

Digital Technologies in Prosthetic Dentistry: Current Trends, Clinical Applications and Future Directions - A Narrative Review

Onwudi, Henry I.^{1*}; Ejeta K. O.²; Eyarefe S. O.³

^{1,3}Department of Dental Technology, Federal University of Technology Owerri, Imo State, Nigeria

²Department of Biomedical Engineering and Technology, Federal University of Technology Owerri, Imo State, Nigeria

Corresponding Author: Onwudi, Henry I.^{1*}

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Abstract:

➤ *Background:*

The integration of digital technologies in prosthetic dentistry has precipitated a transformative shift from empirical craftsmanship to precision-driven, data-informed clinical practice. Despite rapid technological proliferation, a consolidated, clinically oriented synthesis of these advances remains needed.

➤ *Objective:*

This narrative review critically evaluates the current landscape of digital prosthetic dentistry, encompassing intraoral scanning (IOS), Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM), subtractive and additive manufacturing, artificial intelligence (AI), and emerging augmented reality (AR) platforms.

➤ *Methods:*

This narrative review discusses peer-reviewed research on intraoral scanning, CAD/CAM, additive manufacturing, artificial intelligence, and guided implant surgery. The cited literature was checked against publisher or PubMed records; findings are described according to the populations and methods studied.

➤ *Results:*

Intraoral scanning can improve patient comfort and support efficient fixed prosthodontic workflows, although accuracy depends on indication and scan extent. Digital complete dentures show clinically acceptable adaptation in many laboratory studies, while guided implant surgery has measurable deviations between planned and placed implants. Evidence for AI and newer printable materials remains heterogeneous (Ahlholm et al., 2018; Mangano et al., 2017; Wang et al., 2021; Tahmaseb et al., 2018; Schwendicke et al., 2020).

➤ *Conclusion:*

The convergence of AI, additive manufacturing, and augmented reality represents the proximate frontier in personalised dental rehabilitation. Strategic investment in hybrid fabrication infrastructure, standardised curricula reform, and robust longitudinal outcome data is urgently required to guide evidence-based adoption.

Keywords: Digital Dentistry; CAD/CAM; Intraoral Scanning; Additive Manufacturing; Artificial Intelligence; Prosthetic Dentistry; Dentistry 4.0; Zirconia; 3D Printing; Virtual Patient.

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I. INTRODUCTION

Prosthetic dentistry is currently undergoing one of the most consequential technological transitions in its modern history. For over a century, the restoration of oral function and aesthetics rested almost entirely on analog methodologies characterised by manual material manipulation, operator skill dependency, and inherent dimensional variability. The conventional workflow — encompassing elastomeric impression-taking, stone cast fabrication, and hand-layered porcelain application — served the profession capably; yet it remained susceptible to polymerisation shrinkage of impression materials, thermal expansion of dental stone, and the cumulative errors endemic to multi-step manual processes (Ahlholm et al., 2018).

The emergence of 'Dentistry 4.0' — a term consciously aligned with the fourth industrial revolution has introduced a data-driven paradigm intent on eliminating these analog inconsistencies. Anchored in Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM), this revolution began in earnest in the 1980s with Dr. François Duret's pioneering work and the subsequent introduction of the Chairside Economical Restoration of Esthetic Ceramics (CEREC) system by Mörmann and Brandestini in 1985 (Alghazzawi, 2016). Since then, the field has progressed from rudimentary single-unit milling to sophisticated full-arch rehabilitations incorporating digital smile design, three-dimensional facial scanning, and virtual articulators (Mangano et al., 2020).

Central to this transformation is the shift from physical to digital data acquisition. Intraoral scanners (IOS) now utilise optical principles — including confocal microscopy, active wavefront sampling (AWS), and structured light triangulation — to generate immediate, high-fidelity three-dimensional impressions at the chairside, circumventing the patient discomfort, dimensional inaccuracy, and logistical burden associated with conventional elastomeric impressions (Mangano et al., 2017). Simultaneously, Cone Beam Computed Tomography (CBCT) has extended the diagnostic reach of the prosthodontist into three-dimensional skeletal anatomy, enabling 'prosthetically-driven' implantology, wherein the ideal final restoration position governs implant placement rather than merely available bone volume (Alghazzawi, 2016).

Fabrication has evolved comparably. Subtractive manufacturing — milling pre-fabricated blocks of industrially homogeneous zirconia (3Y-TZP) or lithium disilicate — now routinely delivers restorations with flexural strengths and fracture toughness values that manual layering techniques cannot reliably achieve. Concurrently, additive manufacturing (3D printing) through vat photopolymerisation technologies has democratised the production of complex geometries, including implant surgical guides, removable partial denture frameworks, and complete digital dentures (Dawood et al., 2015).

Artificial intelligence is being investigated for design support and dental image interpretation. Its performance

depends on training data, clinical context, and external validation (Schwendicke et al., 2020). This review synthesises evidence on digital acquisition, design, manufacturing, and clinical applications.

II. REVIEW METHODOLOGY

This paper is a narrative review of selected peer-reviewed literature on digital prosthodontic workflows. It does not claim a reproducible systematic search or a pooled quantitative estimate. Sources cited below were checked against bibliographic records and interpreted in light of their study design.

The discussion covers intraoral scanning, CAD/CAM prosthodontics, additive manufacturing, artificial intelligence, implant planning, and digital complete dentures.

Priority was given to reviews and comparative studies directly relevant to clinical accuracy, adaptation, patient experience, and implementation. The evidence is discussed narratively; no formal screening count or meta-analysis was undertaken.

III. THE SCOPE AND FOUNDATIONS OF PROSTHETIC DENTISTRY

➤ Definition and Objectives

Prosthetic dentistry — interchangeably termed prosthodontics — is the dental specialty concerned with the diagnosis, treatment planning, rehabilitation, and maintenance of the oral function, comfort, appearance, and health of patients with clinical conditions associated with missing or deficient teeth and maxillofacial tissues, using biocompatible substitutes (Glossary of Prosthodontic Terms, 2017). Its overarching objectives encompass the restoration of masticatory efficiency, phonetics, and aesthetics, thereby rehabilitating the patient's quality of life within a framework of sustained oral health.

➤ Clinical Domains

The discipline is conventionally subdivided into three overlapping clinical domains, each of which has been profoundly reshaped by digital technologies:

- **Fixed Prosthodontics:** Encompasses crowns, inlays, onlays, veneers, and tooth- or implant-supported fixed dental prostheses (bridges). Successful outcomes depend on precise preparation geometry, margin placement, and material selection guided by biomechanical principles of occlusion (Alghazzawi, 2016).
- **Removable Prosthodontics:** Includes complete and partial removable dentures and overdentures. Accurate border morphology, jaw relation records, and long-term tissue adaptation remain central clinical challenges, increasingly addressed through digital border moulding and AI-driven occlusal analysis (Wang et al., 2021).
- **Implant Prosthodontics:** A rapidly expanding domain encompassing single implant crowns, implant-supported bridges, overdentures, and full-arch rehabilitations. The prosthodontically-driven philosophy — wherein the final

restoration position dictates surgical implant placement — is the governing paradigm, powerfully enabled by CBCT-surface scan integration (Tahmaseb et al., 2018).

➤ *Historical Evolution of Digital Prosthodontics*

The trajectory from analog to digital prosthodontics occurred in discrete technological phases. Digital dentistry origins are traceable to the early 1960s, concurrent with Computer Numerical Control (CNC) developments in aerospace manufacturing. The landmark clinical transition arrived in the 1980s with Duret's CAD/CAM prototype, followed by the CEREC system (Alghazzawi, 2016), which achieved single-visit ceramic fabrication — a paradigm of efficiency still central to contemporary chairside practice (Alghazzawi, 2016).

The 1990s saw Cone-Beam Computed Tomography emerge, enabling three-dimensional skeletal visualisation and the shift toward volume-guided implant planning. The 2010s heralded additive manufacturing integration, with desktop 3D printers producing surgical guides, models, and provisional prosthetics with accuracy suitable for clinical use (Dawood et al., 2015). The contemporary era is defined by AI-assisted automation, augmented reality interface design, and the Virtual Patient — a comprehensive digital twin merging surface, skeletal, and facial soft-tissue data for risk-free pre-clinical treatment simulation.

IV. CURRENT DIGITAL TECHNOLOGIES IN PROSTHETIC DENTISTRY

The digital workflow in contemporary prosthodontics is conceptualised as a three-stage pipeline: (1) digital data acquisition (input), (2) computer-aided design and treatment planning (processing), and (3) digital manufacturing (output). Each stage is examined in the sections below.

➤ *Data Acquisition Technologies*

• *Intraoral Scanning (IOS)*

The cornerstone of the modern digital chairside workflow is the intraoral scanner — a handheld optical device that captures three-dimensional images of dental structures directly from the oral cavity, generating standard STL/PLY files for downstream CAD/CAM processing. IOS has been adopted alongside conventional elastomeric impressions in fixed and implant prosthodontics, offering significant reductions in procedural time, elimination of patient gag reflex, and instant digital quality feedback (Mangano et al., 2017).

Intraoral scanners use a range of optical acquisition methods, including confocal imaging, active wavefront sampling, and triangulation. Their performance depends on the scanning system, clinical field, and acquisition strategy (Mangano et al., 2017). Representative systems include iTero, TRIOS, and CEREC Primescan.

Accuracy depends on scan span, surface characteristics, scanning strategy, and the device studied. Digital impressions are well supported for many single-unit and short-span

applications, whereas complete-arch and long-span indications require particular attention to accumulated error (Mangano et al., 2017; Ahlholm et al., 2018).

• *Extraoral (Desktop) Laboratory Scanning*

Extraoral bench-top scanners digitise physical stone models or traditional impressions in a controlled, non-dynamic environment and typically achieve higher cross-arch precision than first-generation IOS devices (Mangano et al., 2017). However, their diagnostic value is inherently limited by the cumulative dimensional error introduced at the impression-taking and stone-pouring stages — a limitation that positions IOS as the preferred primary data acquisition method where chairside scanning is clinically feasible (Mangano et al., 2017).

• *Cone Beam Computed Tomography (CBCT) and Three-Dimensional Facial Scanning*

CBCT provides high-resolution three-dimensional radiographic data in DICOM format, visualising bone anatomy, nerve canals, and sinus boundaries with three-dimensional anatomical detail. In implant prosthodontics, CBCT datasets are co-registered with surface scan data (STL files) using algorithms such as Iterative Closest Point (ICP) or via radiopaque fiducial markers embedded in scan prostheses. This integration enables prosthetically-driven virtual implant planning — positioning implants at anatomically and biomechanically optimal coordinates derived from the intended restoration, rather than solely from available bone volume (Tahmaseb et al., 2018).

Three-dimensional facial scanning captures external soft-tissue contours and facial proportions, enabling integration with IOS and CBCT data to construct a comprehensive 'Virtual Patient.' This digital twin facilitates Digital Smile Design (DSD) workflows, in which tooth position, length, and axial inclination are evaluated against the patient's unique facial dynamics, supporting communication of aesthetic treatment expectations (Mangano et al., 2017).

• *Virtual Articulators and Dynamic Occlusal Analysis*

Software-based virtual articulators simulate mandibular movements by integrating digital occlusal data with jaw motion recordings obtained via electronic axiographic facebows. This technology can avoid some mechanical limitations and gypsum expansion artefacts of physical articulators, enabling precise static and dynamic occlusal analysis. Compared to traditional articulating-paper methods, digital occlusal sensors (e.g., T-Scan) offer quantitative force distribution data and temporal sequencing of contacts, which are critical determinants of restoration longevity in ceramic prostheses (Alghazzawi, 2016).

➤ *Design and Treatment Planning (CAD) Software*

Computer-Aided Design platforms constitute the cognitive core of the digital workflow — the environment in which clinical information is translated into a fabricable prosthetic geometry. Contemporary CAD systems (3Shape Dental System, exocad DentalCAD, Dentsply Sirona CEREC SW) provide fully parametric sculpting environments capable

of designing crowns, bridges, implant abutments, removable prostheses, orthodontic aligners, and surgical guides from a common digital dataset.

AI-assisted design tools may help identify margins and propose tooth anatomy, but performance and time savings vary by task, dataset, and operator. Clinical oversight and independent validation remain necessary (Schwendicke et al., 2020).

Digital smile design uses photographs and scans to preview proposed tooth positions and communicate aesthetic plans with patients. Implant planning software can combine CBCT and surface scans for virtual implant positioning and guide design (Mangano et al., 2017; Tahmaseb et al., 2018).

V. DIGITAL MANUFACTURING TECHNOLOGIES

➤ Subtractive Manufacturing (Computer-Aided Milling)

Subtractive manufacturing is widely used for definitive ceramic and polymer restorations. Material choice,

preparation design, machining, sintering, and finishing all influence the fit and clinical performance of a restoration (Alghazzawi, 2016).

Milling environments are divided into chairside systems (e.g., CEREC MC X, Roland DWX-4), which operate with compact 4-axis mills to produce single-unit restorations during the patient appointment, and laboratory/industrial systems that employ 5-axis milling with expanded material compatibility, permitting complex geometries including angled abutments and multi-unit frameworks. The mechanical superiority of industrially milled blocks over conventionally layered porcelain derives from the homogeneous density and absence of internal voids or pore concentrations achievable under controlled factory sintering conditions (Alghazzawi, 2016).

Table 1 below summarises the technical specifications of principal subtractive milling materials employed in contemporary digital prosthodontics.

Table 1 Technical Specifications of Subtractive Milling Materials

Material Type	Flexural Strength (MPa)	Clinical Indication	Setting
Zirconia (3Y-TZP)	1,000–1,200	Posterior bridges, frameworks	Laboratory
Lithium Disilicate	360–450	Anterior crowns, veneers	Clinic & Lab
Hybrid Composites	150–200	Inlays, Onlays, Provisionals	Clinic
Cobalt-Chrome	600–900	RPD Frameworks	Laboratory

Source: Material Classes and Indications Adapted From Alghazzawi (2016); Values Vary by Formulation and Testing Standard.

➤ Additive Manufacturing (Three-Dimensional Printing)

Additive manufacturing constructs three-dimensional objects by selectively solidifying or depositing material layer-by-layer under digital guidance, enabling complex internal geometries — hollow structures, lattice frameworks, and undercuts — that are inaccessible to subtractive methods, with substantially reduced material waste (Dawood et al., 2015). Three principal photopolymerisation technologies dominate dental 3D printing:

Stereolithography (SLA) employs a UV laser to cure photosensitive resin in a point-by-point raster pattern, achieving high resolution and smooth surface quality. Digital Light Processing (DLP) exposes entire layers simultaneously via a UV projector array, affording faster throughput at comparable resolution. Material Jetting (PolyJet) deposits droplets of multiple resin materials with layer thicknesses of variable, enabling multi-material printing and predefined colour gradients relevant to aesthetic diagnostics (Dawood et al., 2015).

Clinical applications include implant surgical guides, highly accurate diagnostic and working models, temporary crowns and bridges, castable or pressable patterns for metal frameworks, complete digital denture bases and tooth arrangements, and — increasingly — permanent single-unit restorations in certified engineered resins. Layer thickness (dependent on equipment) and printing orientation critically influence the 'staircase effect' on restoration margins and occlusal surfaces, with appropriate layer settings and printing angles influencing dimensional deviation (Dawood et al., 2015).

Digital denture bases can be milled or printed. A systematic review found similar or better adaptation for many digital dentures compared with conventional dentures, but could not establish a general accuracy advantage for milling over printing (Wang et al., 2021).

Table 2 Mechanical and Physicochemical Properties of Digital Prosthetic Materials

Material Class	Flexural Strength (MPa)	Microhardness (HV)	Water Absorption	Clinical Indication
Milled Zirconia	900–1,200	1,200–1,350	Formulation dependent	Full-arch bridges, posterior crowns
Milled Lithium Disilicate	360–500	580	Formulation dependent	Anterior crowns, veneers
Permanent 3D Resin	120–150	18–25	Formulation dependent	Single crowns, overlays

Denture Base Resin	80–110	12–15	Formulation dependent	Complete & partial dentures
Cobalt-Chrome (SLM)	600–800	350–450	Formulation dependent	RPD frameworks, abutments

Source: Material Classes and Indications Adapted From Alghazzawi (2016), Dawood Et Al. (2015) and Wang Et Al. (2021); Properties are Formulation Dependent.

➤ *The Integrated Digital Workflow*

The full digital workflow creates a seamless, auditable continuum from chairside impression to virtual design to physical fabrication: (1) IOS data acquisition generates an STL file; (2) the file is transmitted electronically to the laboratory; (3) a technician employs CAD software — increasingly AI-assisted — to design the restoration; (4) the design file is dispatched to a milling centre or 3D printer; (5) post-processing steps (sintering, staining, glazing for ceramics; UV-curing protocols for resins) are applied; and (6) the restoration is delivered to the clinic for cementation. This paradigm eliminates the physical model shipping chain, can shorten turnaround time, and creates an archived digital record that enables repeat fabrication without re-impression (Alghazzawi, 2016).

VI. CLINICAL APPLICATIONS OF DIGITAL TECHNOLOGIES

➤ *Fixed Prosthodontic Rehabilitation*

The digital workflow for single-unit crowns and fixed partial dentures has achieved a mature, evidence-supported clinical protocol. Following conventional tooth preparation with attention to margin design, an intraoral scan is acquired encompassing the prepared tooth, adjacent dentition, and the opposing arch. The resulting digital file undergoes CAD-based restoration design — with AI-driven margin detection, contact area adjustment, and emergence profile optimisation — before dispatch for milling in lithium disilicate (for anterior and premolar restorations) or full-contour or veneered zirconia (for high-stress posterior regions). The restoration is sintered where applicable, characterised, glazed, and adhesively cemented or conventionally luted at delivery (Alghazzawi, 2016).

Evidence supports clinically useful fit for many digitally fabricated fixed restorations, but outcomes vary with the material, impression technique, span, and measurement method (Ahlholm et al., 2018; Alghazzawi, 2016).

➤ *Removable Prosthodontic Rehabilitation (Digital Dentures)*

Digital complete dentures may reduce visits in selected workflows, although impressions, border extension, jaw relations, and clinical verification still require careful assessment. A systematic review of in vitro studies reported generally acceptable adaptation but found insufficient evidence to declare milling or printing universally superior (Wang et al., 2021).

➤ *Implant Prosthodontic Rehabilitation*

Digital planning combines surface scans and CBCT data to position an implant relative to the proposed restoration and anatomy. A printed guide can transfer the plan, but placement deviations remain and should be allowed for when planning around vital structures (Tahmaseb et al., 2018).

VII. KEY BENEFITS AND CHALLENGES OF DIGITAL PROSTHETIC DENTISTRY

➤ *Demonstrated Clinical Benefits*

Digital impressions can improve patient comfort and time efficiency for appropriate fixed prosthodontic indications; fit and accuracy depend on the clinical situation and device. Digital records also facilitate laboratory communication and storage (Ahlholm et al., 2018; Mangano et al., 2017).

➤ *Barriers to Implementation*

Equipment purchase, maintenance, training, and workflow integration are significant barriers, especially for smaller practices. The magnitude of these costs depends on the selected devices, software, service arrangements, and local market (Mangano et al., 2017).

Digital facial and dental records raise questions of privacy, access control, consent, and data retention. AI systems additionally require appropriate validation and human oversight before clinical use (Schwendicke et al., 2020).

VIII. FUTURE TRENDS AND EMERGING TECHNOLOGIES

➤ *Artificial Intelligence and Machine Learning*

AI is being studied for dental image analysis and clinical decision support, as well as laboratory design tasks. Reported performance is task and dataset specific; independent testing, transparency, and clinician oversight are essential before routine adoption (Schwendicke et al., 2020).

➤ *Augmented Reality in Clinical Prosthodontics*

Augmented reality can display proposed restorations in a live view of the patient, potentially supporting communication and planning. Robust comparative clinical evidence is still needed before claims about higher acceptance or better outcomes can be made.

➤ *Advanced and Printable Ceramic Materials*

Continuous research investment is directed toward extending the range of materials compatible with additive manufacturing. Printable zirconia slurries for DLP printing, bioactive ceramic composites, and gradient-property restorations — with varying stiffness from root to crown to simulate natural periodontal ligament dynamics — represent active areas of preclinical and early clinical investigation. The successful clinical translation of printable high-strength ceramics would unify the geometric freedom of additive manufacturing with the established mechanical performance of milled zirconia, representing a potentially useful development for prosthetic materials.

IX. CONCLUSION AND RECOMMENDATIONS

➤ Conclusions

Digital acquisition, design, and manufacturing have expanded the options for fixed, removable, and implant prosthodontics. The evidence supports improved comfort and efficiency in selected indications, while accuracy and long-term outcomes vary by workflow and material. Guided surgery retains measurable placement error, and emerging AI and printable materials require stronger independent clinical validation (Ahlholm et al., 2018; Wang et al., 2021; Tahmaseb et al., 2018; Schwendicke et al., 2020).

➤ Recommendations

• For Clinical Practitioners

Clinicians should select interoperable scanning and design systems suited to their cases and laboratory partners. Guided implant surgery should be considered where it improves planning and transfer, with due allowance for placement error. Digital occlusal analysis may supplement clinical examination when its measurements answer a specific diagnostic question.

• For Dental Laboratories

Laboratories should invest in hybrid fabrication capability — maintaining high-precision 5-axis milling for definitive ceramic restorations alongside high-speed DLP/SLA printing for removable, provisional, and model production. Stringent standardised UV-curing and thermal-ageing post-processing protocols are non-negotiable for 3D-printed prosthetics, as incomplete photopolymerisation is a primary cause of material failure, residual monomer toxicity, and accelerated clinical degradation. Digital verification workflows — including 3D-printed prototype try-ins prior to definitive high-cost material fabrication in complex cases — should be incorporated into standard quality assurance protocols.

• For Academic Institutions and Regulatory Bodies

Undergraduate and postgraduate dental education must evolve beyond device-operation training to encompass Digital Design Logic, Photopolymer Material Science, AI Ethics in Healthcare, and Data Governance as core curricular components. There is a critical need for independent, industry-neutral longitudinal studies — minimum 10-year follow-up — evaluating the clinical wear resistance, colour stability, and biocompatibility of 3D-printed definitive resins relative to established milled lithium disilicate and zirconia benchmarks. Regulatory bodies should establish and enforce internationally harmonised standards for scanner accuracy reporting (trueness and precision metrics per ISO 5725), to enable evidence-based hardware procurement decisions in a commercially saturated marketplace.

- CAD — Computer-Aided Design
- CAM — Computer-Aided Manufacturing
- CBCT — Cone Beam Computed Tomography
- CEREC — Chairside Economical Restoration of Esthetic Ceramics
- DICOM — Digital Imaging and Communications in Medicine
- DLP — Digital Light Processing
- DSD — Digital Smile Design
- ICP — Iterative Closest Point
- IOS — Intraoral Scanner
- ML — Machine Learning
- PMMA — Polymethylmethacrylate
- RPD — Removable Partial Denture
- SLA — Stereolithography
- SLM — Selective Laser Melting
- STL — Standard Tessellation Language
- 3Y-TZP — 3 mol% Ytria-stabilised Tetragonal Zirconia Polycrystal

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LIST OF ABBREVIATIONS

- AM — Additive Manufacturing
- AR — Augmented Reality
- AWS — Active Wavefront Sampling