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# Photogrammetry in Full-Arch Implant Rehabilitation: Accuracy, Workflows, and Clinical Outcomes

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## Abstract

Accurate transfer of implant positions is critical for achieving passive fit in full-arch implant-supported prostheses. Photogrammetry has emerged as a promising digital impression technique, offering superior accuracy by eliminating cumulative stitching errors inherent to intraoral scanning. This narrative review synthesizes current evidence on photogrammetry technologies for full-arch implant rehabilitation, comparing accuracy, workflow efficiency, clinical outcomes, and limitations against conventional and intraoral scanning methods. Electronic searches of PubMed, Scopus, and Web of Science were conducted (2015-2026). Photogrammetry systems demonstrate significantly superior trueness (10-50 µm) and precision (4-18 µm) compared to intraoral scanning (trueness up to 731.7 µm in full-arch applications). A 2025 meta-analysis confirmed photogrammetry's superior trueness in distance deviation ($p = .001$) and angular deviation ($p = .02$). Intraoral photogrammetry achieves comparable accuracy to extraoral systems while capturing soft tissue in a unified scan. Navigated photogrammetry enables conversion-less provisional fabrication. While equipment costs and learning curves remain barriers, emerging smartphone-based systems promise broader accessibility. Photogrammetry represents the most accurate digital method for full-arch implant position capture, with emerging intraoral and navigated systems addressing workflow limitations.

**Keywords:** Photogrammetry, Full-arch implant rehabilitation, Digital impression, Passive fit, Intraoral scanning, Implant-supported prosthesis, Accuracy.



## INTRODUCTION

This narrative review synthesizes evidence drawn from structured electronic searches of PubMed, Scopus, and Web of Science (2015–2026), using keywords including "photogrammetry," "full-arch implant rehabilitation," "digital impression," "intraoral scanning," and "implant-supported prosthesis." Studies evaluating photogrammetry for complete-arch implant impressions were included, encompassing in vitro accuracy studies, clinical trials, case series, and systematic reviews. Data on trueness, precision, workflow parameters, and clinical outcomes were extracted and synthesized narratively.

Achieving an accurate transfer of implant positions from the oral cavity to the definitive prosthesis represents one of the most technically demanding steps in full-arch implant rehabilitation. The concept of passive fit, defined as a prosthetic superstructure that seats without generating static loads or strains within the prosthesis or surrounding bone, has been recognized as a prerequisite for long-term implant success (Branemark PI *et al.,* 1985). Unlike natural teeth, which can accommodate minor misfits through the periodontal ligament's viscoelastic properties (approximately 100 µm of movement), osseointegrated implants exhibit minimal displacement (approximately 10 µm), making them far less tolerant of dimensional inaccuracies (Sahin S *et al.,* 2001; Skalak R, 1983). Framework misfit has been definitively linked to both mechanical complications (screw loosening, framework fracture, veneer chipping) and biological complications (marginal bone loss, peri-implantitis, loss of osseointegration), with technical complications including abutment or screw loosening (5.3% at 5 years) and veneer material fractures (13.5% at 5 years), with only 66.4% of patients remaining free of any complications over 5 years (Pjetursson BE *et al.,* 2012).

The clinically acceptable misfit threshold has been a subject of ongoing debate. An early prosthodontic standard of 10 µm, while theoretically ideal, has given way to more pragmatic targets. Contemporary literature suggests 50-100 µm for distance deviation and under 1 degree for angular deviation as realistic goals for passive framework fit, while a widely cited practical threshold of 150 µm serves as the upper limit below which biological and technical complications are unlikely over time (Jemt T *et al.,* 1996). The implications of these thresholds become particularly significant when one considers that cumulative errors from impression techniques, framework fabrication, and component machining can each contribute 20-100 µm of deviation, meaning the impression technique must contribute minimal additional error to keep total misfit within acceptable bounds (Jemt T, 1991; Skalak R, 1983).

Conventional splinted open-tray impression techniques, despite remaining the clinical gold standard against which digital methods are compared, are inherently susceptible to multiple sources of error: impression material distortion, polymerization shrinkage of splinting resin, gypsum expansion during cast fabrication, and wax pattern inaccuracies during framework fabrication (Assuncao WG *et al.,* 2008). Each of these steps introduces cumulative deviations that can compromise the final prosthetic fit. Digital intraoral scanning (IOS) promised to eliminate many of these analog error sources, and indeed, IOS has proven highly accurate for single-unit and short-span implant restorations. However, its application to full-arch edentulous cases reveals a critical limitation: the sequential image-stitching process depends on stable anatomical landmarks for pattern recognition, and edentulous ridges, by definition, lack these landmarks (Revilla-Leon M *et al.,* 2022). Each stitching step introduces minor deviations that compound across the arch, with reported trueness values reaching up to 731.7 µm in full-arch applications, and 18 of 30 studies in a 2021 systematic review exceeding the 100 µm acceptability threshold (Zhang YJ *et al.,* 2021).

Photogrammetry offers a fundamentally different approach to implant position capture. Rather than stitching sequential surface images, photogrammetry uses multiple calibrated cameras to capture optical markers (scan bodies) attached to implants from different angles, calculating exact three-dimensional spatial coordinates through triangulation. This method eliminates the cumulative stitching errors inherent to IOS and is minimally affected by intraoral conditions such as blood, saliva, and soft tissue mobility (Joda T *et al.,* 2022; Cario N *et al.,* 2023). The first commercial dental photogrammetry system, the PIC System (PIC Dental, Spain), was launched in 2010, followed by the iCam4D (Imetric, Switzerland) in 2018, which combined photogrammetry with structured light scanning (Revilla-Leon M *et al.,* 2024). The field has since expanded rapidly, with the introduction of intraoral photogrammetry (IPG) in 2024 (Aoralscan Elite, Shining 3D), navigated photogrammetry (FastMap, Nobel Biocare/X-Nav) in 2024, and even smartphone-based photogrammetry applications in 2025 (Shining 3D, 2025; Nobel Biocare, 2024; Santamaria-Laorden A *et al.,* 2025).

This review aims to provide a comprehensive synthesis of current evidence on photogrammetry technologies for full-arch implant rehabilitation, encompassing accuracy validation, clinical workflow analysis, comparison with alternative impression techniques, and emerging innovations that promise to reshape the landscape of digital implant prosthodontics.

## PRINCIPLES OF DENTAL PHOTOGRAMMETRY

### Fundamental Concepts

Photogrammetry is a three-dimensional measurement technique based on the triangulation of multiple high-resolution images. In dental applications, specially designed scan bodies with optical markers are attached to implant abutments or multi-unit abutments (MUAs), and a series of photographs are captured from different positions. Software algorithms then reconstruct the precise XYZ coordinates of each implant in three-dimensional space (Mitchell HL, 2013). The mathematical foundation relies on the collinearity equation, which establishes a straight-line relationship between a point in object space, the camera's optical center, and the corresponding image point. When multiple images from different camera positions are available, the system solves for the unknown three-dimensional coordinates through bundle adjustment, a simultaneous least-squares optimization of all camera positions and object points.

The key distinction from intraoral scanning lies in the acquisition and identification of targets. During a photogrammetry capture, the targets and 3D positions of implants can be measured extraorally from multiple angles simultaneously; the entire scan body is not required to register the implant location. In contrast, intraoral scanning must register the scan region (typically the top third of the scan body) to determine implant positioning, and accuracy is progressively lost when measuring between scan bodies across long edentulous spans (Fernandez M *et al.,* 2015).

**Classification of Photogrammetry Systems**

Contemporary dental photogrammetry systems can be categorized into four distinct technological approaches, as summarized in Table 1.

**Table 1: Classification of contemporary dental photogrammetry systems**

| Category | Representative Systems | Key Characteristics | Linear Trueness |
|---|---|---|---|
| Extraoral Photogrammetry (EPG) | PIC System, iCam4D, Micron Mapper, Tupel 3D, Grammee, OxoFit | Dedicated stereo camera captures coded markers extraorally; requires separate IOS for soft tissue | 10-77 µm (Revilla-Leon M *et al.,* 2024) |
| Intraoral Photogrammetry (IPG) | Aoralscan Elite (Shining 3D) | Photogrammetric algorithms embedded within intraoral scanner; captures implant + soft tissue in unified scan | 20-35 µm (Revilla-Leon *et al.,* 2025) |
| Navigated Photogrammetry | FastMap (Nobel Biocare/X-Nav) | Integrated with surgical navigation; tracker-based coordinate preservation; conversion-less workflow | Comparable to EPG (Nobel Biocare, 2024) |
| Smartphone-Based PG | PIC app | Consumer smartphone with photogrammetry algorithm; ultra-low-cost entry point | 12.7 µm difference vs. PIC (Santamaria-Laorden A *et al.,* 2025) |

**Scan Body Design and Optical Markers**

The design of photogrammetry scan bodies significantly influences capture accuracy. EPG systems employ various marker configurations: the PIC System uses black flag-shaped scan bodies with white dot patterns (PIC Transfers); the iCam4D uses calibrated radiopaque titanium scan bodies (iCamBodies) with matte black surfaces decorated with white polka dot patterns; OxoFit employs flag-like configurations with white surfaces bearing gray geometric patterns (Revilla-Leon M *et al.,* 2024). IPG systems use horizontally oriented coded scan bodies that serve as precise reference points, with the photogrammetry algorithm detecting coded points and extracting 3D coordinates. The recent introduction of coded cap scan bodies has further streamlined immediate-loading protocols by enabling implant position capture directly through healing caps without additional scan body placement (Shining 3D, 2025).

## ACCURACY OF PHOTOGRAMMETRY SYSTEMS

**Trueness and Precision: Definitions and Measurement**

In the context of digital implant impressions, trueness refers to the closeness of agreement between the measured value and the true value (systematic error), while precision describes the closeness of agreement among repeated measurements under the same conditions (random error) (Abuduwaili K *et al.,* 2025). These parameters are typically quantified as linear (3D) deviation (the Euclidean distance between corresponding implant positions in the test and reference datasets, measured in µm), angular deviation (the angular discrepancy between implant long axes, measured in degrees), and root mean square (RMS) error (a composite measure reflecting overall three-dimensional surface deviation). Reference standards for accuracy evaluation vary across studies, with some employing coordinate measuring machines (CMM) and others using high-resolution laboratory scanners with reported accuracies of 4-8 µm (Abuduwaili K *et al.,* 2025; Pozzi A *et al.,* 2025). This methodological heterogeneity complicates direct cross-study comparisons and represents an important consideration when interpreting pooled accuracy data.

**Comparative Accuracy: PG vs. Conventional vs. IOS**

A growing body of in vitro and clinical evidence has consistently demonstrated the superior accuracy of photogrammetry compared to both conventional splinted open-tray impressions and intraoral scanning for full-arch implant applications. The landmark study by Abuduwaili et al. (2025) compared two photogrammetry systems (iCam4D and PIC) against conventional splinted open-tray impressions and intraoral scanning (TRIOS 3) on an edentulous mandibular model with six parallel implants, providing some of the most comprehensive head-to-head accuracy data to date (Abuduwaili K *et al.,* 2025).

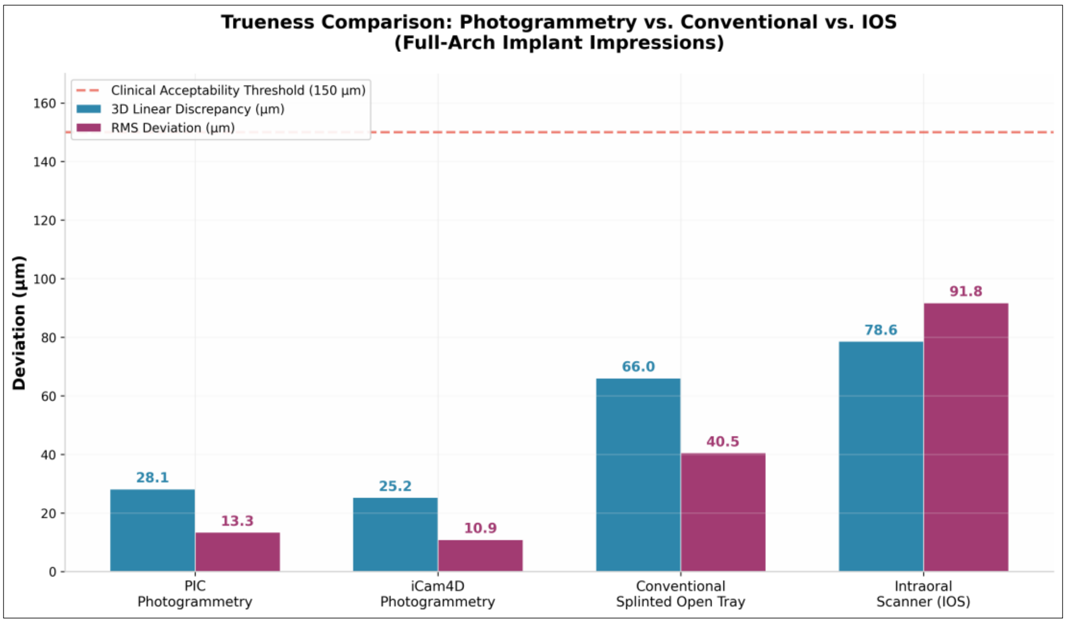


**Figure 1: Trueness comparison across impression techniques for full-arch implant impressions. PG = photogrammetry; IOS = intraoral scanner**

The results revealed a clear hierarchy of accuracy. For trueness (3D linear discrepancy), photogrammetry systems achieved median deviations of 25.23 µm (iCam4D) and 28.15 µm (PIC), compared to 66.05 µm for conventional impressions and 78.58 µm for IOS. For RMS deviation, the contrast was even more pronounced: 10.87 µm (iCam4D) and 13.35 µm (PIC) versus 40.50 µm (conventional) and 91.75 µm (IOS). Angular deviations followed the same pattern, with photogrammetry achieving 0.12-0.14 degrees compared to 0.35 degrees (conventional) and 0.52 degrees (IOS) (Abuduwaili K *et al.,* 2025). Critically, all measured deviations remained well below the 150 µm clinical acceptability threshold, though the substantially lower deviations achieved by photogrammetry suggest a greater margin of safety when accounting for subsequent manufacturing tolerances.

These findings have been corroborated by multiple independent investigations. A 2025 systematic review and meta-analysis by Altalla et al. analyzing 14 studies confirmed that photogrammetry demonstrated significantly better trueness than IOS in distance deviation ($p = .001$) and angular deviation ($p = .02$), with precision analysis also favoring PG for both distance ($p = .01$) and angular deviation ($p < .001$) (Altalla H *et al.,* 2025). Similarly, a 2025 in vivo prospective study by Eldabe et al. reported median 3D deviations of 17.00 µm for photogrammetry versus 48.95 µm for IOS, with the authors noting that IOS results in some cases approached or exceeded the 150 µm threshold while photogrammetry remained consistently within safe margins (Eldabe AK *et al.,* 2025).

**Table 2: Comparative accuracy metrics across impression techniques for full-arch implant rehabilitation**

| **Parameter** | **PIC System** | **iCam4D** | **Conventional** | **IOS** | **Threshold** |
|---|---|---|---|---|---|
| Trueness (3D linear, µm) | 28.15 (Abuduwaili K *et al.,* 2025) | 25.23 (Abuduwaili K *et al.,* 2025) | 66.05 (Abuduwaili K *et al.,* 2025) | 78.58 (Abuduwaili K *et al.,* 2025) | < 150 µm |
| Precision (3D linear, µm) | 17.78 (Abuduwaili K *et al.,* 2025) | 15.80 (Abuduwaili K *et al.,* 2025) | 39.32 (Abuduwaili K *et al.,* 2025) | 45.33 (Abuduwaili K *et al.,* 2025) | < 150 µm |
| RMS Deviation (µm) | 13.35 (Abuduwaili K *et al.,* 2025) | 10.87 (Abuduwaili K *et al.,* 2025) | 40.50 (Abuduwaili K *et al.,* 2025) | 91.75 (Abuduwaili K *et al.,* 2025) | < 100 µm |
| Angular Deviation (degrees) | 0.14 (Abuduwaili K *et al.,* 2025) | 0.12 (Abuduwaili K *et al.,* 2025) | 0.35 (Abuduwaili K *et al.,* 2025) | 0.52 (Abuduwaili K *et al.,* 2025) | < 1.0 degree |
| Acquisition Time | < 2 min (Faria JC *et al.,* 2025) | < 1 min (Imetric4D Imaging Sàrl, 2024) | ~ 15 min (Faria JC *et al.,* 2025) | ~ 4 min (Faria JC *et al.,* 2025) | - |

**Accuracy Across Photogrammetry Platforms**

While photogrammetry as a category consistently outperforms alternative impression methods, significant differences exist among individual systems. A 2025 comparative study by Revilla-Leon et al. evaluated five photogrammetry systems, four extraoral (PIC Legacy, iCam4D, Grammee, OxoFit) and one intraoral (Aoralscan Elite), on an edentulous maxillary cast with six implant abutment analogs. The PIC and iCam4D systems demonstrated the best linear trueness (17-30 µm range across all systems), with PIC achieving the best linear precision. Grammee obtained the best angular trueness, while PIC again showed the best angular precision (Revilla-Leon *et al.,* 2025). The intraoral photogrammetry system (Aoralscan Elite) achieved accuracy values similar to two of the extraoral systems (Grammee and OxoFit), suggesting that IPG technology has reached parity with established EPG platforms for linear and angular measurements (Revilla-Leon *et al.,* 2025).

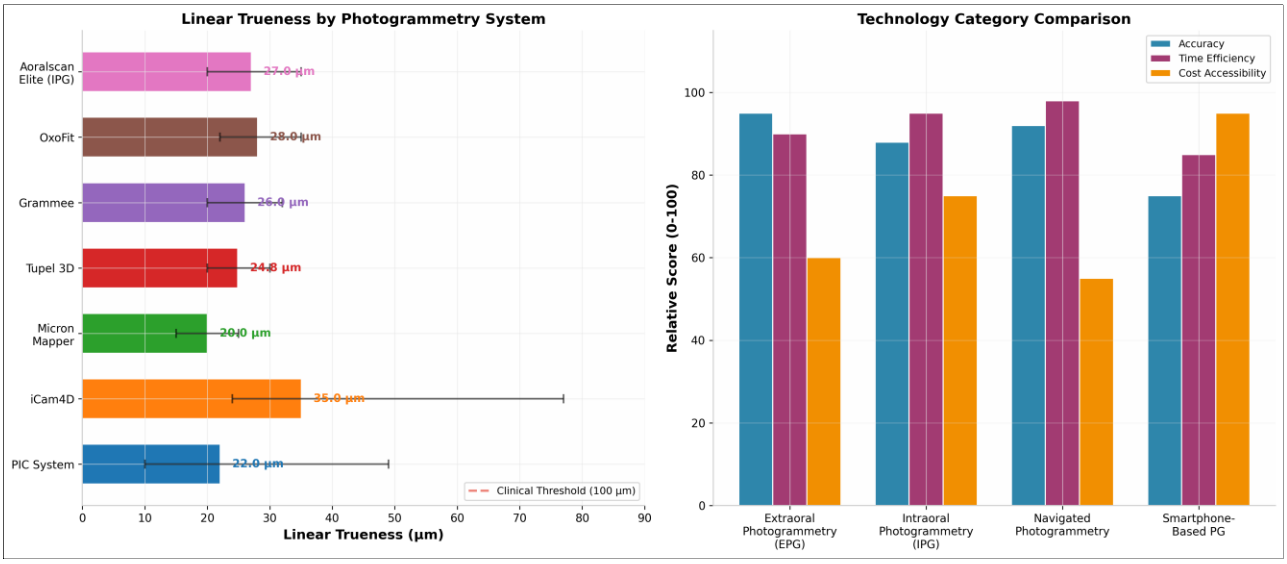


**Figure 2: (A) Linear trueness by photogrammetry system. (B) Technology category comparison across accuracy, time efficiency, and cost accessibility dimensions**

**Factors Influencing Photogrammetry Accuracy**

Several technical and clinical factors can influence the accuracy of photogrammetry captures. Camera-to-marker scanning distance, marker visibility, and the angulation and depth of implant placement can all affect the reliability of coordinate reconstruction, since subgingival or deeply placed markers may be partially obscured during capture. Systematic reviews of dental photogrammetry have nonetheless reported that these systems remain comparatively robust to such challenging intraoral conditions relative to intraoral scanning (Revilla-Leon *et al.,* 2024). Standardizing the capture protocol and ensuring adequate marker exposure are therefore recommended to maximize accuracy.

One-phase versus two-phase capture protocols represent another consideration, particularly for the PIC system where posterior scan bodies may be obscured by anterior structures. A 2025 study found no significant differences in linear, angular, or overall discrepancies between one-phase and two-phase protocols, with both exhibiting deviations within the prescribed range for well-fitted complete-arch prostheses (< 100 µm) (Pozzi A *et al.,* 2025). However, selecting an appropriate reference scan body for multi-phase captures, ideally the most posterior abutment, may help maximize accuracy (Pozzi A *et al.,* 2025).

## CLINICAL WORKFLOWS AND EFFICIENCY

**Extraoral Photogrammetry (EPG) Workflow**

The conventional extraoral photogrammetry workflow involves several distinct steps that require coordination between the clinical and laboratory phases. First, photogrammetry-specific scan bodies (PIC Transfers, iCamBodies, or equivalent markers) are placed on the implant abutments or multi-unit abutments. The photogrammetry camera is positioned 15-30 cm from the patient's oral cavity, and calibrated photographic images are captured from multiple angles. The proprietary software reconstructs the 3D implant positions and exports an STL file containing only the implant coordinate data (Revilla-Leon M *et al.,* 2024; Clozza E, 2023).

A critical limitation of EPG is that the system only records implant position information; it does not capture soft tissue contours, occlusal relationships, or adjacent dentition. Therefore, a second scan is required using either an intraoral scanner or a conventional impression to obtain soft tissue and occlusal data (Clozza E, 2023). The photogrammetry data and soft tissue data must then be digitally aligned (merged) using best-fit algorithms within CAD software. This two-scan requirement adds complexity to the workflow and introduces a potential source of alignment error during the merging process (Pozzi A *et al.,* 2025).

Despite this limitation, EPG workflows have been successfully integrated into comprehensive digital protocols for full-arch rehabilitation. The total chair time for photogrammetry capture is remarkably short, under 2 minutes for most systems, and the extraoral nature of the capture means that intraoral conditions (blood, saliva, moisture) have minimal impact on accuracy (Faria JC *et al.,* 2025; Clozza E, 2023). Patient comfort is also enhanced, as there is no need for bulky impression trays or extended mouth-opening periods.

**Intraoral Photogrammetry (IPG) Workflow**

Intraoral photogrammetry represents a paradigm shift in full-arch digital capture by integrating photogrammetric algorithms directly into the intraoral scanner. The Aoralscan Elite (Shining 3D), launched in September 2024, was the first commercially available system to offer this capability (Shining 3D, 2025; Shining 3D, 2026). The IPG workflow employs horizontally oriented coded scan bodies that serve as precise reference points. During scanning, the photogrammetry algorithm detects the coded points on these scan bodies and calculates their relative positions using absolute coordinates, thereby eliminating the cumulative stitching errors of conventional IOS (Shining 3D, 2025).

The transformative advantage of IPG is its unified capture capability: in a single scanning session, the system records both ultra-precise implant positions via photogrammetry and soft tissue contours, occlusal relationships, and adjacent dentition via conventional intraoral scanning (Shining 3D, 2025). The workflow allows seamless transition from coded scan bodies to preferred regular scan bodies within the same project file, eliminating the need for separate scans and digital alignment steps. The introduction of coded cap scan bodies has further streamlined immediate-loading protocols by enabling implant position capture directly through healing caps, even in challenging environments with blood and saliva (Shining 3D, 2025).

Since its launch, IPG technology has achieved significant adoption milestones: 7 accuracy studies published, 66 implant systems supported, and adoption in 93 countries as of early 2026 (Shining 3D, 2026). The system received the Best IOS Award 2024 from the Institute of Digital Dentistry and achieved DDS Precision Certification in July 2025 (Shining 3D, 2026). Independent in vitro and human cadaver investigations have since corroborated the accuracy of the Aoralscan Elite intraoral photogrammetry system, reporting marginal discrepancies broadly comparable to those of extraoral photogrammetry while noting greater variability for individual intraoral scans, and confirming that ambient lighting conditions exert only a negligible effect on capture accuracy (DeFee M *et al.,* 2026; Gomez-Polo M *et al.,* 2025).

**Navigated Photogrammetry (FastMap)**

FastMap (Nobel Biocare/X-Nav Technologies), introduced in October 2024, represents a novel category of navigated photogrammetry that integrates with the X-Guide dynamic surgical navigation system (Nobel Biocare, 2024). This technology preserves the spatial relationship between implants and the patient's anatomy throughout the surgical procedure using a patient tracker that is registered preoperatively. Following implant placement, the X-Guide camera system, already positioned for surgical navigation, captures scan body locations without requiring additional scanner hardware (X-Nav Technologies, 2024).

The key innovation of FastMap is its conversion-less workflow: because the photogrammetry data and the preoperative treatment plan exist in the same coordinate system (maintained by the patient tracker), there is no need for post-surgical soft tissue scans with fiducial screws or complex digital alignment procedures (Pozzi A *et al.,* 2026). The scan bodies are interchangeable at any implant location with the same connection interface, and the system works with all Nobel Biocare multi-unit abutments as well as various third-party abutments (Nobel Biocare, 2024). FastMap enables clinicians to scan, plan, place, and provisionalize full-arch cases in just half a day, representing a significant efficiency gain over traditional workflows (X-Nav Technologies, 2024).

**Table 3: Workflow comparison across photogrammetry technology categories**

| Workflow Parameter | EPG | IPG | FastMap |
|---|---|---|---|
| Implant Capture | Extraoral stereo camera | Intraoral scanner | X-Guide navigation camera |
| Soft Tissue Capture | Separate IOS required | Unified in same scan | Pre-op IOS in same coordinate system |
| Alignment Step | Digital merge required | Not required (auto) | Not required (tracker-based) |
| Additional Hardware | PG camera + IOS | Single IOS device | X-Guide system only |
| Chair Time | < 5 min total | < 5 min total | Integrated with surgery |
| Learning Curve | Moderate | Moderate | Low (if familiar with X-Guide) |

## CLINICAL OUTCOMES AND PROSTHETIC PERFORMANCE

**Passive Fit Achievement**

The ultimate clinical validation of any impression technique lies in its ability to produce prostheses with passive fit, a property that can only be truly confirmed at the time of prosthesis delivery. While in vitro accuracy studies provide valuable comparative data, they measure only the impression-related component of total misfit, which is subsequently compounded by laboratory fabrication tolerances (20-100 µm), framework material properties, and cement layer thickness (for cement-retained restorations) (Eldabe AK *et al.,* 2025).

Photogrammetry's substantially lower impression-related deviations (typically 10-50 µm versus 40-90 µm for conventional and IOS methods) provide a greater safety margin for accommodating these downstream tolerances while still keeping total misfit within the 150 µm clinical threshold (Abuduwaili K *et al.,* 2025; Revilla-Leon M *et al.,* 2024). The improved angular accuracy of photogrammetry (0.12-0.14 degrees versus 0.35-0.52 degrees) is particularly significant because angular deviations at the implant platform are amplified at the prosthetic crown level due to lever arm effects, potentially generating substantial stresses even with small initial misalignments (Abuduwaili K *et al.,* 2025).

Clinical studies evaluating photogrammetry-based full-arch prostheses have reported favorable prosthetic outcomes. A 2024 retrospective study by Yao et al. evaluating immediate full-arch rehabilitation on 4 or 6 implants using photogrammetry reported successful outcomes with up to 2 years of follow-up, noting significantly reduced patient tooth loss time and minimized overall treatment duration (Yao S *et al.,* 2024). +

**Complications and Failure Modes**

Despite its accuracy advantages, photogrammetry is not immune to complications. Framework misfit can still occur due to factors downstream of the impression capture, including CAD design errors, milling or printing inaccuracies, material distortion during polymerization or sintering, and improper torque application during prosthesis insertion (Sahin S *et al.,* 2001). The clinical significance of these downstream errors may actually be greater than impression-related errors in well-executed photogrammetry workflows, given the very small deviations introduced at the impression stage.

Screw loosening remains the most common mechanical complication in full-arch implant prostheses, with misfit being a well-established contributing factor. When a restoration does not fit passively, a portion of the preload applied during screw tightening is consumed closing gaps between components rather than generating clamping force. During mastication, non-fitting surfaces press against each other, further reducing traction on screw surfaces and increasing the risk of loosening and fracture (Bulaqi HA *et al.,* 2015). By minimizing impression-related misfit, photogrammetry may reduce the incidence of these complications, though long-term comparative data are still emerging.

**Patient-Reported Outcomes**

While photogrammetry-specific patient-reported outcome studies remain limited, the broader literature on digital versus conventional full-arch implant workflows provides relevant insights. Digital workflows, including photogrammetry-based approaches, consistently demonstrate improved patient comfort due to elimination of bulky impression trays, reduced chair time, and fewer appointments (Clozza E, 2023; Kim JH *et al.,* 2023). A qualitative study of 30 implant patients found that 86.7% reported positive overall experiences, with satisfaction strongly correlated with comfort, aesthetics, and perceived treatment efficiency (Kim JH *et al.,* 2023).

The reduced acquisition time of photogrammetry (under 2 minutes versus 15 minutes for conventional impressions) is particularly beneficial for patients with limited mouth opening, gag reflexes, or anxiety, as the extraoral capture eliminates the need for intraoral tray placement and extended procedure times (Clozza E, 2023). Patient education and expectation management remain critical, as a significant relationship exists between comfort ratings and how well-informed patients feel about their treatment (Kan JY *et al.,* 2003).

## LIMITATIONS AND CHALLENGES

**Equipment Cost and Accessibility**

The primary barrier to widespread photogrammetry adoption remains equipment cost. Dedicated extraoral photogrammetry systems (PIC System, iCam4D) represent significant capital investments, typically requiring practices with substantial full-arch case volumes to achieve cost-effectiveness (Flugge T *et al.,* 2020). This has limited photogrammetry primarily to specialized implant centers, academic institutions, and high-volume practices. The emergence of intraoral photogrammetry (IPG) and smartphone-based alternatives promises to democratize access by leveraging existing IOS hardware or consumer devices, though the long-term durability and clinical validation of these newer platforms require continued evaluation.

**Learning Curve and Technique Sensitivity**

While photogrammetry capture itself is relatively straightforward, achieving consistent clinical results requires proper training in scan body placement, camera positioning, and troubleshooting. Unlike IOS, where scanning strategy can be modified in real-time based on on-screen feedback, photogrammetry captures are less forgiving of suboptimal positioning, and errors may not be immediately apparent until the data are processed (Clozza E, 2023). The learning curve is described as moderate, steeper than conventional impressions for novice users but comparable to IOS once basic competencies are established.

### System-Specific Limitations

Each photogrammetry platform carries specific limitations. EPG systems require a second scan (IOS or conventional) for soft tissue capture, introducing an additional step and potential alignment error (Pozzi A *et al.,* 2025). IPG systems, while capturing soft tissue in a unified scan, may still struggle with highly mobile soft tissues or excessive bleeding during immediate-loading scenarios (Shining 3D, 2025). Navigated photogrammetry (FastMap) requires the X-Guide surgical navigation system, limiting its applicability to practices already invested in this technology. Smartphone-based systems, while highly accessible, currently lack the comprehensive clinical validation of dedicated hardware platforms.

### Evidence Gaps

Despite the rapidly expanding photogrammetry literature, several significant evidence gaps persist. The majority of accuracy studies are in vitro investigations using idealized master models, which cannot fully replicate the challenging intraoral conditions of real patients (blood, saliva, limited mouth opening, perioral tissue interference) (Abuduwaili K *et al.,* 2025). Long-term clinical outcome data comparing photogrammetry-based prostheses versus conventional or IOS-based prostheses in randomized controlled trials are essentially nonexistent (Barreto DFCM, 2022). Cost-effectiveness analyses comparing the total cost of photogrammetry workflows (including equipment, maintenance, training, and consumables) against conventional and IOS approaches have not been published. Patient-reported outcome measures specific to photogrammetry-based full-arch rehabilitation remain undeveloped.

## EMERGING INNOVATIONS AND FUTURE DIRECTIONS

### Smartphone-Based Photogrammetry

The PIC app, launched in 2025, represents a groundbreaking development in democratizing photogrammetry access. This smartphone application integrates a photogrammetry algorithm that captures implant positions through scan body geometry, with data automatically aligned to intraoral soft-tissue scans (PIC Dental, 2025). An in vitro validation study comparing the PIC app against the dedicated PIC system reported a mean linear difference of just 12.70 µm and virtually identical angular precision (difference of less than 0.1 degree) (Santamaria-Laorden A *et al.,* 2025).

This innovation has profound implications for global access to precision implant dentistry. By leveraging ubiquitous smartphone technology, photogrammetry becomes accessible to clinicians and laboratories in resource-limited settings who could not previously justify dedicated photogrammetry hardware investments. However, the authors appropriately note that high-volume practices delivering hundreds of cases annually will still benefit from the gold-standard accuracy and efficiency of dedicated PIC system hardware (Santamaria-Laorden A *et al.,* 2025). Further in vivo validation studies under real clinical conditions are eagerly anticipated.

### Artificial Intelligence Integration

Future photogrammetry systems are anticipated to incorporate artificial intelligence (AI) for real-time error detection and correction during capture; these possibilities represent the authors' projections rather than capabilities established in the current literature. In principle, AI algorithms could identify suboptimal camera angles, insufficient marker visibility, or potential misalignments before the capture is complete, providing immediate feedback to clinicians and reducing the need for retakes. Machine learning models trained on large datasets of successful captures could similarly optimize scanning protocols based on individual patient anatomy, implant configuration, and clinical conditions. While descriptive reviews of fully digital workflows note the growing role of such technologies (Auduc C *et al.,* 2025), dedicated clinical validation of AI-assisted photogrammetry has yet to be reported.

### Multi-Modal Integration

The convergence of photogrammetry with CBCT, facial scanning, and jaw tracking technologies promises to create comprehensive virtual dental patients (VDPs) for full-arch rehabilitation (Auduc C *et al.,* 2025). By combining precise implant position data from photogrammetry with facial scan data for smile design, CBCT for bone assessment, and dynamic jaw tracking for occlusal analysis, clinicians will be able to plan and execute full-arch rehabilitations with unprecedented predictability. The integration of intraoral photogrammetry with facial scanners and jaw motion tracking has already been demonstrated in clinical case reports, enabling same-day full-arch provisionalization with optimal occlusal and esthetic outcomes (Shining 3D, 2026).

### Research Priorities

The photogrammetry research agenda for the coming years should prioritize: (1) randomized controlled trials comparing long-term clinical outcomes of photogrammetry-based versus conventional or IOS-based full-arch prostheses; (2) cost-effectiveness analyses from healthcare system and patient perspectives; (3) development and validation of photogrammetry-specific patient-reported outcome measures; (4) standardization of accuracy assessment methodologies to enable meaningful cross-study comparisons; and (5) investigation of photogrammetry applications in partially edentulous, single-arch, and complex multi-implant scenarios beyond standard All-on-4/All-on-X configurations.

## DISCUSSION

Photogrammetry has established itself as the most accurate digital impression technique for full-arch implant rehabilitation, with a robust and rapidly expanding evidence base supporting its superiority over both conventional splinted open-tray impressions and intraoral scanning. The 2025 meta-analysis by Altalla *et al.,* provided definitive statistical confirmation of photogrammetry's advantages in trueness and precision, while multiple independent in vitro and clinical studies have consistently demonstrated linear deviations of 10-50 µm and angular deviations of 0.1-0.3 degrees, well within clinically acceptable thresholds (Altalla H *et al.,* 2025; Revilla-Leon M *et al.,* 2024).

The technology landscape has evolved rapidly from the single-category extraoral photogrammetry of 2010 to a diverse ecosystem encompassing extraoral systems (PIC, iCam4D, Micron Mapper, Tupel 3D, Grammee, OxoFit), intraoral photogrammetry (Aoralscan Elite), navigated photogrammetry (FastMap), and smartphone-based alternatives (PIC app). Each category offers distinct advantages in accuracy, workflow efficiency, and accessibility, enabling clinicians to select the most appropriate solution for their specific practice context.

Despite these advances, important challenges remain. Equipment costs continue to limit adoption in smaller practices and developing regions, though IPG and smartphone-based solutions are actively addressing this barrier. The predominance of in vitro evidence and the scarcity of long-term randomized clinical trials comparing photogrammetry-based prostheses against alternatives represent the most significant gaps in the current literature (Barreto DFCM, 2022). Cost-effectiveness analyses and photogrammetry-specific patient-reported outcome measures are urgently needed to inform healthcare policy and clinical decision-making.

Looking forward, the integration of photogrammetry with AI-driven error correction, multi-modal imaging (CBCT, facial scanning, jaw tracking), and increasingly accessible hardware platforms suggests that this technology will transition from a specialized tool for high-volume implant centers to a standard component of digital full-arch implant workflows within the next decade. For prosthodontists, implantologists, and dental technicians, developing competency in photogrammetry-based workflows is becoming an essential skill for delivering predictable, high-quality full-arch implant rehabilitation in the digital age.

**Clinical Recommendations**

Based on the current evidence base, the following clinical recommendations can be offered for photogrammetry use in full-arch implant rehabilitation:

**Table 4: Clinical recommendations for photogrammetry selection based on clinical scenario.**

| Clinical Scenario | Recommended Approach | Rationale |
|---|---|---|
| All-on-4/All-on-X, edentulous | EPG (PIC/iCam4D) or IPG | Highest accuracy for multi-implant capture; well-established evidence base (Abuduwaili K *et al.,* 2025; Altalla H *et al.,* 2025) |
| All-on-X with immediate loading | IPG with coded cap scan bodies | Unified capture in challenging soft-tissue environment; streamlined same-day workflow (Shining 3D, 2025) |
| X-Guide navigated surgery | FastMap navigated PG | Conversion-less workflow; same coordinate system as surgical plan (Nobel Biocare, 2024) |
| Low-resource setting | Smartphone PG (PIC app) | Validated accuracy; minimal equipment investment (Santamaria-Laorden A *et al.,* 2025) |
| Single-arch, 2-3 implants | IOS with horizontal scan bodies | Photogrammetry benefits less pronounced; IOS accuracy acceptable for short spans (Revilla-Leon M *et al.,* 2024) |

# CONCLUSION

Photogrammetry represents a transformative advancement in digital impression technology for full-arch implant rehabilitation, consistently demonstrating superior accuracy compared to both conventional splinted open-tray impressions and intraoral scanning. With linear trueness values of 10-50 µm and angular deviations under 0.3 degrees, photogrammetry provides clinicians with the precision necessary to achieve passive fit in complex full-arch prostheses. The evolution from extraoral to intraoral and navigated photogrammetry systems has addressed key workflow limitations while maintaining this accuracy advantage.

The emergence of smartphone-based photogrammetry promises to democratize access to this technology, potentially bringing precision implant dentistry to resource-limited settings worldwide. However, the current evidence base remains heavily weighted toward in vitro studies, and long-term randomized clinical trials comparing photogrammetry-based prostheses against alternative impression techniques are urgently needed. As the technology continues to evolve through AI integration and multi-modal imaging convergence, photogrammetry is poised to become a standard component of digital full-arch implant workflows, fundamentally improving the predictability and quality of implant rehabilitation outcomes.

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