Accuracy in Digital Dentistry: A Complete Literature Review

Abstract

The transition from conventional to digital workflows has fundamentally transformed restorative dentistry, prosthodontics, implant dentistry, and oral rehabilitation. Digital dentistry now includes intraoral scanning, computer-aided design/computer-aided manufacturing, additive manufacturing, guided implant surgery, dynamic navigation, robotic implant placement, photogrammetry, and artificial intelligence-assisted image processing. Among these technologies, accuracy remains the principal determinant of clinical reliability because errors in data acquisition, virtual planning, prosthesis fabrication, or surgical transfer may result in marginal discrepancy, prosthetic misfit, occlusal error, biological complications, or compromised esthetic outcomes.

This literature review evaluates the accuracy of digital dentistry across intraoral scanning systems, digital versus conventional impression techniques, CAD/CAM fabrication, guided implant surgery, and photogrammetry. According to ISO 5725, accuracy includes both trueness, defined as closeness to the true value, and precision, defined as repeatability among measurements. In dental research, these parameters are commonly assessed using three-dimensional surface superimposition, root mean square deviation, linear deviation, angular deviation, and marginal or internal gap analysis.

Current evidence indicates that contemporary intraoral scanners achieve clinically acceptable accuracy for single-unit and short-span restorations, with trueness values commonly ranging from approximately 15–50 μm. However, accuracy decreases in full-arch, edentulous, and multi-implant situations because of cumulative stitching errors, lack of anatomical landmarks, implant angulation, scan body geometry, saliva, lighting, operator experience, and software-related factors. Digital and conventional impressions demonstrate comparable accuracy for single crowns, short-span fixed partial dentures, and partially dentate implant restorations, whereas conventional or hybrid techniques may remain preferable for some complete-arch prostheses. For full-arch implant-supported prostheses, photogrammetry has emerged as one of the most accurate methods for implant position capture. Computer-assisted implant surgery significantly improves implant placement accuracy compared with freehand placement, although deviations of approximately 1 mm and 2–4° may still occur.

Overall, digital dentistry has achieved clinically acceptable accuracy for many routine and advanced indications. Nevertheless, accuracy depends on proper case selection, scanner technology, calibration, scanning strategy, operator training, environmental control, software validation, manufacturing protocol, and workflow integration. Future developments in artificial intelligence, advanced optics, photogrammetry, structured light scanning, and robotic surgery are expected to further improve the reliability of digital

dental workflows.

Keywords: digital dentistry; intraoral scanning; accuracy; trueness; precision; CAD/CAM; guided implant surgery; photogrammetry; conventional impressions; implant prosthodontics.

Keywords

1. Digital dentistry
2. Intraoral scanning
3. Trueness
4. Precision
5. CAD/CAM
6. Additive manufacturing
7. Guided implant surgery
8. Photogrammetry
9. Conventional impressions
10. Implant prosthodontics
11. Full-arch rehabilitation
12. Marginal adaptation
13. Passive fit
14. Computer-assisted implant surgery
15. Three-dimensional printing
16. Artificial intelligence

1. Introduction and Methodology

Digital dentistry has undergone substantial development over the past two decades. Initially introduced for chairside single-unit restorations, digital workflows now extend to fixed prosthodontics, implant rehabilitation, removable prosthodontics, orthodontics, maxillofacial prosthetics, surgical guide fabrication, and complete-arch rehabilitation. The clinical value of digital dentistry lies not only in convenience but also in its potential to improve reproducibility, patient comfort, communication between clinicians and laboratories, treatment efficiency, and standardization of complex restorative procedures.

Accuracy is the central requirement for any digital dental workflow. According to ISO 5725, accuracy is composed of two related but distinct concepts: trueness and precision. Trueness refers to the closeness of agreement between the mean of repeated measurements and a true or reference value, whereas precision refers to the closeness of agreement among repeated measurements under the same conditions. In dentistry, a system may be precise but not true if it consistently reproduces the same incorrect geometry, or true but not precise if repeated scans vary widely around the correct value. Both parameters are clinically important. Poor trueness may produce systematic prosthetic misfit, while poor precision may lead to unpredictable outcomes.

In digital dentistry research, accuracy is commonly evaluated through three-dimensional surface superimposition against a reference model, root mean square deviation, mean absolute deviation, best-fit alignment analysis, coordinate-measuring machine data, marginal and internal gap measurements, or angular and linear deviation analysis. For implant placement, accuracy is typically assessed by comparing the planned implant position with the actual postoperative position using cone-beam computed tomography data. Common parameters include coronal deviation, apical deviation, vertical deviation, and angular deviation.

This review synthesizes evidence from systematic reviews, meta-analyses, randomized clinical trials, prospective studies, and high-quality in vitro investigations published mainly between 2018 and 2026. The review focuses on five major areas: intraoral scanning systems, digital versus conventional impressions, CAD/CAM fabrication accuracy, computer-assisted implant surgery, and photogrammetry for full-arch implant rehabilitation.

2. Accuracy of Intraoral Scanning Systems

2.1 Trueness and Precision of Current IOS Technologies

Intraoral scanners have become a central component of digital dentistry. They eliminate many disadvantages of conventional impressions, including patient discomfort, gag reflex, material distortion, tray deformation, disinfection challenges, model storage requirements, and delays in laboratory communication. Modern intraoral scanners use optical triangulation, confocal microscopy, active wavefront sampling, structured light, video scanning, or hybrid imaging technologies to acquire intraoral geometry.

Contemporary intraoral scanners, including systems such as TRIOS, Primescan, Medit i700, and iTero Element, generally demonstrate excellent accuracy for single-unit and short-span restorations. In limited-span applications, reported trueness values commonly range from approximately 15–50 μm, while precision values may range from approximately 10–30 μm under controlled conditions.[1–3] These values are generally compatible with the clinical requirements of single crowns, inlays, onlays, veneers, and short-span fixed partial dentures.

Full-arch scanning is more challenging. In complete-arch dentate scans, trueness values may increase to approximately 30–150 μm, with precision deteriorating further depending on scanner type, operator experience, scanning strategy, software version, arch shape, and clinical environment.[3–6] A major reason for this reduction in accuracy is cumulative stitching error. Intraoral scanners acquire sequential overlapping images or video frames and reconstruct them into a continuous three-dimensional model. Small alignment errors between sequential images may accumulate as the scan progresses across the arch.

Edentulous arches and complete-arch implant scans present additional challenges. In edentulous arches, the absence of teeth reduces the number of anatomical landmarks available for software stitching. In implant cases, scan bodies may have reflective surfaces, simplified geometry, and limited distinctive features. Implant angulation, inter-implant distance, scan body design, mucosal mobility, and arch curvature may further influence the accuracy of the final scan.[5,6,16]

Mangano et al.[5] reported wide variability in full-arch digital implant impression accuracy, with trueness values ranging from 7.6 to 731.7 μm and precision values ranging from 15.2 to 204.2 μm. This wide range reflects differences in scanner technology, scanning protocol, clinical scenario, scan body geometry, and evaluation methodology. Network meta-analytic evidence also indicates that dentate arches generally demonstrate superior scanning accuracy compared with edentulous arches and implant-supported complete-arch situations.[6]

2.2 Factors Influencing IOS Accuracy

2.2.1 Operator Experience and Learning Curve

Operator experience significantly affects intraoral scanning accuracy. Unlike conventional impressions, where errors are often related to tray selection, impression material properties, and pouring procedures, intraoral scanning requires active control of scanning distance, angulation, speed, field dryness, scan path, tissue management, and software feedback. Novice users are more likely to lose tracking, rescan areas inconsistently, or generate stitching discrepancies. Experienced operators generally produce more accurate and reproducible scans.[10,11]

The learning curve for intraoral scanning appears to stabilize after approximately 20–30 scans, although this may vary depending on scanner model and clinical complexity.[10,11] Full-arch and implant scans require more advanced operator training than single-unit scans because they involve fewer anatomical landmarks and are more vulnerable to cumulative stitching errors.

2.2.2 Scanning Strategy

Scanning strategy is a key determinant of accuracy. Effective scanning protocols maintain adequate overlap between sequential images, minimize unnecessary rescanning, and avoid abrupt changes in direction. S-shaped scanning patterns, systematic occlusal-buccal-lingual pathways, and the use of artificial landmarks have been shown to improve scanning accuracy, especially in full-arch and edentulous situations.[12]

For tooth-supported restorations, a predictable scan usually begins with the occlusal surface, followed by buccal and lingual or palatal surfaces. For prepared teeth, the finish line must be clearly visible and free from saliva, blood, or gingival tissue obstruction. Digital impressions do not compensate for inadequate tooth preparation, poor isolation, subgingival bleeding, or insufficient retraction.

2.2.3 Calibration and Maintenance

Scanner calibration helps ensure that optical components remain within manufacturer-defined tolerances. Although some newer intraoral scanners are designed to require less frequent calibration, routine maintenance remains clinically advisable. Kanmaz et al.[13] found that prolonged absence of calibration in a TRIOS 3 scanner produced only minor numerical differences that were not statistically significant; however, routine calibration remains recommended as a quality-control procedure, especially for complex prosthodontic and implant cases.

Scanner tips should also be inspected regularly for scratches, fogging, contamination, and sterilization-related degradation. Software updates, hardware maintenance, scanner-tip replacement, and adherence to manufacturer instructions are essential for maintaining long-term accuracy.

2.2.4 Arch Complexity and Clinical Scenario

Clinical complexity strongly influences intraoral scanning accuracy. Partial-arch scans are generally more accurate than complete-arch scans because they involve smaller scan areas and fewer stitching steps.[1–6] Edentulous arches and complete-arch implant scans remain among the most difficult digital impression scenarios because of reduced anatomical landmarks, movable mucosa, reflective scan bodies, and long inter-implant distances.[16]

The relative accuracy of intraoral scanning can be summarized as follows:

Clinical situation	Expected IOS accuracy	Main limitation
Single crown, inlay, onlay	High	Margin visibility and isolation
Short-span fixed partial denture	High	Span length and scanning path
Partially dentate implant restoration	Moderate to high	Scan body geometry and implant angulation
Complete dentate arch	Moderate	Cumulative stitching error
Complete edentulous arch	Lower	Lack of anatomical landmarks
Full-arch multi-implant rehabilitation	Most challenging	Scan body reflection, inter-implant distance, implant angulation, and stitching error

3. Digital versus Conventional Impression Techniques

3.1 Overview

Digital impressions provide several clinical advantages compared with conventional impressions. These include reduced patient discomfort, shorter appointments, less gag reflex, immediate visualization of errors, simplified remakes, digital storage, faster laboratory communication, and integration with CAD/CAM design software.
Conventional impressions, however, remain well validated, relatively inexpensive, and reliable across many indications. They may also avoid some limitations of digital scanning, especially cumulative stitching error across long spans.
For single crowns and short-span fixed partial dentures, most evidence suggests that digital and conventional impressions provide comparable clinical accuracy.[7,18,22–25]
However, for complete-arch fixed prostheses and full-arch implant-supported restorations, conventional impressions or hybrid digital techniques may still be more accurate in certain situations.[17,18,20]
Kaitatzidou et al.[18] reviewed systematic reviews comparing digital scans and conventional impressions in fixed prosthodontics and found no statistically significant differences in accuracy, trueness, precision, or marginal and internal adaptation for many crown and fixed partial denture applications. However, complete-arch fixed dental prostheses remained more challenging for digital workflows, primarily due to cumulative stitching errors.[18]

3.2 Implant-Supported Prostheses

Implant-supported prostheses require stricter accuracy than tooth-supported restorations because osseointegrated implants lack periodontal ligament mobility. Small discrepancies may generate stress within the prosthetic framework, screws, abutments, or peri-implant bone. Prosthetic misfit may contribute to screw loosening, framework distortion, veneering material fracture, marginal bone loss, peri-implant inflammation, or patient discomfort.
For short-span implant-supported prostheses, intraoral scanning generally demonstrates accuracy comparable to conventional impression techniques.[19,21] In partially dentate cases, adjacent teeth provide anatomical landmarks that assist software stitching and improve spatial orientation. Digital impressions also reduce patient discomfort and allow immediate evaluation of scan body seating and data completeness.
Complete-arch implant prostheses are more demanding. Conventional splinted open-tray impressions have historically been considered reliable because splinting reduces implant analog movement. Nevertheless, conventional impressions are not error-free and may be affected by impression material distortion, tray deformation, splinting

shrinkage, gypsum expansion, and analog positioning errors. Digital impressions eliminate some of these errors but introduce others, particularly stitching distortion.[17,20,21]

For full-arch implant impressions, photogrammetry has emerged as one of the most accurate techniques.[18,20,44–46] It enables direct recording of implant positions without relying on continuous surface stitching across the arch.

3.3 Fixed Prosthodontics

In fixed prosthodontics, restoration success depends on marginal adaptation, internal fit, proximal contact, occlusal accuracy, emergence profile, and esthetics. Digital impressions are particularly effective for single crowns and short-span restorations because the scanned area is limited and the digital dataset can be transferred immediately to CAD software.

Digital workflows allow clinicians to magnify preparations, evaluate occlusal reduction, identify undercuts, inspect finish lines, and rescan deficient regions before the patient leaves the chair. These advantages reduce the risk of impression remakes and improve communication with the dental laboratory.

Hasanzade et al.[24] found no significant differences in marginal and internal adaptation between digital and conventional workflows for single crowns and fixed dental prostheses. Similarly, other systematic reviews have reported clinically acceptable marginal adaptation for tooth-supported fixed restorations fabricated from digital scans.[22,23,25]

However, complete-arch fixed prosthodontic cases remain more sensitive to scanning error. As span length increases, the likelihood of cumulative stitching distortion increases. Therefore, conventional impressions, verification casts, printed models, or hybrid workflows may still be preferred for extensive full-arch rehabilitations.

3.4 Removable Prosthodontics

Digital workflows are increasingly used in removable prosthodontics, including complete dentures, removable partial dentures, occlusal splints, immediate dentures, and trial prostheses. However, removable prosthodontics presents unique challenges because mucosal tissues are compressible and border extensions are functional rather than purely anatomical.

For complete dentures, intraoral scanning can accurately record certain denture-bearing areas, but capturing functional borders, movable mucosa, and tissue displacement remains difficult. Al Hamad and Al-Kaff[26] reported that TRIOS produced trueness comparable to polyvinyl siloxane impressions, whereas Medit showed higher deviations. These findings suggest that scanner model and clinical protocol strongly influence outcomes.

For removable partial dentures, digital scanning may provide accurate capture of teeth, guide planes, rest seats, and undercuts when scanning conditions are controlled. Yoon et al.[27] reported that removable partial denture frameworks fabricated from intraoral scanning demonstrated a significantly smaller mean gap than those fabricated using conventional impressions. Digital workflows may also reduce clinical and laboratory time.[28]

4. CAD/CAM Fabrication Accuracy

4.1 Milling versus 3D Printing

CAD/CAM fabrication includes subtractive manufacturing, commonly referred to as milling, and additive manufacturing, commonly referred to as 3D printing. Subtractive manufacturing removes material from premanufactured blocks, discs, or pucks, whereas additive manufacturing builds objects layer by layer.

Milling is well established for zirconia, lithium disilicate, PMMA, titanium, and hybrid ceramic restorations. It provides predictable mechanical properties because industrially manufactured materials have controlled density, polymerization, microstructure, and strength. However, milling is limited by bur diameter, tool wear, milling path, material waste, and difficulty reproducing sharp internal line angles.[29–33]

Additive manufacturing enables rapid production, complex geometries, efficient material use, and fabrication of surgical guides, temporary restorations, denture bases, occlusal splints, models, custom trays, and castable patterns. However, its accuracy and mechanical behavior depend on printer type, resin chemistry, build orientation, layer thickness, light intensity, washing, post-curing, support placement, and storage conditions.[29,30,34]

Both subtractive and additive manufacturing can produce clinically acceptable restorations when validated protocols are followed. However, milling currently remains more predictable for many definitive prosthodontic applications, while 3D printing is especially advantageous for guides, models, provisional restorations, and increasingly for selected definitive prostheses.

4.2 Accuracy of Milled Restorations

Milled restorations are widely used for crowns, fixed partial dentures, implant abutments, frameworks, occlusal splints, and denture bases. Their accuracy is affected by CAD design parameters, cement spacer settings, bur diameter, machining strategy, material properties, machine calibration, and post-milling procedures.

For zirconia restorations, sintering shrinkage compensation is critical. Presintered zirconia is milled in an enlarged form and then sintered to final dimensions. Errors may arise from nonuniform shrinkage, furnace calibration, restoration thickness, connector design, or material batch variation. Lithium disilicate restorations are often milled in a partially crystallized state and then crystallized, with dimensional changes generally controlled by manufacturer protocols.

A key clinical implication is that CAD/CAM tooth preparations should have rounded internal line angles and adequate occlusal clearance. Sharp internal angles may not be reproduced accurately because of bur diameter limitations, leading to internal binding or excessive adjustment.

4.3 Accuracy of 3D-Printed Restorations and Prostheses

Three-dimensional printing technologies used in dentistry include stereolithography, digital light processing, material jetting, selective laser melting, direct metal laser sintering, and fused deposition modeling. For dental models and surgical guides, 3D printing can achieve clinically acceptable accuracy when printers are calibrated and post-processing is standardized.

For denture bases and provisional restorations, mechanical properties remain a key concern. Printed resins may exhibit polymerization shrinkage, anisotropic mechanical behavior, and post-curing dimensional changes. Build orientation strongly influences both dimensional accuracy and mechanical strength.[34] Therefore, printing protocols must be validated for each material and indication.

4.4 CAD/CAM Post-and-Core Restorations

CAD/CAM post-and-core restorations provide an alternative to conventional cast post-and-core techniques. Digital design allows standardized post geometry, controlled cement space, improved visualization of canal morphology, and more efficient fabrication.[35,36]

However, the accuracy of CAD/CAM post-and-core restorations depends on scanning accuracy, canal geometry, software design parameters, milling or printing accuracy, and cementation technique. Direct intraoral scanning of deep post spaces may be difficult because of limited optical access, moisture, shadowing, and narrow canal geometry. In such cases, indirect digitization of conventional impressions or resin patterns may still be useful.[35,36]

5. Accuracy in Guided Implant Surgery

5.1 Digital Planning

Digital implant planning integrates cone-beam computed tomography, intraoral scans, diagnostic wax-ups, prosthetic design, and anatomical analysis. This enables prosthetically driven implant placement, where implant position is determined by the planned final restoration rather than by bone volume alone.

Accurate data merging is essential. CBCT provides bone anatomy, while intraoral scanning provides detailed surface morphology of teeth, soft tissue, and prosthetic reference structures. Errors in dataset alignment may compromise the accuracy of the surgical plan.[37–39]

5.2 Static, Dynamic, and Robotic Computer-Assisted Implant Surgery

Computer-assisted implant surgery can be classified into static guided surgery, dynamic navigation, and robotic-assisted surgery. Static guided surgery uses a prefabricated surgical guide to transfer the virtual plan to the patient. Dynamic navigation uses real-time tracking of the handpiece and patient anatomy. Robotic systems provide automated or semi-automated positional guidance with potential haptic or mechanical control.

Khaohoen et al.[40] reported no significant difference between static and dynamic computer-assisted implant surgery, but both methods were significantly more accurate than freehand placement. Static and dynamic systems generally achieve clinically acceptable outcomes, with deviations of approximately 1 mm at the implant platform or apex and angular deviations below 4°.[40,41]

A 2025 meta-analysis reported that guided surgery reduced apical deviation and angular deviation compared with freehand surgery.[41] Fully guided protocols generally provide better accuracy than partially guided protocols because they control both osteotomy preparation and implant insertion.

Robotic systems may provide the highest reproducibility, although clinical evidence remains more limited than for static and dynamic systems.[42] The use of robotics may be particularly valuable in anatomically complex cases, esthetic-zone placement, limited bone volume, or situations near vital structures.

5.3 Clinical Acceptability

Although guided surgery improves accuracy, it does not eliminate error. Deviations may occur due to CBCT resolution, guide design, sleeve tolerance, guide seating, drill length, handpiece movement, mucosal resilience, fixation instability, surgical access limitations, and registration error. Therefore, clinicians must maintain safety margins around critical anatomical structures, including the inferior alveolar nerve, mental foramen, maxillary sinus, adjacent roots, and facial cortical plate.

Static and dynamic guided surgery should be considered especially useful for full-arch immediate loading, esthetic-zone implant placement, narrow ridges, tilted implants, and cases requiring precise prosthetic screw-access positioning.[37–42]

6. Photogrammetry in Full-Arch Implant Impressions

6.1 Scientific Principles

Photogrammetry reconstructs three-dimensional coordinates by triangulating multiple two-dimensional images of known reference markers. In implant dentistry, coded or reflective scan bodies are attached to implants or multi-unit abutments. The photogrammetry system captures these markers from multiple angles and calculates their exact spatial positions.

The principal advantage of photogrammetry is that it does not rely on continuous surface stitching across the arch. Instead, it records implant coordinates directly. This eliminates a major source of error encountered in full-arch intraoral scanning.[43–45]

6.2 Comparative Accuracy

Photogrammetry has emerged as one of the most accurate methods for full-arch implant position capture. Hussein[44] concluded that photogrammetry provides highly accurate implant position recording and is particularly useful for complete-arch implant rehabilitation. Abuduwaili et al.[45] found that photogrammetric systems outperformed conventional open-tray impressions and intraoral scanning in full-arch implant rehabilitation.

For complete-arch implant-supported prostheses, photogrammetry can achieve deviations within ranges considered compatible with passive fit requirements.[18,20,44,45] This is clinically important because passive fit is essential for minimizing mechanical and biological complications in implant-supported frameworks.

6.3 Clinical Integration

Photogrammetry is most effective when integrated into a hybrid digital workflow. In this approach, photogrammetry records implant positions, intraoral scanning captures soft tissue morphology and prosthetic contours, CBCT provides bone anatomy, and CAD software integrates the datasets for prosthesis design.

A typical full-arch implant workflow may include:

Workflow step	Technology	Purpose
Implant position capture	Photogrammetry	Accurate implant coordinate registration
Soft tissue capture	Intraoral scanner	Gingiva, palate, ridge contour, opposing arch
Bone assessment	CBCT	Bone volume, anatomy, implant planning

Esthetic reference	Facial scan or photography	Smile design and facial integration
Prosthetic design	CAD software	Framework and prosthesis design
Manufacturing	Milling or 3D printing	Prototype, framework, denture, or final prosthesis

Photogrammetry is especially valuable in immediate full-arch implant rehabilitation because it allows rapid and accurate digital transfer of implant positions without conventional impression materials or gypsum casts. See Fig.1

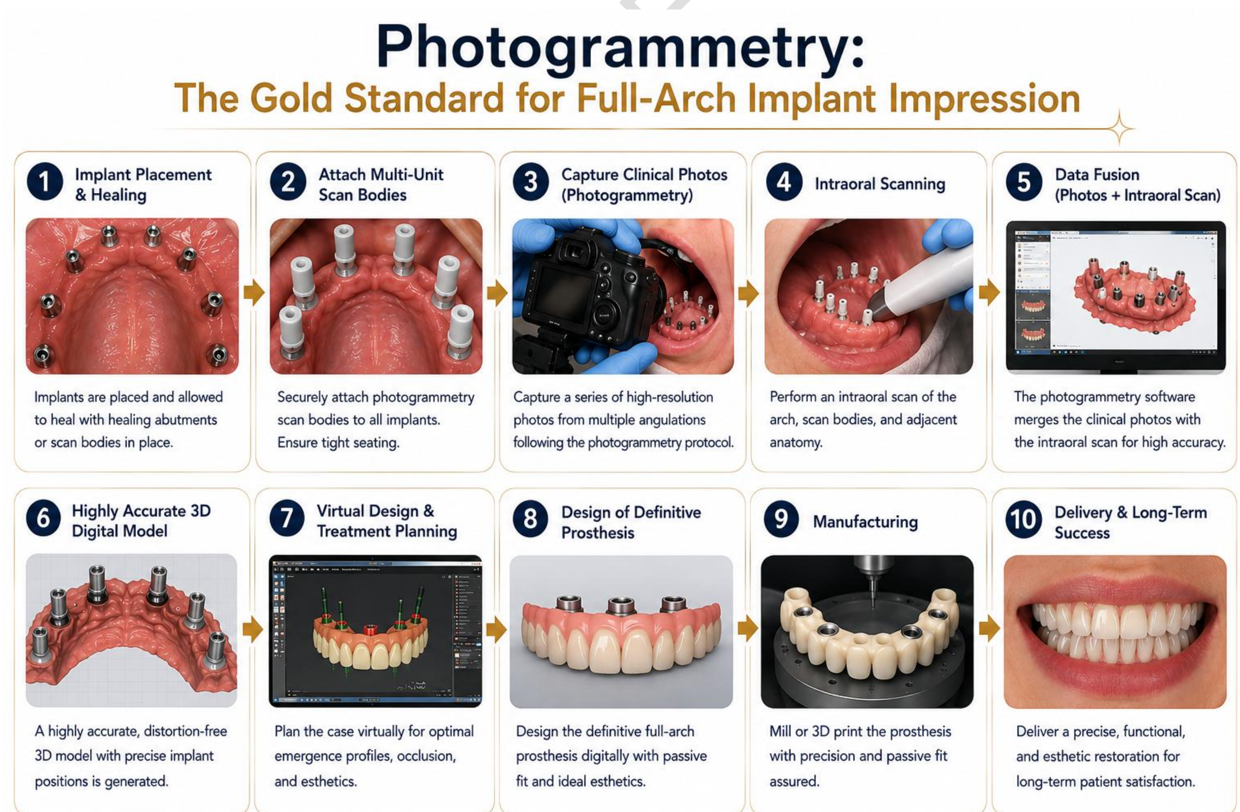

Fig.1 Photogrammetry: The Gold standard for Full-Arch Implant Impression : workflow

7. Factors Affecting Accuracy Maintenance

7.1 Scanner Technology and Generation

Scanner generation significantly affects accuracy. Newer scanners generally have faster acquisition, better depth of field, improved stitching algorithms, artificial intelligence-assisted artifact removal, enhanced color capture, and improved handling of reflective surfaces.[46] However, performance varies by indication. A scanner that performs well for single crowns may not be optimal for full-arch implant scanning. Scanning head size and scanning distance also influence accuracy. Larger scanning heads may improve surface capture but reduce access in posterior regions or in patients with limited mouth opening. Smaller heads may improve access but require more image stitching. Optimal scanning distance is usually manufacturer-specific but commonly falls within a short working range.[47,48]

7.2 Environmental and Clinical Factors

Lighting, saliva, blood, humidity, restorative material, and surface wetness can significantly influence scan accuracy. Excessive ambient light, direct operatory light, reflective restorations, polished zirconia, titanium scan bodies, and wet enamel may interfere with optical acquisition.[49,50]
Clinical measures to improve scanning accuracy include rubber dam isolation when appropriate, high-volume suction, air drying, retraction cord or paste, hemostatic control, and immediate inspection of the digital scan. Subgingival margins, bleeding, saliva contamination, and movable soft tissues remain important sources of error.

7.3 Software and Algorithm Updates

Software influences image acquisition, stitching, artifact removal, margin detection, scan body recognition, and mesh generation. Software updates may improve accuracy, although effects vary by scanner model, clinical indication, and operator experience.[51,52]
Some updates appear to benefit inexperienced operators more than experienced users by reducing technique sensitivity.
Artificial intelligence is increasingly incorporated into intraoral scanning. AI may assist with real-time error detection, soft tissue removal, margin identification, scan path

correction, and complete-arch stitching.[53] Nevertheless, AI-generated smoothing or automatic hole filling should be validated carefully because excessive software correction may obscure clinically relevant detail.

7.4 Digital Workflow Integration

The final accuracy of a digital dental workflow depends on every step in the chain. A highly accurate scan may be compromised by poor CBCT alignment, incorrect CAD spacer settings, milling error, sintering distortion, 3D-printing shrinkage, or cementation error. Therefore, accuracy should be managed as a complete workflow rather than as a property of one device.

Three broad workflow models are commonly used:

Workflow model	Description	Common indication
Laboratory digital workflow	Conventional impression is digitized in the laboratory	Complex prosthodontics requiring analog verification
Chairside digital workflow	Scan, design, and fabricate in-office	Single crowns, inlays, onlays, provisional restorations
Combined clinical-laboratory workflow	Digital clinical data are transferred to the laboratory	Implant prosthodontics, esthetic cases, full-arch rehabilitation

Combined workflows are increasingly used because they integrate intraoral scanning, CBCT, photogrammetry, facial scanning, jaw-motion data, and CAD/CAM manufacturing.[54],[55]

8. Clinical Recommendations for Accuracy

Based on the available literature, the following clinical recommendations may improve accuracy in digital dentistry:

Clinical factor	Recommendation
Case selection	Use digital impressions confidently for single-unit and short-span restorations; consider conventional, photogrammetry, or hybrid workflows for full-arch implant prostheses.
Scanner selection	Prefer newer-generation scanners with validated evidence for the intended indication.
Scanning protocol	Follow manufacturer-recommended strategies and use continuous, systematic scan paths.
Field control	Maintain a dry field using suction, retraction, air drying, and hemostatic measures.
Edentulous scanning	Use artificial landmarks or auxiliary devices when anatomical landmarks are limited.

Implant scanning	Verify scan body seating and consider photogrammetry for complete-arch implant cases.
Calibration	Calibrate scanners according to manufacturer instructions and after environmental or software changes.
Software	Keep scanner and CAD software updated, but validate accuracy after major updates.
Operator training	Provide structured training; expect a learning curve of approximately 20–30 scans.
Guided surgery	Use static or dynamic guided surgery when implant position is anatomically or prosthetically critical.
Quality control	Inspect digital scans immediately and verify fit clinically before final prosthesis delivery.

9. Future Directions

9.1 Artificial Intelligence-Enhanced Scanning

Artificial intelligence is expected to play an increasing role in digital dentistry. Potential applications include real-time scan correction, automatic margin detection, artifact removal, scan body recognition, soft tissue filtering, occlusal analysis, and complete-arch stitching optimization.[53,56] AI may reduce operator variability and improve consistency, particularly in complex full-arch scans.

9.2 Advanced Optical Technologies

Future intraoral scanners may incorporate multi-wavelength imaging, improved confocal optics, structured light, polarization control, and better surface-recognition algorithms. These developments may improve scanning of reflective, wet, or low-feature surfaces.

9.3 Hybrid Full-Arch Workflows

Hybrid workflows combining intraoral scanning, photogrammetry, CBCT, facial scanning, and jaw-motion tracking are likely to become increasingly common. These workflows may provide a more complete digital representation of the patient and improve the precision of full-arch prosthetic rehabilitation.[54,55]

9.4 Robotic and Navigation-Based Implant Surgery

Robotic implant surgery may offer improved reproducibility, reduced operator-dependent error, and enhanced safety in anatomically complex cases. However, broader clinical validation is needed before robotic systems can be considered superior to established static and dynamic guided workflows.[42]

9.5 Standardized Accuracy Metrics

A major limitation of the current literature is methodological heterogeneity. Studies differ in scanner models, reference scanners, alignment methods, scan bodies, test models, deviation metrics, operator experience, and statistical analysis. Standardized reporting of trueness, precision, RMS deviation, linear deviation, angular deviation, marginal gap, and clinical thresholds would improve comparability among studies.

10. Conclusion

Digital dentistry has reached a level of accuracy that is clinically acceptable for many restorative, prosthodontic, and implant applications. Intraoral scanners are highly reliable for single-unit and short-span restorations, and digital impressions are generally comparable to conventional impressions in these indications. However, full-arch scans, edentulous arches, and complete-arch implant-supported prostheses remain more technically demanding because of cumulative stitching error, absence of anatomical landmarks, scan body geometry, implant angulation, environmental factors, and operator technique.

For implant prosthodontics, digital impressions are reliable for short-span and partially

dentate cases. For full-arch implant rehabilitation, photogrammetry currently represents one of the most accurate methods for implant position capture and is best used within a hybrid workflow that also includes intraoral scanning for soft tissue morphology.
Computer-assisted implant surgery improves implant placement accuracy compared with freehand surgery, although deviations remain inevitable and safety margins must be maintained.
The accuracy of digital dentistry is not determined by technology alone. It depends on appropriate case selection, scanner generation, calibration, scanning protocol, operator experience, environmental control, software performance, manufacturing quality, and workflow integration. As artificial intelligence, advanced optical systems, photogrammetry, structured light scanning, and robotic surgery continue to develop, the accuracy and predictability of digital dental workflows are expected to improve further. Nevertheless, clinical judgment, evidence-based protocol selection, and rigorous quality control will remain essential for successful outcomes.

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