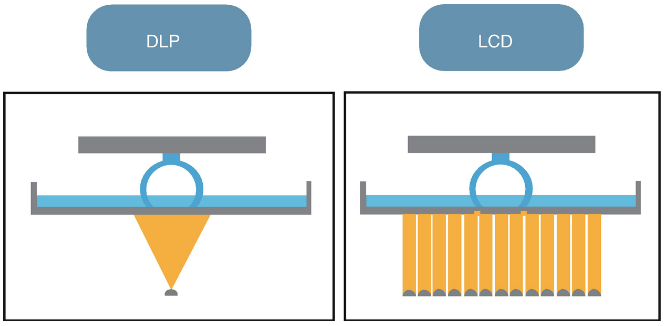


Figure-22: UV light is directed in a more perpendicular way and no mirror is needed

A screen acts as a mask, revealing only the pixels necessary for each layer. As the layer is cured all at once, build speed can be compared to DLP printers. As inferred, print quality will depend on pixel density. In general, LCD printers also use cheaper components, leading to costs reductions and competing with FDM printers.[118]

They are cost-effective, compact, and suitable for in-office production. Their resolution depends on the pixel density of the LCD screen. They offer decent accuracy and are widely used for printing guides and models on a budget.[118]

However, these printers have limitations caused mainly by overheating. The high light intensities required for layer-by-layer printing lead to significant heating of the LCD screen, and the cooling provided by the fans inside the printer is insufficient to resolve this issue. Moreover, an LCD screen degrades much faster than an SLA or a DLP chip and must be regarded as a consumable to be replaced after a certain number of hours of use. Thus, the print quality gradually declines as the printer is used until a new LCD screen is installed. The light intensity in LCD AM is relatively low, as only 10% of the light can pass through the LCD screen, with the remaining 90% absorbed by the screen. Additionally, as noted earlier, partial light leakage may lead to uneven exposure of the photosensitive resin at the bottom, requiring regular cleaning of the liquid tank.[117]

The most common dental-specific printers include the Ackuretta SOL (Ackuretta, Taipei City, Taiwan), the NextDent LCD1 (NextDent, Soesterberg, The Netherlands), and the Sonic 4K 2022 (Phrozen, Taipei City, Taiwan).

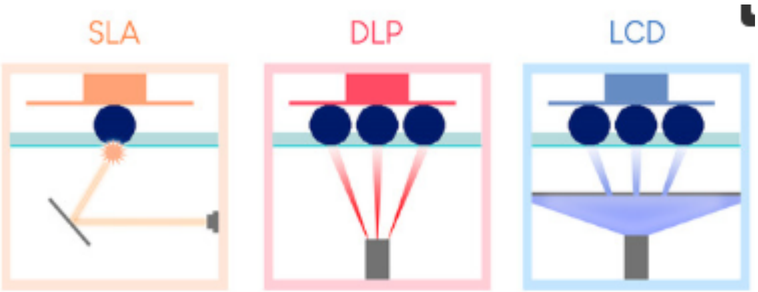


Figure-23: Summary of the differences between the three-resin tank polymerization printing processes[117]

4. FDM (Fused Deposition Modeling): [118]

FDM printers extrude melted thermoplastic filament through a heated nozzle to form layers. They are less precise than resin-based printers but are useful for printing anatomical models and mockups. Materials like PLA and PETG are common. Surface finish is coarse and often requires sanding or smoothing. [118]

Regarding mechanical properties, as layer adhesion creates weak areas, parts created can be weaker in one direction in relation to others and so, may be unsuitable for critical loading applications. [118]

Post-processing usually involves support removal and surface smoothing. Moreover, warping tends to be a regular and undesirable outcome when using these apparatuses. Cooling process of the material usually leads to dimensional changes and different cooling times (from one layer to another) causes stress which is released by pulling and bending the edges of the printed part. [118]

Sanding and polishing is mandatory after a part is printed, as visible additive lines can be often seen. Cost-effectiveness of FDM printing makes it choice number one whenever productivity comes prior to accuracy or surface definition (i.e., bone models for surgical planning or implant placement practice).[118]

5. SLS (Selective Laser Sintering): [118]

SLS employs a high-powered laser to sinter polymer or metal powders, building parts layer-by-layer. It's used in high-end applications like metal frameworks (e.g., titanium meshes or custom implant bars). Laser melting technology uses a laser to selectively fuse or melt metal powder particles. Some printers can produce parts from a single metal while others can produce alloys. a powder layer contained in an adjacent vat is deposited and leveled using a roller. Then, a laser scans the desired area, melting or fusing the particles together. Once the layer is finished, the platform descends and another powder layer is deposited. [118]

The process needs support structures to minimize warping that usually occurs whenever increasing and decreasing temperatures (fusing and cooling). Post-processing includes detaching support parts (sometimes using CNC technology), loose powder removal and heat treatment to improve mechanical properties. [118]

6. PolyJet and Multijet (Material Jetting) Printing:[119]

Polyjet and Multijet technologies come from different brands but share the same printing principle. PolyJet printers deposit droplets of photopolymer materials and immediately cure them with UV light. They support multi-material printing and offer the highest resolution and surface quality. This technology is used for highly detailed prototypes and models, often in dental labs.[119]

Due to its multiple printheads, the printer is capable of using different materials; so, different colors or even materials with different physical properties can be used all at once. The result is a combined object, unlike with SLA printers. Moreover, some printers offer the possibility of mixing materials to achieve customized properties. [119]

Material Requirements:[120]

- SG resins: Specifically designed for guided surgery; biocompatible, sterilizable, and approved for intraoral use. Parts fabricated with these resins can be steam sterilized (121 °C) to use them directly into surgery and can maintain contact with oral tissue as they are biocompatible.
- General-purpose resins: Suitable for diagnostic models and mockups, not for surgical application.
- Thermoplastics (FDM): PLA, ABS, PETG – for educational models, less for clinical use.

Printing Tips

Model Preparation: Hollowed models and resin scape canals are recommended as a way of reducing the total weight of the part . This decreases tension produced by gravity in bottom-up printers and helps save resin material. Additionally, minimum wall thickness is recommended and inspection of meshing errors is highly recommended before printing.[41]

Support: Except for some printers, support structure is usually required to achieve a good result. Auto-support option is always recommended as a starting point within the printing software . Later, additional pins can be added where necessary and pins compromising critical surfaces can be removed. If auto-support function suggests multiple pins over said critical surfaces, reorientation of the model may be considered. Most of the times, support structures are printed in the same material as the part and must be manually removed after printing.[41]

Orientation: Changes in orientation can make printing time, amount of material, and accuracy vary. Overhanging parts may need extra support, which may alter its surface because of post-processing manoeuvres. Modification on the object orientation can avoid overhanging areas and can protect critical surfaces. Moreover, orientation is more complicated in bottom-up printers, like most of desktop resin printers available. Here, the moment where the build platform arises to give space to the following layer is critical. This step, known as the peeling step, may cause the part to detach from the platform. For this reason, objects should be oriented in an angle, so that the cross-section area of each layer is reduced as minimum as possible. As it can be inferred, support is also increased using an angled orientation.[41]

Post-curing: To achieve the best mechanical properties, photopolymer parts (SLA printed objects) must be post-cured, either by placing them into a cure box under intense UV light or by leaving the part in the sun. This process improves hardness and temperature resistance of the SLA printed object. Nevertheless, extended exposure to UV light has detrimental effects in physical properties and appearance of the piece. Common consequences are: curling, becoming more brittle, and color changing. To avoid appearance changes, some products offer an acrylic spray coating to use before curing.[41]

Postprocessing:

3D-printed resin elements cannot be used immediately after fabrication because their mechanical, optical, and biological properties are insufficient due to incomplete polymerization. Postprocessing is therefore essential, particularly for intraoral devices. The workflow typically includes five steps:[117]

1. Rinsing with a solvent to remove residual resin
2. Drying
3. Postcuring with light and heat
4. Support removal
5. Optional polishing

High-quality postprocessing ensures safety, precision, and clinical suitability, though it remains one of the most limiting steps in resin-based 3D printing.

1. Rinsing

The first step is removal of unpolymerized resin, most commonly using 99% isopropyl alcohol (IPA). While highly effective, IPA evaporates easily, is flammable, and can irritate mucosa or skin upon prolonged exposure. Safer alternatives like water or TPM exist but are not yet certified for biomedical use. To maximize cleaning efficiency, solvents are agitated in wash units, which reduce residual resin.[117]

Adequate rinsing ensures proper geometry and prevents resin remnants from fusing during postcuring, which could compromise fit. It also improves biocompatibility, provided exposure times are carefully controlled (usually 5–20 minutes depending on resin). Overexposure may weaken the material by disrupting polymer chains, reducing flexural strength. Separate alcohol baths for biocompatible and non-biocompatible resins are recommended to avoid contamination. [117]

Environmental concerns arise because solvents become saturated with resin and must be replaced. IPA disposal into wastewater is prohibited yet remains common. Two sustainable solutions are (1) decanting to recover reusable IPA, and (2) recycling circuits offered by waste facilities. Organized collection by manufacturers would further minimize environmental impact. [117]

2. Drying Printed Elements

After rinsing, the object must be actively dried to remove solvent residues. Air syringes or short evaporation periods are typical. Some curing devices include integrated hot air-drying systems (e.g., FormCure, Formlabs) that promote complete removal of IPA prior to postcuring. [117]

3. Postcuring

Postpolymerization enhances biological safety, optical stability, and mechanical strength. This step employs devices with strong light irradiance and controlled heat. Since light wavelength and resin formulation vary, only the manufacturer’s recommended curing device should be used. Incorrect parameters may cause shade changes or incomplete polymerization. [117]

Modern systems have shortened postcuring from hours to minutes, improving efficiency. However, oxygen inhibits surface polymerization, leaving weaker surface layers. To counter this, vacuum or nitrogen environments can be used during curing, producing higher-quality results. [117]

4. Support Structure Removal

Supports stabilize objects during printing but must be carefully removed afterward. Breakaway supports can be detached manually, while thicker supports often require milling. For some applications, such as dental models, printing directly on the build plate avoids supports entirely, saving both resin and time. [117]

5. Polishing and Finishing

Polishing is often the most labor-intensive step, yet it significantly influences surface quality, esthetics, and long-term performance. Manual polishing is still standard, though semirigid resins (e.g., for occlusal splints) are more difficult to finish than rigid materials. Excess heat from polishing can damage surface integrity, so low speeds and pressure are recommended. [117]

Emerging solutions include finishing glazes (e.g., Optiglaze Color, GC Corporation), which rapidly achieve smooth, esthetic surfaces and enhance integration of intraoral devices. Advances in automated finishing are an active research area to improve accessibility and consistency.[117]

Advantages:[121]

- Affordable equipment for small practices
- Quick turnaround time for guide fabrication
- Minimal material waste compared to milling
- Versatility in applications from models to fully functional guides

Limitations: [121]

- Inferior mechanical properties to milled components
- Accuracy affected by printer calibration and resin shrinkage
- Post-processing critical to dimensional stability and clinical fit

Clinical Relevance:

- SLA and DLP are most commonly used for printing surgical guides with excellent fit
- LCD printers are ideal for affordable in-house production
- SLS and PolyJet are preferred in specialized labs for high-performance and multi-material applications

Table2: Subtractive vs Additive CAM

Feature	Subtractive (Milling)	Additive (3D Printing)
Process	Material removal from block	Layer-by-layer material addition
Materials	PMMA, PEEK, Zirconia, Co-Cr	Resins, PLA, PETG, Metal powders
Surface Quality	High, smooth with minimal post-processing	Variable, often needs polishing
Mechanical Strength	High	Moderate to low
Accuracy	Very high	Moderate to high (depending on technology)
Cost of Equipment	High	Low to medium
Time Efficiency	Longer production time	Faster for simple guides and models
Waste Generation	High (material subtraction)	Low (layered deposition)
Best Used For	Final prostheses, custom abutments	Surgical guides, models, temporaries

Protocol for Guide Design and Printing[41]

Creating a surgical guide involves multiple technical and clinical steps:

1. File Preparation:

- Import and align DICOM (from CBCT) and STL (from intraoral scan) data into planning software.
- Perform accurate merging using at least three matching anatomical landmarks or radiopaque markers.
- Evaluate bone volume, proximity to anatomical structures, and prosthetic requirements before virtual implant placement (Joda et al., 2017).

2. Virtual Guide Design:

- Choose the guide support type (tooth, mucosa, bone).
- Define the insertion axis to avoid undercuts or retentive zones.
- Draw the base outline of the guide and position metal or resin sleeves aligned to the planned osteotomy.
- Customize design features such as thickness, offset from implant platform, and inspection windows to verify seating during surgery.
- Add mechanical or text indicators (e.g., patient ID, orientation markers).

3. Material Selection:

- Select CE/FDA-approved resins or PMMA blanks validated for intraoral surgical use.
- Ensure compatibility with sterilization and manufacturing devices.
- Consider properties like stiffness, translucency, and fracture resistance.

4. Manufacturing (Printing or Milling):

- Slice the STL file for 3D printing or convert to machine-readable G-code for milling.
- Print layer-by-layer (SLA/DLP) or carve using burs (milling).
- Post-process printed guides by cleaning in isopropyl alcohol and curing under UV light.
- Finish the guide by polishing, removing supports, and verifying sleeve fit.

5. Quality Control:

- Fit-check the guide on a printed model or intraorally.
- Evaluate for warping, cracks, and tolerance mismatch.
- Check sleeve dimensions and orientation to ensure guide precision.

6. Sterilization and Packaging:

- Use low-heat sterilization (autoclave or hydrogen peroxide plasma) depending on material compatibility (Geng et al., 2010).
- Label and store the guide in sterile packaging with a surgical report detailing implant positions and drill sequences.

When each stage of this protocol is followed with precision, the final guide provides a reliable surgical tool that translates the virtual plan accurately into a clinical reality.

Technique[30]

This step-by-step technique describes the digital design and fabrication of a hybrid bone- and tooth-supported implant drilling guide, particularly useful for distal extension partially edentulous patients with few remaining teeth. The technique starts with merging the bone and teeth data into one STL file, followed by implant planning and surgical guide design. The hybrid design improves stability and accuracy by integrating both tooth and bone support, overcoming the bending tendency of conventional guides in long-span free-end edentulous cases. This allows precise transfer of prosthetically planned angulation and depth, reducing risks of compromised implant positioning and mechanical failures. The bone-supported segment also provides a vertical stop to prevent guide deformation.

These guides are indicated when only a few unilateral teeth remain, whereas conventional tooth-supported guides are preferable with bilateral dentition.

1. Obtain a CBCT scan of the patient and export the data in the form of a Digital Imaging and Communication in Medicine (DICOM) file. [30]

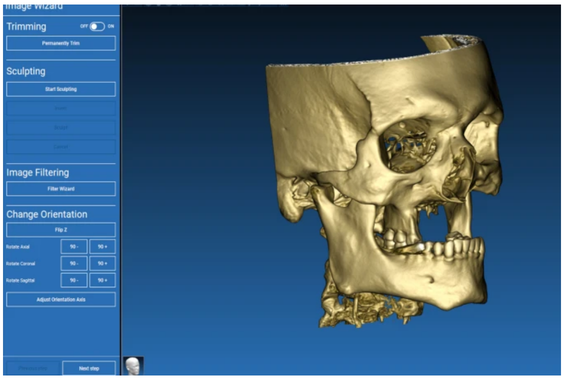


Figure-24: A Dicom file representing the bone and teeth of a patient with few remaining natural teeth and long-span distal extension edentulous area[30]

2. Make an optical scan of the remaining natural teeth either directly intraorally or indirectly by extraoral optical scanning of a conventional impression, then export the data in the form of a standard tessellation language (STL) file. The STL file represents the teeth surfaces and the surrounding soft tissue. [30]

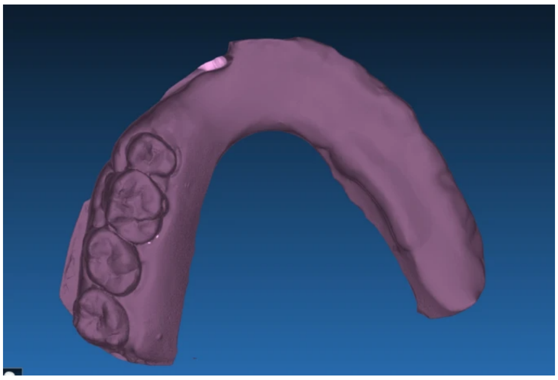


Figure-25: An STL file representing soft tissue and teeth of a patient with few remaining natural teeth and long-span distal extension edentulous area[30]

3. Import both the STL and DICOM files into an implant planning and surgical guide design software program (e.g., Real Guide 5.0 software, 3DIEMME). [30]

4. Use the sandbox panel and trim any data other than the teeth and their surrounding soft tissue that will provide support for the future surgical guide. [30]

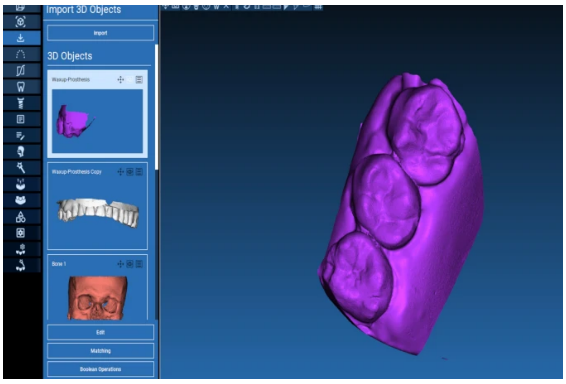


Figure-26: An STL file representing the teeth of interest and their soft tissue only[30]

5. Align the Dicom and the STL files through the built-in software artificial intelligence using an assisted alignment software tool or can also align the two data files by picking up similar points in the two files, followed by best-fit alignment. **[30]**

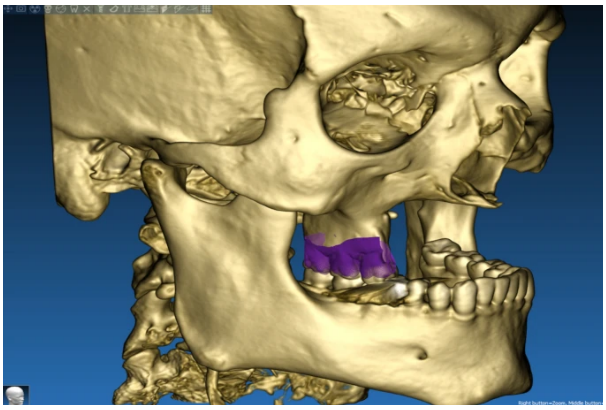


Figure-27: Superimposition between the Dicom file representing the bone and the STL file representing teeth and soft tissue[30]

6. Use the segmentation panel to convert the bone Dicom file into an STL file on which a surgical guide can be designed. The segmentation is made by adjusting the bone threshold and using the Select software tool to choose area of interest only. At the end of this step, two STL files are present; one representing the bone and the other representing the teeth of interest and their soft tissue surrounding. [30]

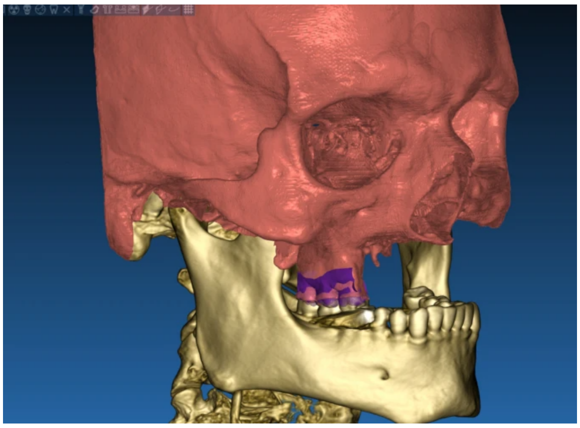


Figure-28: Segmentation of the Dicom file to transform the area of interest into an STL file[30]

7.Merge the two STL files into one STL file using the sandbox software panel and the Boolean union software tool. [30]

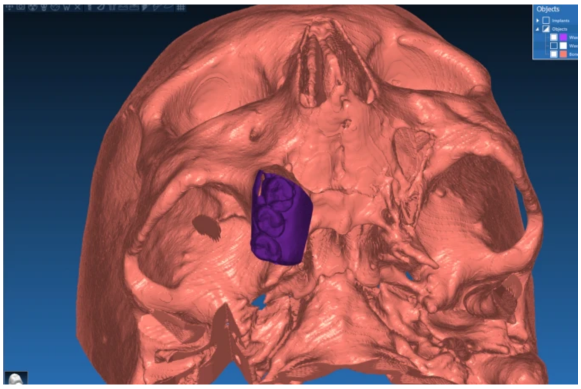


Figure-29: Combining the bone, teeth, and soft tissue data in one STL file[30]

8. After determining the panoramic curve, start with a virtual setting of the missing teeth and plan the implant position, length, and diameter according to the prosthetically driven implant concept. Choose the sleeve diameter and offset according to the drill length while using a universal guided surgical kit. [30]

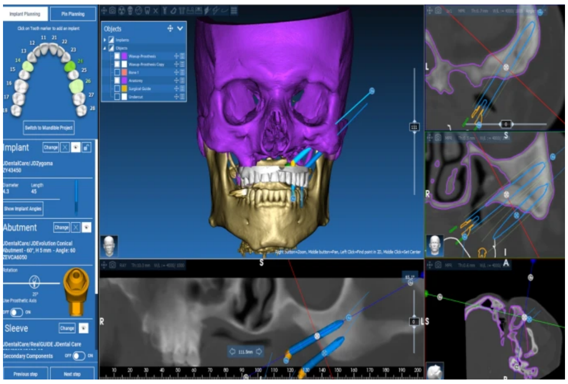
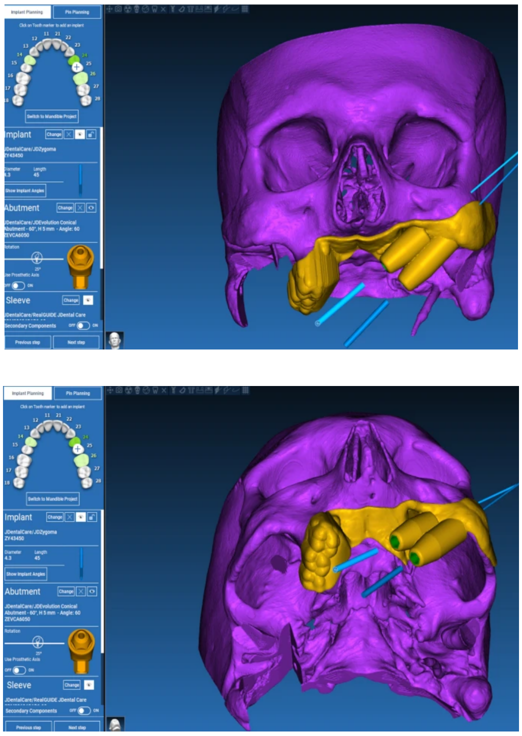


Figure-30: Implant planning according to prosthetically driven implant placement protocol[30]

9. To design the surgical guide, start with selecting the surgical guide path of insertion by blocking out any unfavourable undercuts, followed by drawing the surgical guide borders, and finally guide generation. Control the guide thickness, but it is better not to be less than 3 mm to prevent surgical guide breakage during the surgery. Add an oval hole in the surgical guide as a reference for complete guide seating during the surgery.[30]



Implant

JDentalCare/JDZygoma
ZY43450

Diameter 4.3
Length 45

Abutment

JDentalCare/JDEvolution Conical
Abutment - 60°, H 5 mm - Angle: 60
ZEVCA6050

Use Prosthetic Axis OFF ON

Sleeve

JDentalCare/RealGUIDE JDental Care

Secondary Components OFF ON

Figure-31: The final design of the hybrid teeth and bone-supported surgical guide[30]

10. Export the finalized surgical guide design in the form of an STL file and then 3D print the file in clear surgical guide resin (EPAX Resin, EPAX 3D) **[30]**

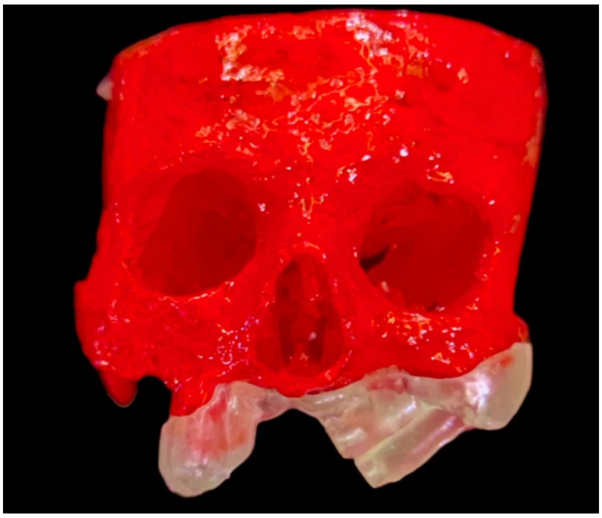


Figure-32: The 3D printed surgical guide in clear resin[30]

GUIDED IMPLANT SURGERY

Dental implantology has undergone a remarkable evolution over the last four decades. What began as a biologically driven surgical procedure has now become a digitally integrated discipline, in which prosthetic outcomes, surgical accuracy, and patient comfort are carefully interwoven. At the heart of this digital transformation lies guided implant surgery (GIS)—a technique that employs computer-based planning and surgical templates to transfer a virtual plan into the patient's mouth with high fidelity.[122]

The motivation for GIS arises from one central fact: the position of an implant determines the long-term success of both function and aesthetics. An implant placed at the wrong angulation or depth can result in complications such as peri-implantitis, prosthetic misfit, mechanical failure of components, or unsatisfactory aesthetic results. Traditional freehand methods rely heavily on the surgeon's experience and tactile judgment, but even skilled clinicians show measurable deviation when compared with prosthetically ideal positions. Guided surgery reduces this dependence on manual skill and translates a digitally simulated plan into reality with much greater accuracy.[99]

Beyond precision, GIS also embodies the philosophy of prosthetically driven implantology. Instead of placing an implant first and then adjusting the prosthesis, the workflow begins with the final restoration in mind. Using CBCT imaging and virtual wax-ups, the prosthetic requirements dictate the optimal implant position. The surgical guide, therefore, becomes the physical bridge between digital planning and the patient's anatomy.[123]

Early Surgical Templates: The Analog Era

Long before CBCT and CAD/CAM existed, clinicians attempted to improve implant placement using conventional radiographic and cast-based surgical templates. These guides were usually made on dental stone models with the aid of diagnostic wax-ups. The waxed prosthetic design was duplicated, and metal tubes or acrylic channels were incorporated to indicate implant positions.[124]

While ingenious for their time, these analog templates suffered from major drawbacks:[124]

1. Two-dimensional planning – Conventional radiographs such as panoramic films were prone to distortion, magnification, and lacked buccolingual information.
2. Inaccurate representation of anatomy – Soft tissue resiliency, bone topography, and anatomical landmarks (e.g., mandibular canal, maxillary sinus floor) were not adequately captured.
3. Operator dependency – Success relied heavily on the clinician's ability to interpret radiographs correctly and translate them into the template.
4. Higher risk of malposition – With limited visualization, implants were often placed too close to nerves or adjacent roots, sometimes requiring corrective procedures.

Although these guides allowed a basic sense of orientation, they did not offer true three-dimensional control. Predictability was low, chair time was longer, and patient morbidity was greater.[124]

The Digital Revolution: Emergence of CBCT and CAD/CAM

The landscape changed dramatically in the 1990s and early 2000s with the introduction of cone-beam computed tomography (CBCT). Unlike panoramic radiography, CBCT provided volumetric imaging with relatively low radiation exposure. This enabled precise visualization of bone height, width, and density, as well as the spatial relationships of vital anatomical structures. Multi-planar reformatting allowed sagittal, coronal, and axial slices, while 3D reconstructions offered intuitive surgical planning.

At the same time, advances in computer-aided design and manufacturing (CAD/CAM) allowed these digital datasets to be integrated into surgical planning software. By importing DICOM files from CBCT and STL files from intraoral or model scans, clinicians could virtually place implants in harmony with prosthetic wax-ups. Once finalized, these plans could be exported to 3D printers or milling machines to fabricate surgical guides that translated the digital plan into a physical template.[47,89]

The introduction of stereolithography (SLA) was especially pivotal. SLA printing uses light to polymerize liquid resin layer by layer, producing highly accurate and detailed objects. Surgical guides fabricated through SLA could incorporate metal sleeves for drill guidance, inspection windows, and customized thicknesses, making them far more reliable than analog templates. [47,89]

Evolution of Guided Surgery Systems

By the early 2000s, guided surgery systems were commercially introduced by implant companies such as Nobel Biocare (NobelGuide), Simplant, and others. [125]

These systems standardized the digital workflow: CBCT imaging, virtual planning, stereolithographic guide fabrication, and guided drilling protocols with dedicated instrumentation.[126]

Clinical studies from this era confirmed that guided surgery reduced angular deviations and improved prosthetically driven placement compared to freehand surgery. However, the cost and complexity of these early systems limited widespread adoption. Over time, improvements in scanner resolution, software algorithms, and more affordable 3D printing have made GIS accessible to a broader range of practices. [125]

Understanding the historical progression from analog templates to advanced navigation systems is crucial. It highlights how each innovation sought to address the shortcomings of its predecessor:[104]

- From 2D to 3D imaging (overcoming distortion and poor landmark visualization).
- From manual to digital planning (reducing operator error and variability).
- From static to adaptive systems (balancing precision with intraoperative flexibility).

The evolution of guided implant surgery reflects the broader trajectory of modern dentistry: moving away from guesswork and variability, toward precision, predictability, and patient-centered outcomes.

Navigation Systems in Guided Implant Surgery[125]

Guided implantology has evolved into three main navigation paradigms: Static systems, Dynamic navigation systems, and Robot-assisted systems. Each has its own workflow, accuracy profile, costs, and clinical applicability.

A. Static Computer-Assisted Implant Surgery (sCAIS) [125]

In static systems, CBCT and intraoral scans are merged in software to virtually plan implant positions. Static guides are prefabricated templates produced from planning software. This plan is then translated into a physical guide (3D printed or milled). During surgery, they are physically placed in the patient's mouth ,the guide is seated, and drills are passed through sleeves that dictate angulation and depth.[125]

A flap or flapless approach is followed. However, the second approach has many advantages with a lesser amount of bone loss, preserving the papilla, and improves aesthetic effects after surgery. The surgical procedure using this guide follows either fully or partially guided systems for implant placement. The first system is used commonly that includes osteotomy preparation with implant placement using surgical guides or templates. In the second system, only osteotomy preparation has been done using surgical templates and implants placed in a freehand manner. The findings of the 5th International Team for Implantology Consensus Conference concluded "that fully guided protocols performed more accurately compared with partially guided systems." Some systems require serial surgical guides to handle consecutive drill sequences or single surgical guide with different adjustable drills inserted during surgery.[125]

Advantages:

- High accuracy (angular deviation ~2–5°; linear deviation <2 mm).
- Widely available, supported by many implant companies (e.g., NobelGuide, Simplant).
- Cost-effective compared to dynamic navigation and robotics.
- Familiar to most clinicians, with a moderate learning curve.

Limitations:

- Rigid—cannot adapt intraoperatively if anatomy differs from the scan (e.g., unexpected bone quality).
- Restricted mouth opening may hinder guide placement.
- Requires dedicated drill kits, increasing cost.

Clinical Use: Ideal for routine single-tooth or full-arch cases where planning can be trusted and no intraoperative modifications are expected.

B. Dynamic Navigation Systems (dCAIS)[41]

This technique was first introduced for neurosurgery in 1992. In dentistry, it was first used in 2000 in the USA. Dynamic systems bring real-time guidance into the surgical field, functioning like a GPS for implant drills. Light is projected from a special source above the patient. The light is reflected off tracking arrays that are fixed to patient, surgical handpiece and drills. The software recognizes the reference markers and tracking arrays. Then it calculates the position of the jaw, so a virtual reality simulation is created on screen. Dynamic navigation systems use optical motion tracking to provide real-time guidance on a screen, similar to a GPS system. Unlike static guides, they allow intraoperative flexibility to adjust implant position if needed.[41]

The main components of a dynamic navigation system include patient jaw attachment, handpiece attachment, and a system consisting of a camera, overhead-positioned emitting light, computer, and sensor. During surgery, the surgical guide is attached. An open flap or flapless approach may follow depending on the thickness of keratinized tissue. The conventional drilling sequence is used for osteotomy preparation. Once the drilling bur accords with the planned implant position, the procedure is carried out and implant placed. The whole surgery involves direct vision on the computer screen, thereby controlling the direction and depth of implant placement. This provides real motion tracking effect of the surgery. The navigation systems commonly used are DenX Image Guided Implantology, X-Guide Dynamic 3D Navigation, Navident, and Inliant.[125]

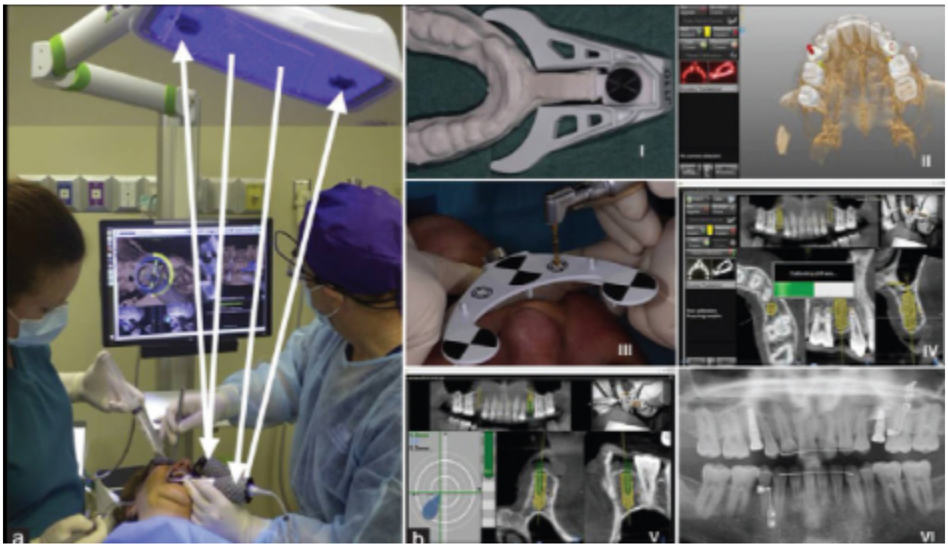


Figure-33: Dynamic navigation system. (a) Components: Patient jaw attachment, handpiece attachment and a system consisting of a camera, overhead blue emitting lights, computer and sensor; (b)) Surgical procedure: I- Thermoplastic stent attaches with the remaining teeth in the arch using the radiographic marker; II-Digital planning; III and IV-Preoperative planning; V- Osteotomy drilling by viewing on the screen; VI-Postoperative image after implant placement

Workflow:

- Reference markers or arrays are attached to the jaw and drill handpiece.
- Cameras track these markers and display the drill's position relative to the planned trajectory on a screen.
- The surgeon watches the monitor to maintain alignment during osteotomy.

Advantages:[125]

- Intraoperative flexibility: If bone density is poor or anatomical surprises occur, the implant trajectory can be adjusted instantly without fabricating a new guide.
- Unlimited access: No bulky guides in the mouth—especially valuable for posterior regions or patients with limited mouth opening.
- Educational benefit: Provides visual feedback for trainees, accelerating the learning curve of implant angulation.

Limitations:[125]

- High capital cost (systems like Navident, X-Guide).
- Steep learning curve; requires hand–eye coordination as the surgeon looks at a screen instead of directly at the surgical site.
- Accuracy is operator-dependent—deviation decreases as experience increases.

Reported Accuracy: Mean linear deviation of ~0.4–1.2 mm and angular deviation of ~3–5°, comparable to static guides in controlled studies.

Clinical Use: Suited for cases where adaptability is important (e.g., poor bone quality, irregular anatomy, or revision surgeries).

C. Robot-Assisted Implant Surgery (rCAIS)[127]

Robotic-assisted surgical systems are the most advanced approach that integrates robotics with digital planning. Here, robotic arms physically control or restrict the drill's movement according to the virtual plan. This provides good stability of the robotic arm and is able to reduce the labor intensity of the operator. Yomi is the first reported surgical robot and it is a fully assisted dental implant surgical robot developed by Neocis, Inc. received approval from the U.S. Food and Drug Administration (FDA) in 2017. In the same year, Zhao Yimin's team developed the first autonomous dental implant surgery robot, which enables interpretation and reproduction of the anatomical structure of the surgical area, accurate pre-implantation design, automatic and precise intraoperative positioning, real-time surgical navigation and calibration.[127]

The novel THETA robotic dental implant system, developed by Hangzhou Jianjia Robot Co. LTD, is a semi-automatic system, which could conduct positioning, drilling and implant placement according to control the integrated button (line setting button, teaching button) with an optical navigation system. All wrist joints of UR-3e manipulator can rotate 360 degrees, and the end joints can rotate infinitely. With force sensors, UR-3e manipulator can cooperate well with users in the same space through force position coupling control and handle high-precision tasks.[127]

Workflow:

- After planning, the robot is programmed with implant coordinates.
- During surgery, the surgeon either guides the drill within robotic constraints (cooperative robotics) or allows the robot to perform drilling with oversight (autonomous robotics).

Advantages:

- Unparalleled precision: Sub-millimeter deviations have been reported.
- Eliminates hand tremor and minimizes human error.
- Provides real-time feedback and haptic resistance if the drill deviates.

Limitations:

- Very high cost—currently prohibitive for most practices.
- Bulky equipment, still in refinement.
- Limited long-term clinical studies compared to static/dynamic systems.

Future Outlook: Expected to become more common as costs decrease and technology matures, particularly in academic and hospital-based settings.

Advantages of computer-aided oral implant surgery include: [128]

(1) flapless surgery with a consequent decrease in surgical time and patient morbidity.

(2) preservation of soft tissue structure and hard tissue volume in the surgical site.

(3) integration of the restorative determinants into the surgical planning, resulting in a more aesthetic, functional, and predictable prosthetic outcome.

(4) simplification of the technique-sensitive and operator-dependent surgical procedure.

However, this technique is not free of drawbacks, some of which are as follows:[129]

(1) the surgeon’s inability to visualize anatomic structures.

(2) the increased risk of axis and depth deviations during implant placement.

(3) a decreased ability to contour the jawbone topography when needed for prosthetic purposes

These navigation systems highlights a spectrum: from static guides (rigid, cost-effective) to dynamic navigation (flexible, adaptable), and finally to robotic systems (precision with futuristic potential). Meanwhile, the design details of the guide—sleeves, number of guides, open vs. closed—can mean the difference between a smooth surgery and complications like poor irrigation, misfit, or guide fracture. Together, these systems and design features illustrate how GIS balances digital accuracy with practical surgical realities.[125]

Complications in Guided Implant Surgery[125]

- Types of complications
    - Can be surgical or prosthetic
    - May occur early or late
- Surgical complications
    - Fracture of the surgical guide during operation

Figure-34: fractured surgical guide[125]

  - Deviation from the planned surgical pathway
  - Lack of primary stability → early implant loss
  - Prosthetic fracture during/after placement
  - Nerve disturbances due to injury of vital anatomical structures
- Prosthetic complications
  - Misfit of the prosthesis
  - Screw loosening
- Reported findings[130,131]
  - Schneider et al.: described several types of intraoperative and postoperative complications
  - Tahmaseb et al.: static computer-guided surgery showed an average complication rate of 13.3%

  - Dynamic approaches: fewer complications overall, but rare cases of implant impingement on the inferior alveolar nerve or adjacent tooth roots

IMPLANT DRILLING SYSTEMS

In digital implantology, the implant drilling system plays a crucial role in translating virtual implant planning into precise clinical outcomes. It is the link between the preoperative 3D planning and the intraoperative execution of implant placement, ensuring that the surgical procedure aligns with the prosthetically driven plan.[41]

Integration with Digital Workflow[41]

The drilling system used in digital implant planning must be compatible with the planning software and the surgical template (guide). Most modern implant planning systems (such as NobelClinician, coDiagnostiX, or SimPlant) include libraries of implant systems from various manufacturers, which contain detailed information about:

- Implant dimensions (length, diameter)
- Drill sequences
- Sleeve offsets
- Guide tube dimensions

This ensures that the drill path created during virtual planning matches the physical tools used during surgery.

Guided surgery kit[132]

A standard guided surgical kit contains mucosal punch, drill handle, c handle, template fixation pins, retentive anchor driver, stop key for guided implants, T-sleeve, guide tubes.

Components of a Guided Drilling System[133]

A digital implant drilling system typically consists of:

- Pilot drill: Used to create the initial osteotomy. It determines the trajectory of the implant.
- Sequential drills: Gradually enlarge the osteotomy to match the planned implant diameter. These often vary in length and taper.
- Sleeve-in-sleeve system or guided drill sleeves: Ensure precise control of angulation and depth.
- Drill keys/adapters: Fit into the guide sleeves and help accommodate different drill diameters.
- Depth stops or built-in depth control: Prevent over-drilling beyond the planned implant length.

These components are designed to work with surgical guides, which are fabricated based on the virtual implant position.

Types of Surgical Guides and Their Influence[37]

One of the significant factors affecting the accuracy of guided implant surgery is the type of guide being designed and used, be it dentate, edentulous, that is, mucosa-borne, or bone-supported. Different types of implant drill guides may be produced when considering the simultaneous placement of several implants in the edentulous arch.[37]

The accuracy variation between these guides is the guide's stability on the soft tissues, teeth and bone.

The surgical guide can be: [37]

- Tooth-supported: For partially edentulous cases; most stable.
- Mucosa-supported: Used in fully edentulous patients; requires careful stabilization.
- Bone-supported: Used when no teeth or soft tissue support is present; requires flap elevation.

The type of guide influences the drilling protocol and the fixation method (e.g., with anchor pins). Fixation pins can be used to secure the latter two types in place, and the position and depth of these fixation pins are designed within the drill guide design software. The edentulous mucosa-borne drill guides can be used with or without a crestal incision to expose the buccal bone surface, whereas obviously, the bone-supported drill guide requires full exposure of the bone with large incisions and full flaps reflected. movement during drilling when using a surgical guide can affect the accuracy of the creation of the osteotomy. Fixation pins, therefore, aim to reduce this error by maintaining the position of the guide.[108]

Drill guide platform[89]

When considering the planning and placement of several implants in the edentulous arch, there are different types of implant drill guides that may be produced:

- Mucosa-borne
- Bone-supported.

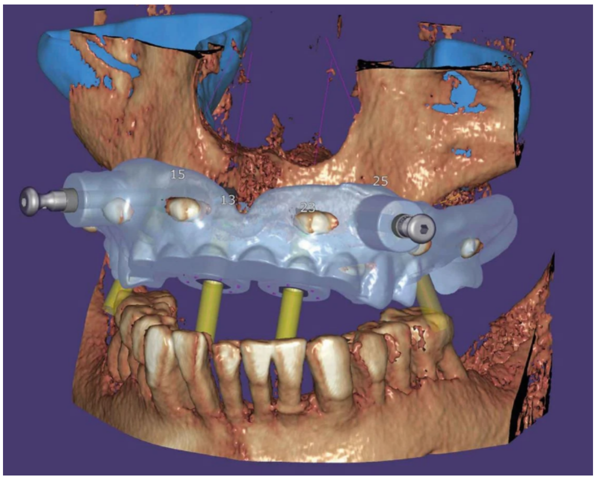


Figure-35: Fixation pins added buccally to the edentulous mucosa borne guide[89]

Fixation pins are employed to stabilize both types of drill guides, with their position and depth determined using drill guide design software. Mucosa-borne drill guides can be utilized with or without a crestal incision for revealing the buccal bone surface. In contrast, bone-supported drill guides necessitate complete bone exposure through extensive incisions and the reflection of full flaps.[89,108]

Drilling Protocol[134,135]

The drilling protocol is predefined by the implant manufacturer and tailored to the patient's bone density.For example:

- Dense bone (D1–D2): May require additional countersinking or tapping.
- Soft bone (D3–D4): May require under-preparation to ensure primary stability.

The protocol often involves stepwise drilling, starting from the smallest pilot to the final drill, ensuring minimal thermal damage and maximal accuracy.

Drill Guide Calibration and Offset[136]

A key consideration in digital implant planning is the offset between the guide sleeve and the drill tip, which must be accounted for during planning. The planning software calculates:

- Sleeve-to-bone distance
- Drill length and stop height
- Implant platform and apex position

Incorrect calibration can result in positional or depth errors, affecting implant success.

Advantages of Guided Drilling in Digital Planning[137]

- Accuracy: Achieves highly accurate implant positioning in 3D space.
- Safety: Reduces risk of damaging anatomical structures (e.g., inferior alveolar nerve, maxillary sinus).
- Efficiency: Streamlines surgery with pre-planned, predictable steps.
- Minimally invasive: Often enables flapless surgery, reducing patient discomfort and healing time.

Limitations and Considerations[100]

- The accuracy of the surgical guide is heavily dependent on the quality of the CBCT or intraoral scan.
- Poor imaging resolution or artifacts can compromise the precision of the guide.
- The clinician’s skill and adherence to the planned procedure are critical. Deviations during surgery can negate the benefits of the guide.

- The surgical guide must fit securely and stably within the patient's oral cavity. Improper fitting can lead to positional errors, affecting the outcome of the procedure.
- The durability and rigidity of the guide material play a role in maintaining its accuracy during surgery -flexible or brittle materials may deform or fracture, reducing the guide's effectiveness.
- High cost of digital technologies and the time required for planning and fabrication may limit accessibility in some clinical settings.
- Not all drills are compatible across different guide systems.
- Long Learning Curve as it requires familiarity with both the digital planning software and the guided system.

The implant drilling system in digital implant planning represents a highly sophisticated component of computer-assisted implantology. By integrating virtual planning with precise drilling protocols and guided templates, it ensures that implants are placed with optimal accuracy, safety, and efficiency. Mastery of the system's technical nuances is essential for achieving consistently successful clinical outcomes.

Surgical kits for guided implant systems generally fall into two types:

1. Integrated Guided Drills – where the guidance mechanism is built into the drill.
2. Handle-Driven Drills – where separate handles adapt the drill to the guide sleeve.

All systems require a tube or also called sleeve cylinder of a defined diameter and height to house the drills. The drills themselves (a) can have vertical stops and use surgical keys or drill-handles that have an inner hole with a diameter that is specific to the diameter of the respective drill and have an outer dimension that matches the sleeve cylinder in the guide, (b) have a drill shank of the compatible diameter as the inner diameter of the sleeve cylinder, which allows for drill-body guidance, or (c) can have a surgical key attached that matches the inner diameter of the sleeve cylinder (key-on-drill). The latter two approaches are considered key-less and do not require a drill-handle.[138]

A critical aspect influencing accuracy is tolerance—the allowable space between components. Increased numbers of components (drills, handles, sleeves) tend to accumulate tolerance errors, reducing overall precision.[89]

Sleeved Surgical Guides

These templates include designated drill holes into which metal sleeves are fitted—provided by the implant manufacturer. Some systems offer different sleeve sizes for varying implant diameters or available mesiodistal space, while others use a single sleeve size for all drills.[139]

The gap between the sleeve and the guide hole—determined by CAD settings and the selected CAM material—must be minimized to reduce sleeve movement and ensure accuracy. Some software even allows for resin channels to fix the sleeve into the guide.[139]

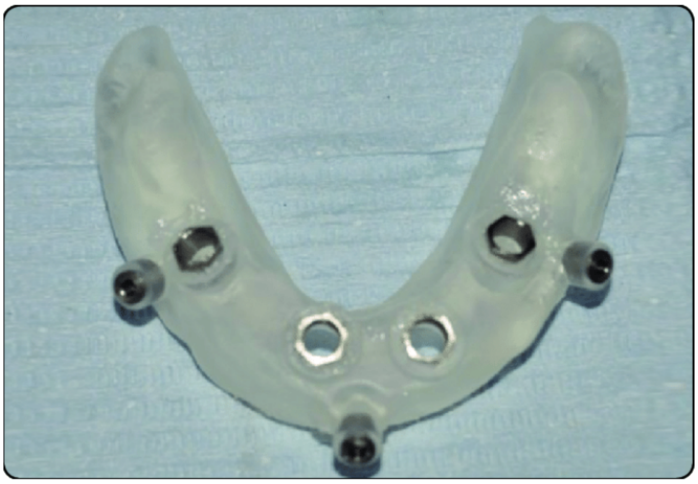


Figure-36: Customized surgical guide with guided sleeves for implants and anchor pins[140]

Both subtractive and additive manufacturing techniques are used to produce these guides. The precision of sleeve and drill production by the implant manufacturer is crucial, as with traditional implant tools.

Drills or handles fit into sleeves depending on the system design.

Figure-37: Different sleeves together with their different guided drills, for either regular or narrow platform implants[41]

Two types of instruments fit on the sleeve: a drill or a handle, depending on the system used.

Figure-38: Guided drill fitting into the sleeve (left) and handle fitting into the sleeve (centre). Drill diameter is adapted by the handle (right)[41]

Guided Drill Systems (For Sleeved Guides)

In this system, the drill comprises two parts:[89]

- A cutting segment for osteotomy- The cutting portion is designed following traditional spiraled drills, in sequential diameter and length.
- A guiding segment that fits precisely into the sleeve- The guided segment is represented by a cylinder that fits into the sleeve and guides osteotomy.

Figure-39: Guided drills design. A cutting portion is followed by a guided segment that corresponds to the inner diameter of the sleeve. the first three drills contain information for a smaller sleeve while the other two adapt to a bigger diameter sleeve, indicating this system has different sleeve sizes for different implant diameters[41]

The use of metal sleeves significantly reduced deviations in implant angulation and position. The metal sleeve acted as a stabilising guide during drilling, minimising the potential for errors and enhancing overall accuracy. The scientific reasoning behind the improved accuracy with metal sleeves can be attributed to several factors. First, the metal sleeve acts as a guide, ensuring precise alignment of the drill with the planned implant position. It eliminates the potential for manual errors that may arise when using sleeveless drill approaches, where the operator relies solely on visual estimation or hand-eye coordination. The rigid nature of the metal sleeve minimises deviations caused by unintentional hand movements, leading to enhanced accuracy.[141]

Furthermore, the metal sleeve offers stability during the drilling process. It prevents lateral movement of the drill, reducing the risk of deflection or deviation. The precise fit between the sleeve and the drill restricts any wobbling, ensuring that the drilling occurs along the intended trajectory. This stability contributes to maintaining the planned angulation and position, thereby improving the overall accuracy of implant placement.[141]

Additionally, the design of the sleeve, such as the presence of flutes or vents, can affect stability and accuracy. Finally, bone density plays a crucial role, as variations in density can impact the stability of the metal sleeve during drilling.

The guiding segment remains the same across all drills, while the cutting portion varies with implant size. Accessories like punches and drivers also have guided segments.[41]

Figure-40: Accessory instruments with guided segment (tissue punches)[41]

Each implant length corresponds to a specific drill. A stepwise drilling protocol is advised, ensuring at least half of the guiding segment is inside the sleeve before drilling begins. This prevents inaccuracies and enhances stability. To give an example: if wanting to achieve an osteotomy for a 12 mm length implant, drilling should be sequenced (8 mm–10 mm– 12 mm) in every instrument used. Moreover, in order to help with overall guidance protocol, all systems include a cortical drill, often very short, to permit a smooth preparation.[41]

Figure-41: Guided drills with their cutting and guided segments. Half the length of the guided segment must be positioned within the sleeve for the drill to be guided. Therefore, a stepped approach is recommended, starting with initial lengths until reaching desired final depth[41]

One common challenge is interference from soft/hard tissue at the crestal level. This occurs when the wide guided segment encounters resistance. To mitigate this, soft tissue removal (flapless technique) or deeper drilling steps may be required. Additionally, sub-crestal preparations may need to use the following length drills to reach the desired depth; or use profile drills to eliminate the stop.

Figure-42: Cortical drills for initial bed preparation [41]

To avoid such issues, some systems include a non-cutting transition zone between guided and cutting parts or use slim implant mounts that allow subcrestal placement without obstruction.[142]

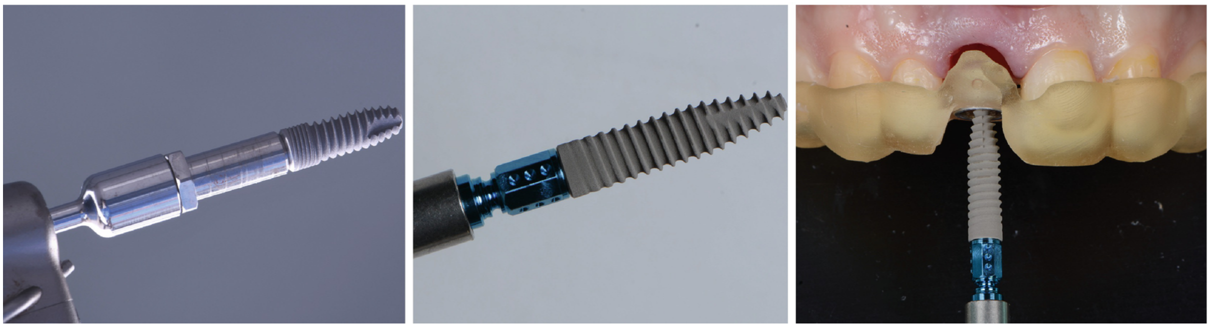


Figure-43: Implant driver wider than implant platform (left), implant driver with switch platform (centre and right)[41]

In guided drill systems, distance between implant shoulder and sleeve position, known as offset, tends to be the same for all planned implants. This is because said offset is already established in every instrument of the surgical cassette. Main disadvantage of this fixed distance is the impossibility to customize it in different clinical situations. On the contrary, a clear advantage of uniform offset is that the implant driver has a clear stop that indicates that implant has reached the desired depth. This is especially advantageous in posterior areas where visualization is often compromised.[41]

Figure-44: Implant driver with guided segment and visual depth stop[41]

Guided drill systems offer streamlined protocols with minimal tolerance buildup but require attention in deep or subcrestal placements.

Drill Handle Systems (For Sleeved Guides)

Metal sleeves in these systems receive a handle that reduces the master cylinder diameter into a smaller one that receives the drill, similarly to a reducing key. Thus, a handle acts as an adapter between the sleeve and the drill. Drills have a fixed coronal stop that contacts the handle at the desired depth. Their uniform diameter allows for subcrestal placement without soft tissue interference.[143]

Figure-45: Master sleeve and reducing keys that adapt and modify the inner diameter of the drilling hole [41]

Drill is fully guided during the whole process, as it goes through the handle. Thus, only one drill of each diameter can be used without the need of a stepped protocol. These systems provide customizable offsets using handles of varying heights and drills of different lengths. However, the complexity increases, requiring the clinician to monitor multiple parameters (offset, handle height, drill length), especially during multi-implant surgeries.[138]

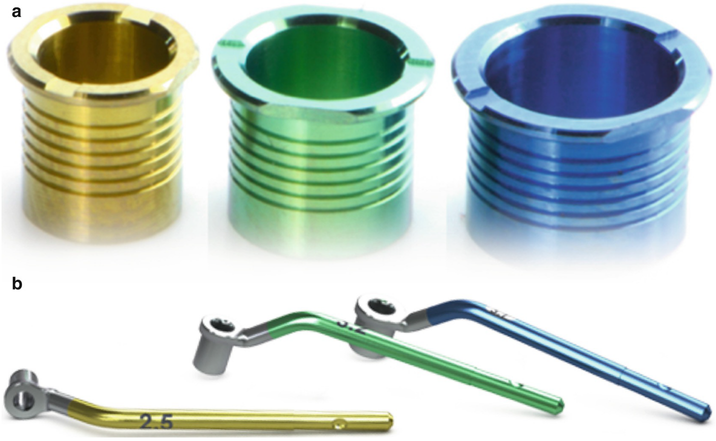


Figure-46: Different sleeve diameters and their corresponding handles, from Biohorizons[41]

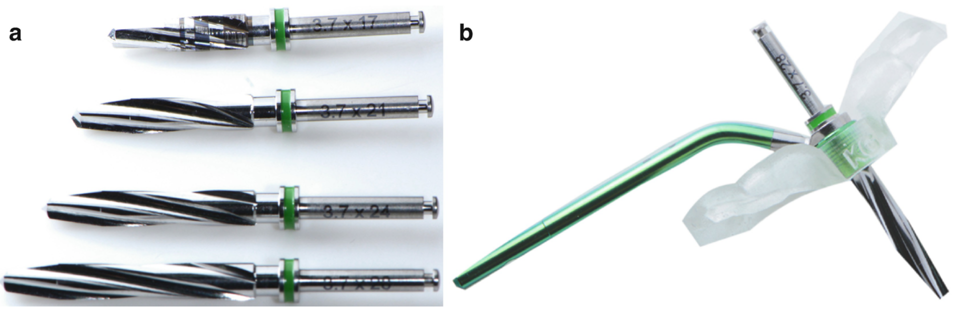


Figure-47: Biohorizons® guided drilling system. Drill length variation depends on the drilling protocol indicated by the software. The length in these drills does not relate to the implant length but to an algorithm proposed by the software to achieve the desired osteotomy depth [41]

Figure-48: Straumann® guided drilling system. Handles codified by color to relate to the corresponding drill. Also, handle height compensation can be visualized with either 1 colored dot (+1 mm) or 3 dots (+3 mm). Note that drills maintain their diameter along the whole active segment length [143]

More components mean more gaps—and thus greater risk of cumulative error. Implant placement often requires visual confirmation of depth marks, which can be challenging in posterior areas.[138]

This system supports subcrestal preparation and customization but demands meticulous intraoperative control and bimanual handling to secure both handle and drill.

SLEEVELESS SURGICAL GUIDES

These guides incorporate the sleeve structure directly into the template design, eliminating metal sleeves to reduce gap-related inaccuracies. Since the drill doesn't contact the guide, materials used for fabrication vary.[144]

Friction between metal (handle) and resin (template) allows tighter fits compared to metal-metal interfaces. This improves guidance precision.[144]

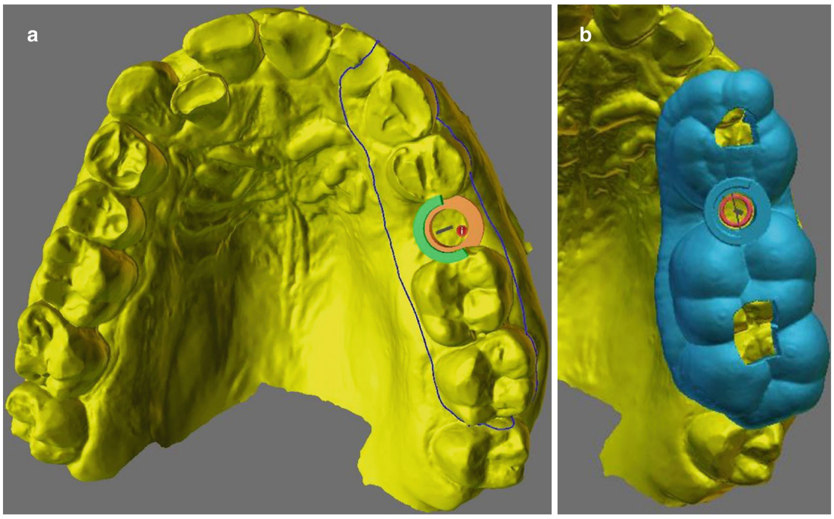


Figure-49: Sleeve is included into template design[41]

Drill Handle Systems (For Sleeveless Guides)

In this configuration, the handle fits directly into the integrated sleeve portion of the template. The system's advantages mirror those of sleeved handle systems. These templates can be printed or milled and can be manufactured with different materials, as no direct drill-to-guide contact occurs. This also avoids debris contamination during osteotomy. Sleeve-handle tolerance reduction is also improved because friction is allowed between metal (handle) and resin (guide) material. Therefore, fit can be adjusted to reduce this gap. On the contrary, tolerance between two metal structures (metal sleeve and handle) does not allow friction and so, gap in sleeved guides has to permit friction-free fit.[41]

Guided Drill Systems (For Sleeveless Guides)

Drills with integrated guiding segments are used directly within the guide hole, eliminating sleeves. This greatly reduces tolerance, and a small friction is allowed. Therefore, the use of a material which does not produce derivates is mandatory.[41]

PMMA or PEEK materials are needed to be milled and fabricate these templates. 3D printed materials cannot be used and so, costs are increased considerably. However, a pre-fabricated metal sleeve is not needed and thus cost can be reduced.

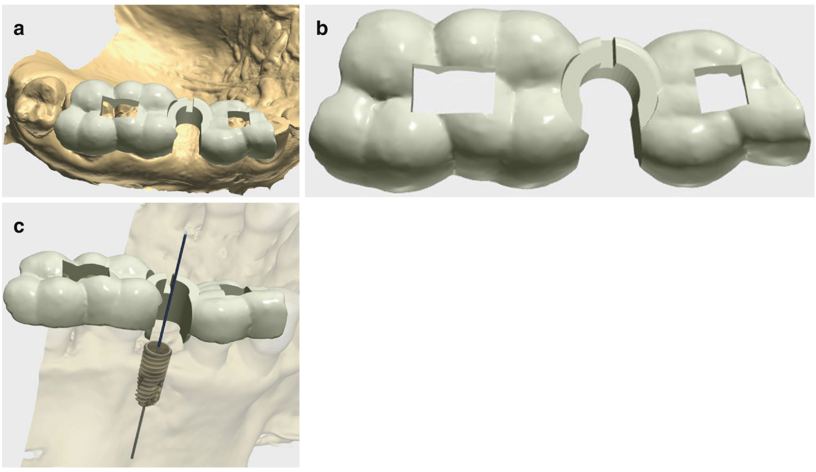


Figure-50: Sleeveless guide design for Osstem® guided drill system. This system provides an open window in the buccal aspect to facilitate drill positioning, especially in a posterior area, and improve irrigation. Caution must be take to avoid weak palatal/lingual areas within this design [41]

These guides allow for greater flexibility in limited spaces and tailored access to different tissue architectures. However, rigidity increases due to material choice, and soft tissue interference remains a potential issue whenever using guided drills, with or without sleeves. [41]

PILOT DRILL SURGICAL GUIDES

Some systems include a small diameter sleeve destined to the first drill, usually known as pilot drill. The sleeve inner diameter wanders around 2–2.2 mm. These are useful in: Narrow edentulous areas where a regular diameter sleeve cannot fit. Also, they are used for osteotomy depth and direction pre-preparations, before continuing with a traditional free-handed surgical protocol. Moreover, these templates are often used to mark implant position in simultaneous bone regenerative surgery, where final implant bed preparation demands direct vision and free-hand control in order to preserve existing bone. [110]

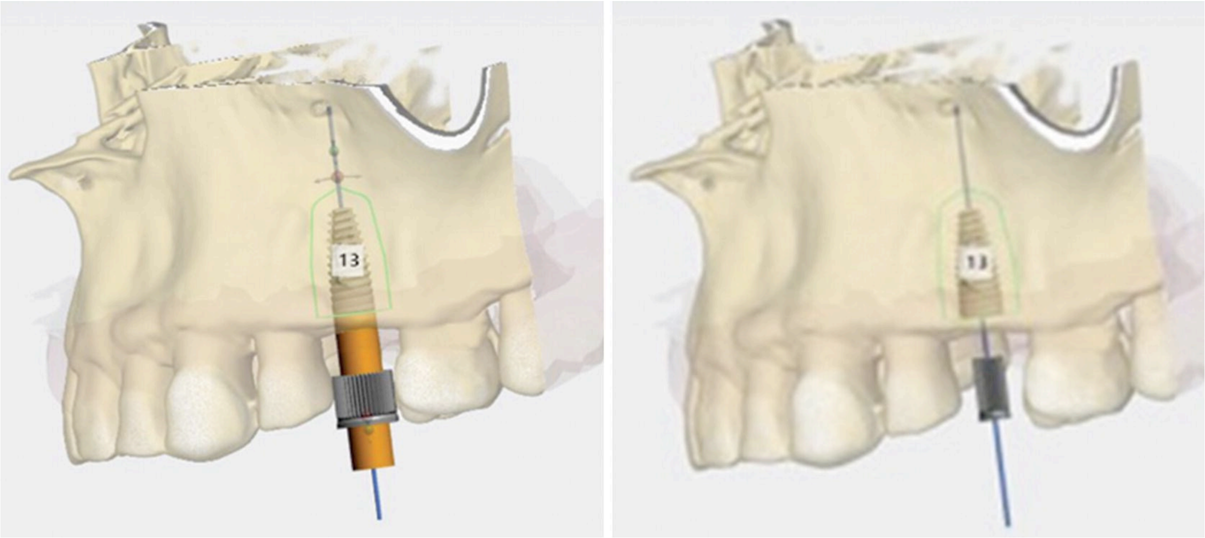


Figure-51: Implant planned for a guided protocol (left) and for a pilot drilling protocol (right). Both planning can be used for pilot drilling sequence only [41]

Implants cannot be driven with these templates; only pilot drill can be used. Nevertheless, these guides can help rapid implant distribution in extended edentulous sites, in cases where the surgeon prefers conventional free-hand protocol. [41]

Pilot drill guides are compatible with all template materials and can be 3D printed or milled. While limited to initial drilling, pilot guides aid implant positioning in complex or regenerative cases.

Implant Placement and Accuracy Assessment[89,132]

Different surgical guide protocols exist for implant placement. The choice of protocol depends on the clinical situation, surgeon’s experience, and preference. Three main options are used:

1. **Pilot Drilling Protocol**
    - The simplest method: the guide directs only the first (pilot) drill, usually 1.8–2.2 mm in diameter.
    - After that, drilling continues freehand.
    - Useful in narrow spaces, grafted sites, or when reducing surgical kit complexity.
    - Not considered guided surgery if only one drill is used for very narrow implants.

2. **Free-Handed Implant Placement (Guided Drilling)/ Partially guided protocol**
    - All Osteotomies drilling is guided by the template, but the implant itself is inserted manually.
    - Useful when the surgeon wants control over implant angulation, depth, or positioning near adjacent teeth.
    - If the guide doesn’t fit well during surgery, drilling should switch to a manual approach.

3. **Fully Guided Protocol**
    - Both osteotomy drilling and implant insertion are performed through the guide.
    - Provides maximum accuracy when planning and clinical fit are ideal.
    - Some systems require special guided implant mounts; others use adapter tools with standard implants.
    - While some claim guided mounts improve accuracy, studies show little difference compared to adapters.

Accuracy Evaluation[41]

The main measure of accuracy is how closely the planned implant position is reproduced in the patient's jaws. The measurement for accuracy in static or dynamic navigation systems is usually performed by superimposing the preoperative planning data and post-operative data. Different studies compare different deviations but mainly there are four types of deviations:

1. Depth deviation: The depth deviation is the distance of planned and placed implants on the axis of the planned implant. i.e, Deviation in apical-coronal direction (mm)

2. Lateral deviation: The lateral deviation is the directional component of the global deviation at the level of the planned implant platform/apex. i.e, Mesial-distal and buccal-lingual direction (mm)

3. Global deviation: The global deviation is the spatial distance between the center of the implant platform/apex of planned and placed implants. i.e, Overall 3D distance regarding apical and coronal deviation (mm)

4. Angular deviation: The angular deviation is the spatial angle between the planned and placed implant axis. i.e, The angle in 3D space between center axes (degree)

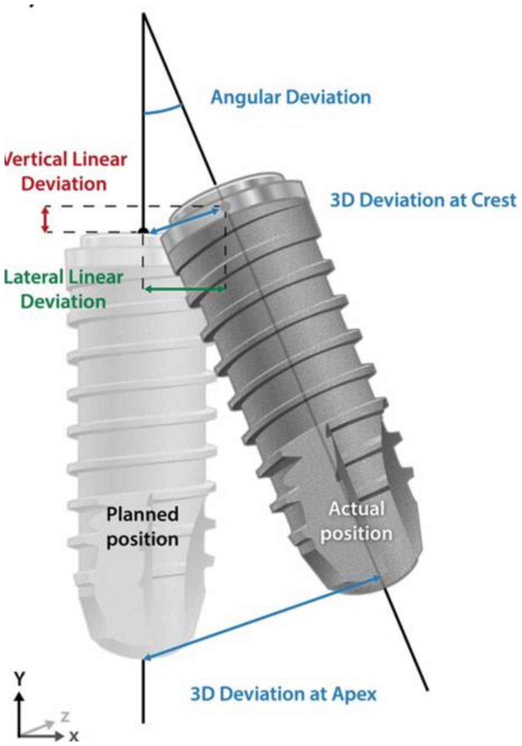


Figure-52: Illustration depicting 3D angular, crestal, and apical implant deviation measurements.[145]

Software are still improving to compensate for these deviation. Some possible error sources that may lead to increased deviations in navigation are voxel settings, slice thickness, patient-related motion or metal artifacts, and non-rigid fixation of fiducial marker clip or screws during CBCT scan may cause problems during STL and DICOM superimposition procedure. Errors during digital planning, limits of optical tracking, software -oriented deviations, and the difficulty of manipulation while keeping the eye on screen might also influence the accuracy.

Guide Design Features

Beyond the navigation system chosen, the micro-design of the guide itself strongly influences accuracy, ease of use, and complication rates. Key aspects include the type of sleeves, the number of guides required, and whether the design is open or closed.

a. Sleeved vs. Sleeve-Free Designs[146,147]

- Traditional Sleeved Guides:
    - Incorporate metal cylinders (sleeves) that direct drills precisely.
    - Advantages: durability, stable drill path.
    - Limitations: require extra mesio-distal space; restrict irrigation, causing potential overheating of bone.
- Resin/Printed Sleeves:
    - 3D printed directly into the guide, eliminating metal.
    - Advantages: cost-effective, customizable, reduced bulk.
    - Limitations: less durable, prone to wear after multiple uses.
- Open-Slot Sleeves:
    - Feature a buccal or lingual “window” instead of a closed cylinder.
    - Allow insertion of drills in limited interarch space.
    - Improve irrigation and cooling during drilling.

b. Single vs. Multiple Guides[145]

- Single-Guide Systems:
    - Use one guide with interchangeable drill keys for different diameters.
    - Faster and simpler but irrigation is often restricted.
- Multiple-Guide Systems:
    - Require sequential guides for different steps.

    - More time-consuming but may improve cooling and visibility.
- Accuracy Consideration: Some studies suggest single universal guides are less accurate due to cumulative tolerance mismatch between sleeves and drill keys.

c. Open vs. Closed Designs[148]

- Closed Guides:
    - Enclose the drill fully, providing maximum stability.
    - Best for high-precision cases where space is not a limitation.
- Open Guides:
    - Incorporate windows or cutouts, allowing better irrigation, visibility, and access in posterior regions.
    - Slightly less stable but more practical for difficult access.

d. Additional Features in Modern Guides[41]

- Inspection Windows: Small openings allow clinicians to visually verify seating of the guide on teeth or mucosa.
- Fixation Screw Holes: Especially important for mucosa- and bone-supported guides, ensuring stability with at least 3 pins.
- Engraved Indicators: Patient ID, implant position, or depth markers may be incorporated for clarity.
- Thickness and Offset Control: Guides can be customized in CAD software to ensure adequate strength without bulkiness.

Studies comparing guided to conventional surgery show better accuracy with guided methods. However, comparison is difficult because freehand placement has no exact pre-planned reference. To address this, virtual implant planning is often performed retrospectively for freehand cases, though results cannot be objectively quantified.

Despite these limitations, static computer-aided implant surgery (sCAIS) demonstrates implant survival rates of 95–100%, confirming its reliability in achieving osseointegration.

Accuracy Considerations[41]

- Assessment: Measured through angular deviation, entry point error, and apex deviation.
- Planning & Imaging:
    - Surface scans and CBCT are key, though patient movement and metal restorations can distort images.
    - Manual segmentation of CBCT scans usually improves precision.
- Guide Design:
    - Reinforcement is important for distal extensions to reduce bending.
    - More supporting teeth in the guide leads to more accurate results.
    - Implant shape (conical vs. parallel) can also affect accuracy.
- Printing Methods: DLP, SLA, and polyjet printers all give clinically acceptable outcomes.
- Clinical Factors:
    - Templates typically stay within a 2 mm margin of error, though edentulous maxilla cases show more deviation.
    - Drill length, offset, and sleeve design strongly influence precision.
    - Bone density and cortical contact can increase angular deviations.
    - Immediate implants in fresh extraction sites show more error than healed sites.

Practical Tips for Accuracy[41]

- Place mesial implants first to stabilize the guide for distal implants.
- Avoid extensive anesthesia in mucosa-supported guides to prevent tissue swelling.
- Raise a flap if soft tissue thickness exceeds 3.5 mm.
- Keep offset as short as possible and use longer guiding sleeves to reduce lateral drill movement.

REVIEW OF LITERATURE

1. In a study authors evaluated the effectiveness of 3D computer-aided modelling and surgical guides in implant placement for prosthodontic rehabilitation. In which 148 patients (female (n = 72), male (n = 76), (age range 38-62 years) underwent prosthodontics rehabilitation using dental implants in 2015-2020. All patients underwent complex clinical, laboratory, and instrumental examinations for diagnosis and treatment planning. CT was used for information regarding anatomical constraints, bone volume and bone quality. Total of 583 implants were installed. During the diagnostic and planning stages of the operation, patients of group A (included 75 patients) underwent a scan of the alveolar bone, which was loaded into 3 Shape Implant Studio. In group B (included 73 patients) the preparation of implants sites was accomplished without a surgical guide and implants were placed without a surgical guide. Group A, benefiting from guided implantation, exhibited a significantly shorter average surgical time (10.6 ± 2.9 min per implant) compared to Group B (16.4 ± 1.5 min per implant). The findings suggest that controlled implant positioning through 3D modelling minimizes surgical trauma, reduces procedure duration, and lowers the risk of complications, reinforcing the value of digital planning in modern implantology.[4]

2. A study was conducted to assess the accuracy of stereolithographic surgical guides in implant placement, comparing deviations based on support type. Analysing 54 patients and 294 implants, the research utilized CBCT-derived planning and post-osseointegration scans to measure discrepancies. Bone-supported guides exhibited the highest deviations (5.0° angular, 1.70 mm at the implant shoulder, and 1.99 mm at the tip), while mucosa-supported guides showed the lowest (2.9° angular, 0.7 mm at the

shoulder, and 0.76 mm at the tip). However, despite minor deviations, no complications affecting critical anatomy were observed. These findings highlight the effectiveness of CBCT-guided planning, with rigid screw fixation and metal sleeves further enhancing precision.[5]

3. A prospective clinical study evaluated the accuracy of flapless, computer-aided implant placement by comparing planned and actual implant positions. Using 3D planning software and CAD/CAM technology, the study analysed deviations in implant placement by overlapping pre- and postoperative CT scans. Results from 14 implants revealed a mean linear deviation of 0.56 mm at the implant head, 0.64 mm at the apex, and an angular deviation of 2.42°. While computer-guided surgery offers benefits over conventional techniques, some deviations remain inevitable. The findings emphasize the importance of precise presurgical planning to account for anatomical and prosthetic factors, ensuring optimal implant positioning and reducing complications.[149]

4. A randomized controlled trial compared the accuracy of novel computer-assisted, template-based implant placement techniques using CAD/CAM stereolithographic surgical templates with and without metallic sleeves. A total of 90 implants were placed in partially edentulous patients, with 41 using metallic sleeves and 49 without. Among the latter, 16 were placed through open sleeves and 33 through closed sleeves. The study found that implants placed using templates without metallic sleeves showed significantly lower deviation in angle ($p = 0.0212$) and vertical position ($p = 0.0073$) compared to those with metallic sleeves. Furthermore, closed sleeves were more accurate than open sleeves in angle ($p = 0.0268$) and horizontal positioning ($p = 0.0477$). No implant failures or complications were observed. The findings suggest that

surgical templates without metallic sleeves provide improved accuracy in the vertical and angular planes, while open sleeves should be used cautiously in the molar region with limited inter arch space. [150]

5. A study was conducted to evaluate the accuracy of implant placement guided by surgical templates fabricated via digital workflows, using both in vitro and in vivo models. Implants were virtually planned using CBCT and intraoral scan data, followed by fabrication of stereolithographic surgical templates. In vitro, 60 implants were placed in 15 resin mandibular models. In vivo, 74 implants were placed in 54 partially or fully edentulous patients. Implant accuracy was assessed by comparing postoperative CBCT scans with preoperative plans using seven parameters: central, horizontal, and vertical deviations at the apex and shoulder, and angular deviation. Significant deviations were found in all parameters in both in vitro and in vivo settings ($P < 0.001$). In vivo deviations were notably higher than in vitro. Specifically, mucosa-supported templates exhibited greater horizontal deviations at the apex compared to tooth-supported templates. However, no major complications occurred in any cases. Although digital surgical templates enhanced accuracy, clinically significant deviations persisted, particularly in vivo. Within the study's limitations, implant placement guided by surgical templates showed inherent inaccuracies, underscoring the need for further research and optimization of digital workflows.[151]

6. A clinical study evaluated the accuracy of digital implant placement using a fully guided, flapless, single-unit immediate-loading protocol. The primary objective was to measure the deviation between virtually planned and actual implant positions and assess provisional restorations and periodontal factors post-surgery. Fourteen implants

were placed in nine patients using intraoral scans and CBCT data to design and fabricate customized surgical templates, abutments, and provisional restorations. Post-surgical analysis revealed a mean angular deviation of 5.07 ± 2.06° and an apical linear deviation of 1.74 ± 0.63 mm. Two implants failed within the first three months, while the occlusal level differences of nine prefabricated provisional restorations were recorded. Periodontal assessments, including bleeding on probing and peri-implant pockets, were also conducted at the three-month follow-up. The study highlights the accuracy of the DIONAVI protocol and provides clinicians with an estimate of the expected deviations in implant placement.[10]

7. In a randomized clinical trial authors compared patient-reported outcomes and experiences (PROs and PREs) among three dental implant placement techniques: conventional freehand, dynamic, and static computer-aided implant surgery (CAIS). Ninety patients were randomized, with 88 completing self-administered questionnaires assessing preoperative expectations, postoperative healing events, and overall satisfaction. Significant differences were found in expectations regarding chewing difficulty and postoperative experiences such as pain duration, speaking limitations, and impact on daily activities ($p < 0.05$). Patients underestimated postoperative pain ($p = 0.035$) and swelling ($p = 0.001$), though no significant differences in pain intensity, swelling, or painkiller use were observed among groups. Despite short-term functional limitations, 89% of participants were satisfied. The findings suggest that all three techniques yield similar postoperative outcomes and patient satisfaction levels.[8]

8. A study evaluated the accuracy of dental implant placement using stereolithographic (SLA) surgical guides based on CT data. A total of 94 implants were placed between 2005 and 2006, with each case planned virtually using three-dimensional CT images. Radiographic templates were used during imaging, and the implants were placed using guides fabricated by SLA technology. Postoperative CT scans were obtained to compare the planned and actual implant positions using specialized software. The results showed a mean angular deviation of 4.9° ± 2.36, with linear deviations of 1.22 ± 0.85 mm at the implant neck and 1.51 ± 1.0 mm at the apex. Maxillary implants showed slightly higher deviations than mandibular ones. The findings indicate that SLA surgical guides can offer a reliable method for accurate and minimally invasive implant placement, supporting their application in flapless implant procedures.[129]

9. A clinical study was conducted to compare the accuracy of computer-generated (CAD/CAM) and conventional surgical guides for dental implant placement using a split-mouth design. Ten patients received two implants each in symmetric edentulous areas. One side was treated using a CAD/CAM surgical guide based on cone beam computed tomography (CBCT) data and virtual planning, while the other side received implants placed with a conventional guide. Postoperative CBCT scans were used to measure deviations between planned and actual implant positions, focusing on angular, coronal, and apical differences. Results showed that CAD/CAM-guided implants were generally placed closer to the planned positions, with statistically significant improvements in coronal horizontal accuracy and reduced variability in apical placement. The study concludes that while both techniques are clinically viable, CAD/CAM guides offer enhanced precision and consistency in implant placement.[9]

10. A prospective clinical study was aimed to evaluate the accuracy of static guided implant surgery (sGIS) using a fully digital planning workflow. Twenty-one partially edentulous patients underwent 26 implant surgeries with tooth-supported stereolithographic surgical guides. The planning was based on cone-beam computed tomography (CBCT) and intraoral scans aligned using either a surface registration or a fiducial marker protocol. A total of 43 implants were placed using the fully guided approach. Postoperative CBCT scans were compared with the virtual plans to assess angular and positional deviations. Results showed mean deviations of 0.78 mm at the implant platform, 1.28 mm at the apex, and 4.3° in angulation. Implants planned with surface registration showed slightly greater angular and apical deviations compared to those planned with fiducial markers, likely due to metal artifacts. The study concludes that a fully digital workflow offers clinical accuracy comparable to conventional methods and supports its reliability for use in partially edentulous patients.[28]

11. A prospective multicenter study evaluated the clinical outcomes of digitally planned, immediately loaded dental implants using prefabricated prostheses for the rehabilitation of edentulous maxillae. A total of 312 implants were placed in 52 patients across eight Scandinavian clinics, following a digital planning protocol with the NobelGuide® system and immediate placement of Procera Implant Bridges®. After one year, a cumulative implant survival rate of 99.4% was recorded, with only two implant losses. Mean marginal bone resorption was 1.3 mm, although 19% of implants showed resorption greater than 2 mm. Common complications included gingival hyperplasia and prosthesis-related issues such as screw loosening and occlusal adjustments. While the results showed excellent implant and prosthesis stability, the frequency of marginal bone loss suggests a need for longer-term evaluation. The

findings support the feasibility of this digital and immediate-loading approach, though further investigation is needed to fully assess its long-term biological impact.[152]

12. In a RCT authors compared the accuracy of implant placement between static and dynamic computer-assisted implant surgery (CAIS) in single-tooth spaces. Sixty patients were randomly assigned to static (n = 30) or dynamic (n = 30) CAIS groups, with implants placed by a single surgeon. Pre- and postoperative CBCT scans were analyzed for deviations at the implant platform, apex, and angle. No significant differences were found between the two methods, with similar mean deviations at the implant platform (Static: 0.97 ± 0.44 mm, Dynamic: 1.05 ± 0.44 mm), apex (Static: 1.28 ± 0.46 mm, Dynamic: 1.29 ± 0.50 mm), and angular placement (Static: 2.84 ± 1.71°, Dynamic: 3.06 ± 1.37°). However, dynamic CAIS showed a significantly higher mesial deviation ($p = 0.032$). Overall, both techniques demonstrated comparable accuracy in implant placement. [153]

13. A retrospective study was conducted to assess the long-term clinical and radiographic outcomes of immediate flapless full-arch prosthetic rehabilitation in edentulous jaws using computer-guided surgery based on prosthetic-driven planning. A total of 28 patients received 33 prostheses supported by 164 implants placed according to the NobelGuide® protocol, with either an all-on-four or all-on-six conFIG-uration. After a mean follow-up of 6.46 years (up to 10 years), the cumulative implant survival rate was 89.7% for all-on-four and 99.0% for all-on-six protocols. Prosthesis success rates were lower (51.5%), although survival was 88.2% for all-on-four and 100% for all-on-six. Mean marginal bone loss was 1.38 mm at 5 years and 2.09 mm at 10 years, with no significant differences between implant types or conFIG-

urations. Biological complications were minimal, and prosthetic complications were mostly limited to chipping and wear. The findings support the long-term efficiency and safety of computer-guided, immediately loaded full-arch prostheses, particularly when combined with a structured maintenance program.[154]

14. A study was conducted to evaluate the accuracy of dental implant placement using cone-beam CT (CBCT)-based virtual planning and 3D-printed surgical guides compared to the conventional free-hand method. Twenty-three implants were placed in 10 patients using a 3D-planned guide, and identical implants were placed manually in anatomical models by a prosthodontist and a maxillofacial surgeon. Postoperative CT scans were superimposed on the virtual plans to measure deviations. The guided approach showed significantly smaller deviations in implant shoulder (0.9 mm) and apex (0.6–0.9 mm), and better angular accuracy (mean 4.2°), compared to the free-hand method, which showed deviations up to 3.5 mm and angles up to 10.9°. The study concluded that computer-guided implant placement is significantly more accurate than the free-hand method and supports reduced patient radiation through in vitro evaluation techniques.[155]

15. A group of authors conducted a clinical study aimed to evaluate the accuracy of dental implant placement using three different types of computed tomography (CT)-derived stereolithographic (SLA) surgical guides: tooth-supported, bone-supported, and mucosa-supported. A total of 110 implants were placed in 30 patients using SLA guides produced via rapid prototyping, based on preoperative CT imaging and 3D virtual planning. After surgery, postoperative CT scans were compared with the preoperative plans to assess angular and linear deviations at the implant neck and apex.

The mean angular deviation was 4.1° ± 2.3°, while the mean linear deviations were 1.11 ± 0.7 mm at the neck and 1.41 ± 0.9 mm at the apex. Tooth-supported guides demonstrated the highest accuracy, followed by bone-supported and mucosa-supported guides. The study concludes that SLA surgical guides are reliable for accurate implant placement, with tooth-supported guides offering superior precision.[156]

16. A group of authors did a randomized controlled trial to assess the implant- and patient-centered outcomes of guided surgery versus conventional implant placement at 1-year follow-up. A total of 314 implants were placed in 59 patients, who were randomly assigned to either the guided surgery or control group. Radiographic and clinical parameters were recorded at baseline (implant placement and prosthesis installation) and at the 1-year follow-up. Results indicated that no implants were lost in either group. The mean marginal bone loss after the first year was minimal: 0.04 mm (SD 0.34) in the guided surgery group and 0.01 mm (SD 0.38) in the control group. Regarding soft tissue parameters, the guided surgery group had a mean of 1.41 (SD 1.25) surfaces with bleeding on probing (BOP) and 1.10 (SD 1.22) surfaces with plaque, while the control group showed slightly higher values (1.37 [SD 1.25] for BOP and 1.77 [SD 1.64] for plaque). The mean pocket probing depth was 2.81 mm (SD 1.1) in the guided group and 2.50 mm (SD 0.94) in the control group. Both groups showed significant improvements in quality of life ($p \leq 0.01$), with no significant differences between the groups. In conclusion, no significant differences in implant and patient outcomes were observed between guided and conventional implant treatments at the 1-year follow-up. [157]

17. A study was done to compare the accuracy of surgical guides in implant placement using two different construction methods: CAD/CAM milling and Rapid Prototyping (3D printing). A total of 28 implants were divided into two groups: Group I, where implants were placed using CAD/CAM milling surgical guides, and Group II, where implants were placed using 3D printed surgical guides. Pre-operative CBCT scans were obtained to determine the virtual implant positions in terms of coronal, apical, and angular alignment. After implant placement, post-operative CBCT scans were taken, and Blue Sky Plan software was used to superimpose the pre- and post-operative scans. This allowed for comparison of angular, coronal, and apical deviations between the virtual and actual implant positions. The findings revealed statistically significant greater deviations in coronal, apical, and angular measurements between the virtual and actual implant placements in Group II compared to Group I. Thus, CAD/CAM milled surgical guides provided more accurate results than 3D printed surgical guides.[158]

18. A randomized controlled clinical trial (RCT) was conducted to assess and compare the accuracy of implant positioning between static computer-assisted implant surgery (CAIS) and freehand implant surgery in a single edentulous space. Sites with single edentulous spaces and adjacent natural teeth were randomly assigned to either the static CAIS group or the freehand implant surgery group. Both groups utilized digital implant planning based on data from cone beam computed tomography (CBCT) and surface scans. In the static CAIS group, a surgical guide was created and used for fully guided implant placement, while in the freehand group, implants were placed manually. Postoperative CBCT scans were analyzed for nine measurements to assess deviations in angles, implant shoulder positions, and apexes, comparing the planned and actual implant placements. A total of 52 patients received 60 single implants. The median

(IQR) deviations in angles, shoulder positions, and apexes were 2.8 (2.6)°, 0.9 (0.8) mm, and 1.2 (0.9) mm in the static CAIS group, and 7.0 (7.0)°, 1.3 (0.7) mm, and 2.2 (1.2) mm in the freehand group. Statistically significant differences were observed in six out of the nine measured parameters using the Mann–Whitney U test ($p < 0.05$). The study concluded that static CAIS provided greater accuracy in implant positioning compared to freehand placement in a single edentulous space.[159]

19. A group of scientists conducted a study to compare the accuracy of free-handed (FH), pilot-drill guided (PG), and fully-guided (FG) implant surgeries in partially edentulous patients needing two or more implants in the posterior maxilla. Patients were randomly assigned to one of the three groups, and ideal implant positions were determined by combining CBCT (DICOM format) and optical scan data (STL format) using specialized software. The actual implant positions were then compared to the ideal positions, with the primary outcome being the Apical Global Deviation (AGD) and secondary outcomes including Angular Deviation (AD), Coronal Global Deviation (CGD), and others. Results showed that FG surgery was the most accurate (mean AGD: 0.97mm), followed by PG surgery (mean AGD: 1.43mm), while FH surgery showed the largest deviations (mean AGD: 2.11mm). Most secondary outcomes followed the same trend. Additionally, 5 implants in the FH group and 1 in the PG group required cement-retained restorations instead of screw-retained ones. The study concluded that FG surgery should be considered the gold standard when precise implant positioning is essential.[160]

20. A study was aimed to compare the use of digital versus traditional implant guides in patients with missing first molars undergoing implant restoration. A total of 42

patients were randomly assigned to either a digital group, using a CAD/CAM digital implant guide, or a control group, using a traditional impression. Results showed that the digital group had shorter impression and surgery times, higher first intraoral fit success, and a 100% one-time satisfaction rate, while five cases in the control group required reworking. The digital group also demonstrated lower screw access channel deviation, with no significant difference between the left and right sides, compared to the control group, where deviation was lower on the right side. Overall, the digital implant guide was found to reduce clinical operative time and screw access deviation, supporting its use for single tooth implant restoration.[161]

21. A group of authors conducted a study to evaluate the angular and linear deviations of dental implants placed using three different techniques: dual tomography (DT), model-based tomography (MT), and conventional flap surgery with a non-prototyped guide. Sixty implants were placed in mannequin maxillae and divided into three groups (n=20 each): Group DT (guided surgery using dual tomography), Group MT (guided surgery using model-based tomography), and Group C (conventional technique with flap opening and a non-prototyped guide). Postoperative cone beam computed tomography (CBCT) was used to measure the angular and linear deviations from the preoperative virtual plan. The conventional group exhibited significantly higher angular ($4.61° \pm 1.21$, $p < 0.001$) and linear deviations at the crown, center, and apex compared to both DT and MT groups. No statistically significant differences were observed between DT and MT techniques in any of the measured parameters. Both DT and MT guided surgery techniques demonstrated superior accuracy compared to the conventional method. While their precision was comparable, the MT technique offers added benefits in terms of cost-effectiveness and procedural efficiency.[162]

22. A study was aimed to evaluate the accuracy of implant placement using surgical guide templates and compare it with implant placement based on computer-aided design (CAD) planning alone. A total of 60 patients were divided into two groups: group I, where 52 implants were placed based on preoperative planning without guide templates, and group II, where 57 implants were placed using surgical guide templates designed with rapid prototyping. Preoperative and postoperative cone beam computed tomography (CBCT) scans were used to assess deviations between the actual and planned implant positions. The results showed that group II, using surgical guides, had smaller deviations in implant shoulder (1.18 ± 0.72 mm vs. 2.07 ± 0.51 mm), apex (1.43 ± 0.74 mm vs. 2.89 ± 1.02 mm), and angulation (4.21 ± 1.91 mm vs. 8.84 ± 4.64 mm), while group I had greater variation. Both groups achieved successful osseointegration and stable soft and hard tissues. The study concluded that surgical guide templates provide higher precision, making them particularly beneficial for complex procedures such as flapless surgery, immediate loading, aesthetic restoration, and cases with insufficient bone height.[163]

23. A multicenter prospective study was aimed to evaluate a clinical protocol utilizing computed tomographic (CT) scan–derived customized surgical templates and prefabricated fixed prostheses for flapless surgery and immediate loading of implants in fully edentulous maxillae. Twenty-seven patients with edentulous maxillae were treated according to the Teeth-in-an-Hour™ concept. Treatment planning was based on 3D CT imaging, allowing for the fabrication of stereolithographic surgical templates and customized fiber-reinforced acrylic prostheses. Implants were placed flaplessly using these templates and immediately restored with the prefabricated prostheses. Patients were evaluated at multiple time points up to one year postoperatively. All

patients received definitive prostheses within approximately one hour after surgery. Among the 24 patients who completed 1-year follow-up, all implants (n=164) remained stable, and prostheses were functional. Mean marginal bone loss was minimal (1.2 mm mesial, 1.1 mm distal). Complications were infrequent and mostly minor. Both clinician and patient assessments of function and esthetics were highly favorable. The use of CT-derived surgical templates and prefabricated prostheses for flapless implant surgery and immediate loading is a reliable, efficient, and minimally invasive approach for full-arch maxillary rehabilitation. The technique demonstrated high precision and excellent clinical outcomes across multiple centers.[164]

24. A randomized controlled clinical trial was aimed to compare the accuracy of dental implants placed using computer-aided surgical guides fabricated via model-based technique versus the conventional dual scan technique. A total of 40 implants were placed in 21 partially edentulous patients, randomly assigned to two groups. Group A (model-based technique) used a single CBCT of the patient and dental cast, while Group B (dual scan technique) involved two CBCT scans — one of the patient with radiographic guide and one of the guide alone. Postoperative CBCT was used to evaluate angular and linear deviations between the planned and actual implant positions at coronal and apical levels. The model-based technique showed significantly lower angular deviation (2.44° ± 1.16°) compared to the dual scan technique (4.18° ± 2.06°, $p < 0.05$). Similarly, linear deviations at both coronal and apical levels were significantly reduced in the model-based group. No implant failures or complications were reported in either group. The model-based technique demonstrated superior accuracy over the dual scan technique for fabricating computer-aided surgical guides,

suggesting it may be a more efficient and reliable method for guided implant placement in partially edentulous patients.[165]

25. A multicentre randomized controlled trial was conducted to compare the clinical outcomes of computer-guided versus conventional free-hand placement of immediately loaded dental implants in partially or fully edentulous patients. A total of 51 patients requiring at least two implants were enrolled and randomized into two groups: computer-guided surgery using 3D planning software and stereolithographic surgical templates, and conventional free-hand placement. All implants were placed using flapless or mini-flap procedures and immediately loaded if insertion torque exceeded 35 Ncm. Patients were followed for one-year post-loading. Outcomes assessed included implant and prosthesis failures, complications, peri-implant bone level changes, surgical duration, postoperative pain and swelling, patient satisfaction, and cost. No statistically significant differences were observed between the groups in terms of implant or prosthesis survival, complications, or bone level changes. However, the conventional group experienced significantly greater postoperative pain ($P = 0.002$) and swelling ($P = 0.024$), likely due to more frequent flap elevation. Within the limitations of this study, computer-guided implant placement did not offer significant advantages over conventional free-hand methods, except for reduced postoperative discomfort.[166]

26. A case report evaluated the use of a digital workflow for immediate implant placement and chairside provisionalization in the esthetic zone. Three patients with failing anterior maxillary teeth underwent implant placement with flapless surgery, buccal socket grafting, and immediate delivery of individualized CAD/CAM temporary restorations using static computer-assisted surgery. Digital planning combined intraoral

and CBCT scans to ensure prosthetically driven implant positioning and prefabrication of restorations. Clinical, radiographic, and patient-reported outcomes were assessed at baseline, post-temporary restoration, and up to one year after final prosthesis placement. All cases showed favorable results with stable peri-implant tissues, minimal marginal bone loss, satisfactory esthetic scores, and high patient satisfaction. This report demonstrates that a digital workflow can be a predictable and efficient method for immediate implant and restoration procedures in the esthetic zone.[167]

27. A study was aimed to assess the accuracy of stereolithographic template-guided implant surgery and to identify clinical factors influencing deviations between planned and actual implant positions. A retrospective analysis was conducted on 102 implants placed in 48 patients using computer-assisted, template-guided surgery. Surgical guides were fabricated using stereolithography based on preoperative CT data, and implant planning was performed with specialized software. Postoperative CT scans were superimposed with the planned data to measure deviations at the coronal and apical centers, as well as angular discrepancies. The accuracy was statistically analyzed in relation to variables including template support type, implant length, arch location (maxilla/mandible), anterior-posterior (AP) implant position, and clinical site. The mean deviations recorded were 1.09 ± 1.10 mm at the coronal center, 1.56 ± 1.48 mm at the apical center, and 3.80° ± 3.24° in angulation. Horizontal errors had stronger correlations with total deviations compared to vertical errors. Longer implant fixtures and anterior implant locations showed significantly greater deviations. Templates supported by mucosa exhibited slightly reduced apical errors compared to tooth-supported ones, though overall accuracy was not significantly influenced by the type of support or clinical site. Template-guided implant surgery demonstrated clinically

acceptable levels of accuracy. However, greater deviations were observed in anterior regions and with longer implants, highlighting the need for meticulous control at the coronal level and enhanced stabilization of the template, particularly in anterior edentulous cases. These considerations are critical for optimizing implant positioning and minimizing risk to anatomical structures, thereby improving surgical safety and prosthodontic outcomes.[168]

28. A clinical study was done to assess a restoration-guided implant rehabilitation for a patient with complex Class IV partial edentulism. A provisional removable prosthesis was used to evaluate and confirm occlusal vertical dimension, aesthetics, and tooth position. Ridge augmentation was planned to use a clear acrylic duplicate of the wax-up, guiding autogenous bone graft harvesting from the mandibular symphysis and sinus augmentation. Following healing, implants were placed using a surgical guide derived from the diagnostic setup. A two-piece fixed prosthesis was fabricated—a screw-retained substructure veneered with pink composite, and a cement-retained ceramic superstructure—ensuring retrievability and functional stability. This interdisciplinary, prosthetically driven approach enabled precise reconstruction of hard and soft tissues, restoring aesthetics, phonetics, and function without the need for a removable overdenture.[169]

29. A study was conducted to evaluate the accuracy of dental implant placement using surgical templates in both in vitro and in vivo settings. Virtual implant planning was performed using CBCT and intraoral scan data, followed by the fabrication of stereolithographic surgical templates. Sixty implants were placed in 15 resin models (in vitro), and 74 implants were placed in 54 patients (in vivo). Postoperative CBCT scans

were used to assess deviations from planned implant positions in terms of central, horizontal, vertical, and angular parameters. All deviations were statistically significant, with greater inaccuracies observed in vivo. Mucosa-supported templates exhibited significantly higher horizontal deviations at the apex compared to tooth-supported templates. The findings highlight that despite digital planning and 3D-printed guides, measurable inaccuracies persist, especially in clinical conditions. Further research is necessary to improve template-guided implant accuracy and validate its clinical benefits.[151]

30. An in vitro study was conducted to evaluate the time efficiency of various intraoral scanners compared with conventional impression methods. While intraoral scanners are recognized for their accuracy in computer-aided impression making (CAIM), their impact on time efficiency remains underexplored. Three intraoral scanners were used to digitize three clinical scenarios: a single abutment (Scenario 1), a short-span fixed dental prosthesis (Scenario 2), and a full-arch prosthesis preparation (Scenario 3). The duration of each digital procedure was recorded and compared with the compiled times for conventional impressions using three different materials. The mean durations for digital impressions in Scenarios 1, 2, and 3 were 5:57, 6:57, and 20:55 minutes, respectively. CAIM showed significantly shorter procedure times across all scenarios compared to conventional methods (18:15–30:25 minutes). Statistically significant differences were noted among most scanners ($P < .05$).(169)

31. A randomized crossover clinical trial was aimed to compare patient-centered outcomes and clinical efficiency between digital and conventional implant impression techniques for single-tooth implant restorations. Twenty patients requiring implant-

supported crowns underwent both intraoral scanning (IOS) and conventional polyether impressions in a randomized sequence. Visual analogue scale (VAS) questionnaires assessed patient perceptions regarding comfort, anxiety, taste, nausea, and pain. Clinical chairside time was recorded for both procedures. Digital impressions were significantly preferred by patients, showing higher VAS scores for comfort and lower scores for discomfort-related factors ($P < 0.0001$). Additionally, the digital procedure was more time-efficient, with a mean chair time of 14.8 minutes compared to 17.9 minutes for conventional impressions ($P = 0.0001$). The digital impression technique demonstrated superior patient satisfaction and reduced chairside time, making it a more efficient and patient-friendly alternative to conventional implant impression methods. Both workflows were clinically successful in capturing 3D implant positions.[170]

32. A study was conducted to evaluate the impact of three-dimensional accuracy in guided flapless implant surgery on the aesthetic outcomes of single-tooth implants in the anterior maxilla. Twenty-seven patients received single-tooth implants using stereolithographic surgical templates and computer-guided planning. Postoperative cone beam computed tomography (CBCT) scans assessed deviations at the implant shoulder, apex, and angular orientation. Aesthetic outcomes were evaluated after a mean follow-up of 2.3 years using the Pink Aesthetic Score (PES). Mean deviations were 0.84 mm at the implant shoulder and 1.16 mm at the apex, with a mean angular deviation of 2.7°. Buccal deviation occurred in 70% of implants. A significant negative correlation was found between deviation magnitude and PES scores. Implants with deviations ≥0.8 mm showed poorer aesthetic outcomes (median PES: 9.5) compared to those with more accurate placement (median PES: 13; $p = .039$). Although guided implant surgery yields high accuracy, even minor deviations can significantly affect

aesthetic outcomes in the anterior maxilla. Precise execution of the preplanned position is critical to achieving optimal soft tissue aesthetics.[171]

33. A group of authors conducted a clinical study which was aimed to assess the in vivo accuracy of computer-aided, template-guided oral implant surgery by comparing the three-dimensional positions of planned and actually placed implants. Twenty-five patients received 104 implants using CT-based digital planning and stereolithographic surgical guides across two treatment centers. Pre- and postoperative CT scans were aligned to assess deviations in implant position. Out of 104 implants placed, 100 integrated, yielding a 96% survival rate over a mean follow-up of 36 months. In 89 implants assessed for accuracy, the mean lateral deviation at the coronal and apical ends was 1.4 mm and 1.6 mm, respectively; depth deviation averaged 1.1 mm and angular deviation 7.9°. Greater apical accuracy was observed with mucosa-supported guides, in maxillary arches, and in fully edentulous patients. Computer-aided implant placement demonstrated high survival rates and clinically acceptable accuracy, with most deviations remaining within 2 mm and 8°. However, variability in precision highlights the importance of safety margins during virtual planning.[128]

34. A study was conducted to compare the accuracy of computer-aided static navigation (GI) and dynamic navigation (NI) systems for dental implant placement in an in vitro setting. Forty implants were randomly assigned to two groups: static navigation using surgical templates (n = 20) and dynamic navigation with real-time optical tracking (n = 20). Implant positions were planned using preoperative CBCT and 3D scanning, and post-placement CBCT scans were used to measure deviations at the coronal and apical ends and angular deviations. Student's t-test was used for statistical comparison. No

statistically significant differences were observed between static and dynamic navigation systems in coronal ($p = 0.6535$) or apical ($p = 0.9081$) deviations. However, dynamic navigation showed significantly higher angular deviation compared to static navigation ($p = 0.0272$). Both navigation techniques offer clinically acceptable accuracy for implant placement. However, the angular accuracy was better with the static navigation system.[173]

35. A prospective cohort study was conducted to assess the accuracy of computer-guided implant placement using tooth-supported drill guides designed through CBCT imaging and intraoral scanning. A total of 145 Straumann tissue-level implants were placed in 66 partially edentulous patients, following prosthetic and surgical planning in coDiagnostiX software. Postoperative implant positions were evaluated after three months using intraoral scans, measuring deviations in angulation and position at the implant entry point and apex. The results showed a mean angular deviation of $2.72° \pm 1.42$, with mean positional deviations of $0.75\ \text{mm} \pm 0.34$ at the entry point and $1.06\ \text{mm} \pm 0.44$ at the apex. Accuracy was significantly influenced by implant location, length, cortical interference, and the number of unrestored teeth. The 12- and 24-month implant survival rate was 99.3%. These findings suggest that guided implant surgery using a fully digital workflow is accurate and clinically reliable, although certain anatomical and procedural factors can affect precision.[7]

36. A randomized clinical trial was conducted to compare the accuracy of computer-assisted implant surgery (CAIS) guides fabricated using either intraoral scanning of the patient or extraoral scanning of stone models. In this, 47 patients received 60 single implants using stereolithographic CAIS guides. Patients were randomized into two

equal groups: intraoral scan (n = 30) with Trios (3Shape), and extraoral model scan (n = 30) using stone cast scanned by D900L Lab Scanner (3Shape). Preoperative CBCT and scan data were merged in coDiagnostiX for planning. Postoperative CBCT scans were taken to measure deviations in implant angle, platform position, and apex position relative to the plan. Mean angular deviation was 2.42° ± 1.47° in the intraoral group versus 3.23° ± 2.09° in the model-scan group. Mean platform deviation was 0.87 ± 0.49 mm (intraoral) vs. 1.01 ± 0.56 mm (model), and apex deviation was 1.10 ± 0.53 mm vs. 1.38 ± 0.68 mm, respectively. No statistically significant differences were found between groups ($P > 0.05$). CAIS guides produced from intraoral scans and those from extraoral model scans exhibit comparable clinical accuracy in terms of angular and positional deviations.[174]

37. A randomized controlled clinical trial was conducted to evaluate the accuracy of conventional freehand implant placement versus two computer-assisted implant planning and placement (CAIPP) protocols: stereolithographic (T1) and 3D-printed (T2) surgical guides. A total of 73 partially edentulous patients were assigned to the control (n=26), T1 (n=24), or T2 (n=23) groups. Deviations between planned and actual implant positions were assessed in horizontal, vertical, and angular planes. At the implant apex, mean deviations were 2.32 ± 1.24 mm (control), 0.97 ± 0.57 mm (T1), and 1.08 ± 0.57 mm (T2). At the implant shoulder, deviations measured 1.25 ± 0.62 mm (control), 0.97 ± 0.36 mm (T1), and 0.72 ± 0.31 mm (T2). Angular deviations were 7.36° ± 3.36 (control), 4.23° ± 2.68 (T1), and 3.13° ± 2.12 (T2). CAIPP protocols demonstrated significantly greater accuracy than conventional methods ($p < 0.05$), particularly at the apex and in angular orientation. Despite improved outcomes with

CAIPP, deviations persisted, underscoring the need for intraoperative verification and appropriate safety margins during guided implant surgery.[175]

DISCUSSION

Digital implant planning and guided implant surgery (GIS) have transformed implant dentistry from a largely operator-dependent discipline into one rooted in precision, reproducibility, and prosthetically driven outcomes. By integrating imaging, virtual planning, CAD/CAM fabrication, and computer-aided execution, clinicians can now achieve levels of accuracy and safety that were once unthinkable with traditional freehand techniques. [176]

Digital implant planning has a high impact on surgical accuracy. The fusion of CBCT-derived DICOM data with surface STL files ensures that both bone anatomy and soft tissue contours are considered, allowing implants to be positioned with millimetre precision. Surgical guides fabricated from these virtual plans minimize the risk of damaging critical anatomical structures such as the inferior alveolar nerve or maxillary sinus. This surgical precision translates into safer, minimally invasive procedures, especially when flapless protocols are employed. The reduction in postoperative morbidity, pain, and healing time further underscores the patient-centered benefits of this technology.[32]

Traditional implant placement often prioritized bone availability over prosthetic design, leading to compromised restorations and hygiene difficulties. Digital workflows invert this hierarchy by making the restoration the starting point of the treatment plan. Virtual wax-ups and prosthetic simulations guide implant angulation and depth, ensuring optimal aesthetics, occlusion, and long-term function. This paradigm shift not only improves clinical outcomes but also enhances patient satisfaction by allowing patients to visualize the final result before surgery. From single-tooth replacements to complex full-arch rehabilitations, prosthetically driven planning has become the standard of care in digital implantology.[79]

CBCT remains the cornerstone of digital planning, offering high-resolution 3D visualization with relatively low radiation exposure. Its ability to quantify bone quality, identify anatomical landmarks, and facilitate graft assessment is indispensable. When combined with STL files from intraoral or extraoral scanners, clinicians gain a holistic view of both hard and soft tissue anatomy.[32] The merging of these datasets, while technically demanding, is crucial for creating accurate surgical guides. Errors in registration can compromise implant placement, highlighting the importance of meticulous protocols such as the dual- or triple-scan technique in edentulous cases. Advances in segmentation, voxel optimization, and AI-assisted alignment are steadily improving this integration.[32]

The success of digital implant planning hinges on the precision of guided drilling systems. These typically include pilot drills, sequential drills, sleeve-in-sleeve mechanisms, drill keys or adapters, and depth-control features. Each component contributes to minimizing deviation and ensuring accurate translation of the digital plan into reality. For example, pilot drills establish the trajectory, while sequential drills preserve bone viability by reducing heat generation. Drill sleeves and keys provide angular stability, and depth stops prevent over-preparation. However, factors such as sleeve height, tolerance between drills and sleeves, and irrigation limitations remain potential sources of error. Understanding these mechanical nuances is essential to maximize the accuracy of guided surgery.[41]

Despite its advantages, digital implantology is not without shortcomings. Static surgical guides are inherently inflexible: once fabricated, they cannot accommodate intraoperative surprises such as unexpected bone density or anatomical variations. In such cases, one must revert to freehand placement, which undermines the initial precision.[32] Furthermore, mucosa-supported guides in edentulous patients are prone to displacement due to tissue resiliency, necessitating fixation screws for stability. Heat generation during drilling is another concern, as restricted irrigation in guided systems may compromise osseointegration if not carefully managed. Additionally, costs associated with CBCT, intraoral scanners, CAD/CAM systems, and 3D printing can be prohibitive, particularly in resource-limited settings.[32]

Dynamic navigation and robotic-assisted implant placement are emerging as alternatives to static guided surgery. Navigation systems provide real-time feedback, enabling intraoperative adjustments, while robotic arms can physically restrict drilling within preprogrammed boundaries. These technologies offer unparalleled precision and flexibility, reducing the reliance on static guides. However, their widespread adoption is limited by high costs, bulky equipment, and steep learning curves. In contrast, static guided systems strike a practical balance between accuracy, affordability, and accessibility, making them the current standard in most clinical practices.[41,125,127]

Beyond technical accuracy, digital workflows have improved patient engagement and trust. Virtual simulations allow patients to see the proposed restorative outcome, improving treatment acceptance and compliance. Minimally invasive guided surgeries also translate into reduced chair time, quicker recovery, and fewer postoperative complications. In an era where patient expectations are high, these advantages position digital implantology as both a clinical and marketing asset for dental practices.

The trajectory of digital implantology points toward even greater integration and automation. Advances in 3D printing are yielding guides with tighter tolerances and biocompatible materials optimized for sterilization and intraoral use. Smart surgical sleeves embedded with sensors could soon provide real-time feedback on drill angulation, depth, and bone density. Artificial intelligence promises to refine implant planning by analysing patient data to recommend optimal implant positions, sizes, and drilling protocols. Robotic systems are likely to become more compact and affordable, potentially combining static and dynamic guidance in hybrid workflows. Ultimately, the convergence of AI, robotics, regenerative medicine, and nanotechnology may usher in an era of fully automated, personalized implant therapy.

Therefore, the integration of digital planning and guided surgery translates into greater predictability, fewer complications, and improved long-term success rates. However, reliance on technology should not replace clinical judgment. Digital tools must be viewed as adjuncts that enhance, rather than substitute, surgical expertise. Rigorous training, continuous calibration of equipment, and adherence to evidence-based protocols remain paramount. The best outcomes are achieved when technology and surgical skill are harmonized within a prosthetically driven treatment philosophy.[176]

SUMMARY

Dental implantology has evolved into one of the most advanced and predictable treatment modalities for replacing missing teeth, offering superior stability, aesthetics, and long-term success compared to traditional prosthetic options. The integration of digital technologies has marked a shift in implant dentistry, giving rise to digital implant planning and guided implant surgery (GIS). These innovations have enhanced accuracy, safety, efficiency, and patient satisfaction by transforming both the diagnostic and surgical phases of treatment.[176]

Historically, implant placement relied on two-dimensional radiographs, study casts, and operator experience. While effective, these methods lacked precision in visualizing three-dimensional anatomy, often resulting in compromised prosthetic outcomes and increased risk of damaging critical structures. The introduction of computed tomography (CT) and later cone-beam computed tomography (CBCT) revolutionized imaging by providing high-resolution 3D visualization of bone and anatomical landmarks. This paved the way for computer-assisted implant surgery (CAIS), enabling implants to be placed at preplanned positions with unprecedented accuracy.[32]

At the core of digital workflows lies the integration of DICOM files from CBCT scans and STL files from intraoral or extraoral scans. This fusion allows to visualize both internal bone structures and external soft tissue contours, ensuring prosthetically driven planning. Virtual implant placement is simulated using various softwares followed by the design and fabrication of surgical guides using CAD/CAM or 3D printing. These guides—whether tooth-, mucosa-, or bone-supported—translate the virtual plan into the clinical environment with high fidelity.

Intraoral scanners (IOS) have replaced conventional impressions, providing rapid, accurate, and patient-friendly digital models that integrate seamlessly with planning software. Extraoral scanners complement this by digitizing models, prostheses, or wax-ups, particularly useful in edentulous or laboratory-based workflows. Together, these technologies form the foundation of prosthetically driven implantology, ensuring implants are positioned to support the planned restoration rather than adapting the prosthesis to the implant.[32]

Computer-Assisted Designing (CAD) plays a pivotal role by enabling 3D visualization, virtual wax-ups, prosthetic simulations, and surgical guide design. In tandem, Computer-Assisted Manufacturing (CAM) techniques—either subtractive (milling) or additive (3D printing)—produce surgical templates, abutments, and frameworks with high precision. Materials such as PMMA, PEEK, zirconia, and cobalt-chromium are used depending on clinical requirements. 3D printing technologies like stereolithography (SLA) and digital light processing (DLP) allow rapid fabrication of accurate, sterilizable guides that streamline surgical execution.[113,114]

Clinical accuracy in guided implantology is supported by specialized drilling systems, consisting of pilot drills, sequential drills, sleeves, drill keys, and depth-control mechanisms. These components ensure that the osteotomy precisely reflects the virtual plan, minimizing deviation and preserving critical anatomical structures. However, challenges remain, including limited irrigation during guided drilling, static guides lacking intraoperative flexibility, potential errors during data merging, and the financial burden of acquiring digital systems.[41]

Despite these limitations, the benefits of digital workflows are substantial:[2]

- High placement accuracy with reduced risk of complications
- Minimally invasive surgeries, often flapless, that reduce morbidity and recovery time
- Improved prosthetic outcomes through restoration-driven planning
- Enhanced patient communication via visual simulations
- Efficient interdisciplinary collaboration among surgeons, prosthodontists, and technicians

Looking forward, the future of implant dentistry will be shaped by artificial intelligence (AI), robotics, augmented reality (AR), and nanotechnology. Dynamic navigation systems and robotic-assisted surgery promise even greater precision and intraoperative adaptability. AI-driven planning algorithms may further optimize implant positioning, while smart surgical guides with embedded sensors could provide real-time feedback during procedures.[41,127]

In conclusion, digital implant planning and guided implant surgery have revolutionized implant dentistry by bridging the gap between prosthetic goals and surgical execution. They represent a patient-centered, prosthetically driven approach that enhances accuracy, efficiency, and long-term success. As emerging technologies continue to integrate with clinical workflows, implantology is poised to enter an era of even greater precision, predictability, and personalization

CONCLUSION

Digital implant planning and guided implant surgery represent one of the most significant shifts in modern implantology. By moving away from the limitations of freehand surgery and two-dimensional imaging, dentistry has entered an era where technology enables clinicians to achieve unparalleled accuracy, safety, and predictability.[33] Through the integration of cone-beam computed tomography (CBCT), surface scans (STL), and computer-aided design/manufacturing (CAD/CAM), clinicians are now equipped to virtually plan, simulate, and precisely execute implant placement with a prosthetically driven approach. This not only minimizes the risks associated with surgical inaccuracies but also ensures that the restorative outcome aligns seamlessly with functional and aesthetic demands.[177]

The introduction of surgical guides—whether tooth-, mucosa-, or bone-supported—has further enhanced clinical outcomes, especially in anatomically challenging or fully edentulous cases. The use of guided drilling systems, incorporating pilot drills, sequential drills, sleeves, and depth-control mechanisms, has enabled clinicians to replicate the digital plan with high fidelity in the operative field. Such integration reduces angular and linear deviations, safeguards vital anatomical structures, and allows for minimally invasive protocols such as flapless surgery, which improves patient comfort and reduces postoperative morbidity.[107,108]

Equally transformative has been the impact of digital workflows on patient communication and treatment acceptance. The ability to present patients with virtual simulations and prosthetic previews fosters transparency and trust, while the reduced surgical invasiveness translates into faster healing and higher satisfaction.[33] Moreover, interdisciplinary collaboration between surgeons, prosthodontists, and dental technicians has been strengthened by the common digital platform, allowing for seamless communication and coordinated treatment execution.

Nevertheless, the digital approach is not without limitations. Static guides, while accurate, lack intraoperative flexibility and may require abandonment if unforeseen conditions arise. Accuracy may also be compromised by errors in imaging, data merging, or guide fabrication. Restricted irrigation during guided drilling raises concerns about thermal injury, and the cost of acquiring and maintaining digital systems remains a barrier in many settings. Furthermore, clinicians must undergo rigorous training to fully harness these technologies, emphasizing that digital tools are aids rather than replacements for surgical expertise.[33]

Despite these challenges, the overall trajectory of implant dentistry is clear: digital systems are no longer adjuncts but have become integral to evidence-based clinical practice. The ongoing refinement of dynamic navigation systems, robotic-assisted implant placement, and AI-driven planning algorithms promises even greater precision and adaptability.[22] Emerging innovations such as smart surgical guides, biocompatible 3D-printing materials, and sensor-equipped implants hint at a future where diagnostics, planning, and execution are fully integrated and highly individualized. As technology continues to advance, the future holds exciting possibilities for further enhancing implant planning and rehabilitation, paving the way for improved patient care in implantology.[33]

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