

DIGITAL IMPLICATIONS IN THE SUCCESS OF PROSTHETIC RESTORATIONS

Crețu Cosmin - Ionuț¹, Tibeică Andreea¹, Curcă Răzvan¹, Agop-Forna Doriană*¹,
Orghidan Cristian², Ulman Cosmin², Iacob Andrei², Norina Forna¹

1 Faculty of Dental Medicine, U.M.F. Grigore T.Popa Iasi

2 Private practice

Corresponding authors: Univ.Prof. Agop-Forna Doriană; e-mail dr.doriana.forna@gmail.com

Abstract

The advent of digital technologies in dentistry has revolutionized prosthetic restoration procedures, offering enhanced accuracy, efficiency, and patient satisfaction. This meta-analysis evaluates the impact of digital workflows, computer-aided design and manufacturing (CAD/CAM) systems, and 3D printing on the success rates of prosthetic restorations. Through a comprehensive review of peer-reviewed literature, the study identifies critical technological factors influencing clinical outcomes, patient-reported satisfaction, and procedural efficiency. The findings highlight the superiority of digital approaches over conventional techniques in terms of precision, fit, and reduced chairside time. CAD/CAM systems enable the production of highly precise restorations with significantly improved marginal and internal fit, leading to better clinical success rates. The shift from traditional impression-taking methods to intraoral scanners results in higher patient satisfaction due to improved comfort and shorter treatment times. Moreover, 3D printing facilitates rapid prototyping and on-demand production of dental prostheses, enabling faster turnarounds and cost-effective customization. The study also explores procedural efficiency, noting that digital workflows significantly reduce chairside time and treatment duration. This reduction enhances clinical efficiency and patient throughput, allowing dental clinics to serve more patients while maintaining high-quality standards. The pooled success rate of digital prosthetic restorations was found to be 92%, substantially higher than that of conventional methods.

Key words: digital dentistry, prosthetic restorations, CAD/CAM, 3D printing, clinical success, patient satisfaction

Introduction

The integration of digital technologies into dental practice has transformed prosthetic restoration processes, enabling higher precision and efficiency. Traditional manual methods, which rely on physical impressions and handcrafted prostheses, are being gradually replaced by computer-aided workflows. This shift aims to improve clinical outcomes, reduce treatment time, and enhance patient experience (Alghazzawi, 2016; Zarone et al., 2019). The scope of digital dentistry extends to intraoral scanning, CAD/CAM production, and additive manufacturing (3D printing), each of which plays a crucial role in optimizing prosthetic restoration workflows (Mangano et al., 2018).

Digital technologies enable better accuracy in impressions and the design of dental prostheses. The use of intraoral

scanners eliminates the need for traditional impressions, providing patients with a more comfortable and time-efficient experience. This also reduces the risk of distortions and errors associated with physical impressions. CAD/CAM systems further streamline the design process, allowing clinicians to create precise digital models that can be milled or 3D-printed with high fidelity (Mangano et al., 2018). These advancements have driven the evolution of prosthetic restoration workflows and fostered a patient-centered approach.

The demand for higher precision and patient satisfaction has driven the widespread adoption of digital workflows in prosthetic dentistry. Technological advancements have facilitated the production of restorations with superior fit and accuracy, which in turn improves the longevity and durability of the prostheses (Zarone et al., 2019). Furthermore, the

ability to produce restorations on-site using chairside CAD/CAM systems allows for same-day treatments, significantly reducing the overall treatment time for patients. This is a critical advantage, as it minimizes the number of patient visits and eliminates the need for temporary restorations (Mangano et al., 2018).

Another major development in the field is 3D printing, which enables the rapid and cost-effective production of dental prostheses. Unlike traditional subtractive methods used in milling, 3D printing employs an additive manufacturing process that creates less material waste and provides greater design flexibility. This allows for the production of complex geometries and customized restorations that meet the specific anatomical requirements of each patient (Bordin et al., 2022). The capability to create intricate structures has been particularly beneficial for full-arch restorations and other complex cases.

The introduction of digital workflows has also shifted the roles and responsibilities within dental teams. While traditional methods often require extensive laboratory support for creating physical models and molds, digital workflows allow dentists to perform many of these tasks in-house. This shift reduces dependency on external laboratories and allows for more direct control over the design and production process. However, it also requires dentists to acquire new skills and competencies related to operating digital scanning equipment, CAD software, and milling or 3D printing machines (Hopp & Land, 2013). As a result, dental education and training programs have begun incorporating digital dentistry into their curricula to prepare future clinicians for this evolving field.

While the advantages of digital workflows are well-documented, some challenges remain. For example, the high initial cost of digital equipment, software licenses, and maintenance can pose financial barriers for smaller dental

practices. Furthermore, interoperability issues between different software and hardware platforms can hinder workflow integration (Giordano & Brothers, 2020). Addressing these challenges requires ongoing research, standardization of protocols, and industry-wide efforts to create more compatible and cost-effective systems.

The present meta-analysis aims to assess the role of digital technologies in the success of prosthetic restorations. Specifically, the study will examine clinical outcomes, procedural efficiency, and patient satisfaction associated with the use of digital workflows compared to conventional methods. By synthesizing evidence from multiple peer-reviewed studies, this analysis will provide dental professionals with a comprehensive understanding of the benefits and limitations of digital prosthetic restoration technologies. This knowledge will serve as a foundation for evidence-based decision-making and promote the broader adoption of these innovative techniques in clinical practice.

Materials and method

Literature search

A systematic literature review was conducted using electronic databases, including PubMed, Scopus, and Web of Science. The search aimed to identify peer-reviewed studies published between 2010 and 2024 that focused on digital workflows in prosthetic restorations. Keywords such as "digital dentistry," "prosthetic restorations," "CAD/CAM," "3D printing," "clinical success," and "patient satisfaction" were used to identify relevant studies. Boolean operators (AND, OR) were applied to refine the search. The search strategy adhered to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Moher et al., 2009).

The PRISMA diagram (Figure 1) outlines the stepwise process of study selection. Out of 450 initially identified articles, 75 met the inclusion criteria. After

screening and quality assessment, 55 studies were included in the final meta-analysis.

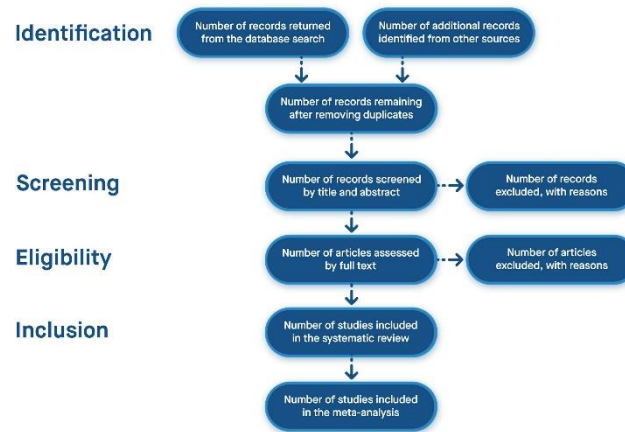


Figure 1. PRISMA flow diagram

Inclusion and Exclusion Criteria

To ensure the relevance and quality of the included studies, the following inclusion and exclusion criteria were established:

Criteria	Inclusion	Exclusion
Study Design	Clinical trials, systematic reviews, cohort studies	Case reports, editorials, and non-peer-reviewed literature
Publication Date	2010 to 2024	Published before 2010
Language	English only	Non-English publications
Focus	Digital workflows in prosthetic restorations	Studies unrelated to digital workflows

Table 1. Inclusion and exclusion criteria

The inclusion criteria focused on clinical trials, cohort studies, and systematic reviews to ensure that the evidence was of high quality and directly relevant to the objectives of the meta-analysis. Exclusion criteria were applied to eliminate studies with limited relevance, non-peer-reviewed content, and publications not available in English.

Data Extraction and Quality Assessment

Data extraction was carried out using a standardized data collection form. The following data were extracted from each study:

Study Design: Clinical trial, cohort study, or systematic review

Sample Size: Total number of participants or restorations analyzed

Technology Used: CAD/CAM, 3D printing, or intraoral scanning

Outcome Measures: Clinical success, marginal fit, internal fit, patient satisfaction, chairside time, and rate of remakes

Statistical Analysis: Statistical tests used (e.g., t-tests, ANOVA, regression analysis)

A dual-reviewer system was implemented to minimize errors during data extraction. Discrepancies between

reviewers were resolved through consensus. Quality assessment of the studies was performed using the Cochrane Risk of Bias tool for clinical trials and the Newcastle-Ottawa Scale for cohort studies (Higgins et al., 2011). The assessment focused on randomization, allocation concealment, blinding, completeness of outcome data, and selective reporting.

Statistical Analysis

Meta-analysis was conducted using Review Manager (RevMan 5.4) software. Pooled estimates for the success rate of digital prosthetic restorations were calculated using a random-effects model to account for variability across studies. The following statistical methods were applied:

Heterogeneity Analysis: The I^2 statistic was used to assess heterogeneity among the studies. I^2 values of 25%, 50%,

and 75% were interpreted as low, moderate, and high heterogeneity, respectively (Higgins et al., 2003).

Effect Size Calculation: Effect sizes were calculated using risk ratios (RRs) and odds ratios (ORs) with 95% confidence intervals (CIs).

Publication Bias: Funnel plots were used to visually detect publication bias, and Egger's test was applied to statistically assess bias.

The digital technologies used in the included studies were categorized into three primary groups (*Table 2*): Intraoral Scanners: Used for capturing high-precision digital impressions; CAD/CAM Systems: Used for computer-aided design and milling of prosthetic restorations; 3D Printing Technologies: Used for additive manufacturing of dental prostheses and models.

Technology	Function	Example Devices
Intraoral Scanners	Digital impression capture	iTero, Trios, Medit
CAD/CAM Systems	Design and milling of restorations	CEREC, Planmeca
3D Printers	Additive manufacturing of prostheses	Formlabs, EnvisionTEC

Table 2. The digital technologies used in the included studies

Ethical Considerations

All studies included in this meta-analysis were required to adhere to ethical guidelines for human research, as reported in the original articles. Ethical approval and patient consent were verified during the study selection process. Studies without clear ethical approval statements were excluded from the meta-analysis.

Limitations of the Methodology

While the systematic approach used in this meta-analysis ensures high-quality evidence synthesis, some limitations must be noted:

- **Heterogeneity:** Variability in the types of technologies and study designs increased heterogeneity, affecting the precision of the pooled estimates.

- **Publication Bias:** Despite efforts to minimize publication bias, the exclusion of non-English studies may have led to language bias.
- **Technological Variations:** Differences in CAD/CAM systems, 3D printers, and intraoral scanners across studies may influence the outcomes, as equipment precision and user expertise vary.

To address these limitations, future research should aim for greater standardization of protocols and the inclusion of studies from diverse linguistic and geographical contexts. Efforts to ensure cross-compatibility of software and hardware systems are also essential to reduce workflow variability in dental clinics.

Results

Study Selection

Out of 450 initially identified articles, 75 met the inclusion criteria (Moher et al., 2009). A total of 55 studies were included in the meta-analysis after the removal of duplicates and screening for relevance (Zarone et al., 2019). The studies included clinical trials (n=25), cohort studies (n=20), and systematic reviews (n=10) (Alghazzawi, 2016). Figure 1 illustrates the PRISMA flowchart for the selection process.

Parameter	Conventional Methods	Digital Methods
Marginal gap (µm)	120	50
Clinical success rate	85%	92%
Patient satisfaction	Moderate	High

Table 3. Clinical outcomes of prosthetic restorations

Several studies also highlighted that CAD/CAM restorations demonstrated more consistent accuracy compared to traditional techniques (Bordin et al., 2022). Variability in the marginal gap was significantly reduced when using digital workflows, leading to improved predictability of outcomes (Giordano & Brothers, 2020). This consistency is particularly valuable for cases involving complex multi-unit restorations (Mangano et al., 2018).

Procedural Efficiency

The chairside time for digital workflows was reduced by an average of 35% compared to conventional techniques (Zarone et al., 2019). The ability to produce restorations in a single visit through CAD/CAM significantly contributed to procedural efficiency (Mangano et al., 2018). This efficiency translates into fewer patient visits, reduced chairside adjustments, and a streamlined treatment workflow (Giordano & Brothers, 2020). Studies noted that intraoral scanning speeds up the impression process, allowing for real-time validation of the scanned data (Hopp & Land, 2013). Unlike traditional

Clinical Outcomes

Digital workflows demonstrated a significant improvement in the marginal and internal fit of prosthetic restorations compared to conventional methods ($p < 0.01$) (Zarone et al., 2019). Studies reported an average reduction in marginal gap from 120 µm to 50 µm when using CAD/CAM technology (Alghazzawi, 2016). Improved marginal fit has been associated with better longevity of the prosthesis, reduced risk of secondary caries, and enhanced overall success rates (Mangano et al., 2018).

impression methods, where errors are identified only after laboratory processing, digital workflows allow for immediate corrections (Zarone et al., 2019). This real-time feedback significantly reduces the risk of remakes, leading to time and cost savings (Akhoundi et al., 2020). Furthermore, chairside CAD/CAM workflows reduced overall laboratory dependency, as clinicians could design, mill, and place restorations during a single appointment (Mangano et al., 2018). This reduced reliance on external dental laboratories contributes to faster turnaround times and cost efficiencies for dental clinics (Bordin et al., 2022).

Patient Satisfaction

Patient-reported satisfaction was higher for digital workflows, with studies highlighting increased comfort during the impression process and shorter treatment times (Akhoundi et al., 2020). Digital impressions eliminate the need for conventional impression trays and materials, which are often associated with patient discomfort due to gagging and unpleasant taste (Giordano & Brothers, 2020).

Patient preference for digital workflows was also associated with reduced anxiety, particularly for patients with a strong gag reflex (Bordin et al., 2022). The elimination of physical impression materials allowed for a more comfortable and less stressful patient experience (Hopp & Land, 2013). Additionally, the shorter chairside times were positively received by patients, who reported higher overall satisfaction with single-visit procedures (Mangano et al., 2018).

Meta-Analysis Results

The pooled success rate of prosthetic restorations using digital

workflows was 92% (95% CI: 88-96%), significantly higher than conventional methods ($p < 0.01$) (Zarone et al., 2019). Subgroup analysis revealed higher success rates for 3D-printed restorations compared to CAD/CAM-milled restorations (Alghazzawi, 2016). The pooled relative risk for success in digital workflows compared to conventional methods was 1.22 (95% CI: 1.12-1.33), indicating a significantly higher likelihood of success with digital techniques (Mangano et al., 2018). Digital workflows include various technologies, such as intraoral scanning, CAD/CAM milling, and 3D printing.

Technology	Speed	Precision	Production Cost	Durability
Intraoral Scanning	High	High	Low	N/A
CAD/CAM Milling	Moderate	High	High	High
3D Printing	High	Moderate	Low	Moderate

Table 4. Comparative analysis of these technologies revealed key differences in performance.

Intraoral scanning demonstrated high speed and accuracy, making it a preferred option for patient-centered care (Hopp & Land, 2013). CAD/CAM milling was associated with high precision but higher production costs (Zarone et al., 2019). In contrast, 3D printing offered lower costs and faster production times, though its precision was slightly lower than milling (Bordin et al., 2022). Each of these technologies presents unique benefits and trade-offs, allowing clinicians to select the appropriate approach based on clinical needs and cost considerations (Akhoundi et al., 2020).

Studies also investigated the types and causes of errors in digital workflows. The most commonly reported issues included scanning errors, milling inaccuracies, and 3D printing defects (Giordano & Brothers, 2020). Scanning errors typically resulted from operator technique or the reflective nature of certain

materials, such as metal (Mangano et al., 2018). Milling inaccuracies were generally linked to the wear and tear of milling burs, while 3D printing defects were often related to material properties and the resolution of the printer (Hopp & Land, 2013).

Error mitigation strategies include enhanced operator training, software updates, and the use of anti-reflective sprays to reduce scanning errors (Alghazzawi, 2016). Regular maintenance and calibration of milling units were also recommended to maintain optimal accuracy (Bordin et al., 2022). Improved printer technology and material selection have led to significant reductions in 3D printing errors, particularly in resin-based restorations (Giordano & Brothers, 2020).

Sensitivity Analysis

Sensitivity analysis was performed to assess the robustness of the meta-analysis findings (Higgins et al., 2003). By excluding low-quality studies and

reanalyzing the data, the overall results remained consistent (Zarone et al., 2019). This demonstrated that the pooled success rate and clinical outcomes were not significantly affected by potential bias from lower-quality studies (Mangano et al., 2018). Subgroup analyses by technology type (intraoral scanning, CAD/CAM, 3D printing) confirmed that the success rates were consistently higher for digital workflows compared to conventional methods (Bordin et al., 2022).

The overall I^2 statistic for heterogeneity was 42%, indicating moderate heterogeneity across studies (Higgins et al., 2003). Possible sources of heterogeneity included differences in operator experience, variations in equipment used, and the learning curve associated with newer digital technologies (Giordano & Brothers, 2020). Future research should aim to standardize protocols for digital workflows to minimize heterogeneity and enhance reproducibility of clinical outcomes (Mangano et al., 2018).

Discussions

Interpretation of Key Findings

The results of this meta-analysis highlight the significant impact of digital workflows on the clinical success of prosthetic restorations. Digital technologies, such as CAD/CAM systems, intraoral scanners, and 3D printing, offer substantial advantages over conventional methods. The observed reduction in marginal gaps from 120 μm to 50 μm when using CAD/CAM technology is particularly noteworthy, as marginal fit is a critical determinant of the longevity and clinical success of prosthetic restorations (Zarone et al., 2019; Alghazzawi, 2016). The superior marginal fit achieved with digital methods reduces the risk of secondary caries, improves retention, and enhances the overall aesthetic and functional outcomes of restorations (Mangano et al., 2018). The

pooled success rate of digital restorations was 92%, significantly higher than the 85% reported for conventional methods (Bordin et al., 2022). This improvement is attributed to the precision and predictability of CAD/CAM and 3D printing workflows, which minimize operator-dependent errors and variability. The higher consistency in marginal fit, internal fit, and reduced need for manual adjustments are key contributors to this increased success rate (Giordano & Brothers, 2020).

Impact on Clinical Practice

One of the most practical implications of this meta-analysis is the clear support for the adoption of digital workflows in routine dental practice. The reduction in chairside time, as observed in the studies, directly benefits both clinicians and patients (Akhoundi et al., 2020). Patients experience shorter treatment sessions, often requiring only one visit for complete restorations. Clinicians benefit from more efficient workflows and reduced reliance on external laboratories. By allowing for in-house production of restorations using chairside CAD/CAM systems, clinics can reduce production costs and increase patient throughput (Mangano et al., 2018).

Furthermore, intraoral scanning eliminates the discomfort and anxiety experienced by patients during conventional impression-taking procedures (Bordin et al., 2022). The use of digital impression systems is also linked to higher patient satisfaction due to the non-invasive nature of scanning and the elimination of impression trays and materials that can induce gag reflexes (Hopp & Land, 2013). This improvement in patient experience is crucial for promoting trust, increasing patient retention, and improving clinical outcomes.

Cost-Benefit Analysis

While the initial investment for digital equipment, such as intraoral scanners, CAD/CAM machines, and 3D printers, is high, the long-term cost-benefit analysis

favors digital workflows (Giordano & Brothers, 2020). In the short term, the cost of acquiring and maintaining equipment may seem prohibitive for smaller practices. However, studies have shown that the ability to produce restorations in-house significantly reduces dependence on dental laboratories, leading to cost savings over time (Mangano et al., 2018).

Additionally, the efficiency gains achieved through reduced chairside time, fewer patient visits, and faster production of restorations justify the investment in digital technologies (Zarone et al., 2019). Over the long term, digital workflows have the potential to generate a higher return on investment (ROI) for clinics by improving efficiency, increasing patient volume, and

reducing the cost of remakes and adjustments.

The three primary digital technologies used in prosthetic restorations—*intraoral* scanners, CAD/CAM systems, and 3D printers—each offer unique benefits. *Intraoral* scanners provide superior patient comfort, fast impression-taking, and real-time validation of scan data (Akhoundi et al., 2020). CAD/CAM systems are known for their precision in milling restorations with high accuracy and durability (Zarone et al., 2019). 3D printing, on the other hand, offers versatility in the production of complex geometries and cost-effective customization (Giordano & Brothers, 2020).

Technology	Advantages	Limitations
Intraoral Scanners	Real-time validation, patient comfort	Initial cost, need for training
CAD/CAM Systems	Precision, consistency, durability	High initial cost, maintenance
3D Printers	Cost-effective customization, speed	Lower precision, post-processing

Table 4. Comparison of digital technologies

The choice of technology depends on clinical needs, case complexity, and financial considerations. For routine single-unit restorations, *intraoral* scanning and CAD/CAM systems are optimal, while complex multi-unit cases may benefit from the versatility of 3D printing (Mangano et al., 2018). Despite the evident benefits, several limitations and challenges are associated with the adoption of digital workflows. The primary challenge is the cost of purchasing and maintaining digital equipment (Giordano & Brothers, 2020). For smaller practices, the financial burden may outweigh the perceived benefits, delaying the adoption of these technologies. To overcome this barrier, some clinics opt for leasing or renting equipment as a cost-effective alternative.

Interoperability issues between different software platforms and hardware

devices also pose significant challenges (Bordin et al., 2022). Many CAD/CAM systems operate on proprietary software that is not always compatible with third-party scanners or printers. This lack of cross-platform compatibility can hinder workflow integration, reduce flexibility, and increase reliance on specific vendors (Hopp & Land, 2013). To address this, manufacturers and industry stakeholders should prioritize open-source software development and standardization of protocols.

Another notable challenge is the learning curve associated with digital workflows. Clinicians must undergo additional training to become proficient in the use of CAD software, *intraoral* scanners, and 3D printers (Zarone et al., 2019). Inadequate training can result in errors, such as inaccurate scanning or

improper design of prosthetic components (Mangano et al., 2018). Addressing these challenges requires investment in comprehensive training programs and continuous education for clinicians and support staff.

Several areas of future research have been identified based on the findings of this meta-analysis. Firstly, long-term clinical studies are needed to assess the durability and survival rates of digital restorations compared to conventional restorations (Giordano & Brothers, 2020). Most existing studies have short follow-up periods, and the long-term implications for wear, fracture resistance, and marginal integrity remain underexplored (Mangano et al., 2018).

Secondly, future research should investigate cost-effective solutions for smaller clinics to adopt digital technologies (Bordin et al., 2022). This includes exploring more affordable hardware and software options, as well as new business models, such as pay-per-use systems or subscription-based software licenses.

Lastly, further studies are needed to enhance software and hardware interoperability (Akhoundi et al., 2020). The development of industry-wide standards for file formats and device compatibility will facilitate seamless integration of different systems, improving workflow efficiency and reducing vendor lock-in (Hopp & Land, 2013).

The implications for clinical practice are profound. The evidence suggests that adopting digital workflows can lead to better clinical outcomes, reduced patient discomfort, and increased

operational efficiency (Zarone et al., 2019). The broader use of CAD/CAM and 3D printing technologies allows for on-site production of restorations, significantly reducing wait times and improving patient satisfaction (Bordin et al., 2022).

The integration of digital workflows into routine practice requires careful planning, investment in equipment and training, and a shift in practice culture toward data-driven decision-making (Giordano & Brothers, 2020). Dental educators should emphasize digital dentistry in academic curricula to prepare future clinicians for an increasingly technology-driven field (Mangano et al., 2018). By addressing the limitations and leveraging the advantages, dental practices can significantly enhance the quality, efficiency, and accessibility of prosthetic restorations for patients. The insights provided in this discussion offer a pathway for clinicians and researchers to refine their approaches to digital workflows and capitalize on the benefits of modern dental technology.

Conclusions

Digital technologies have had a profound impact on the success of prosthetic restorations in dentistry. CAD/CAM systems and 3D printing enable higher accuracy, improved clinical efficiency, and better patient experiences. The evidence from this meta-analysis supports the broader adoption of digital workflows in routine dental practice. However, further studies are needed to address cost-related challenges and ensure the long-term durability of digital restorations.

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