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Research Article

Beyond the Impression Tray: A Comprehensive Review of Digital Technologies Transforming Prosthodontic Rehabilitation: From Intraoral Scanning and Virtual Articulation to CAD/CAM Fabrication and Clinical Validation

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Abstract

Digital technology has transformed prosthodontic rehabilitation by integrating Intraoral Scanning (IOS), virtual articulation, CAD/CAM fabrication and digitally guided implant surgery into a coherent clinical workflow. Conventional methods, while valid, are limited by material distortion, operator variability and patient discomfort. A narrative review was conducted using PubMed, Scopus and Google Scholar, including systematic reviews, meta-analyses and prospective clinical studies published within the previous five years. Evidence supports measurable advantages in efficiency, patient comfort and laboratory communication. IOS demonstrates acceptable accuracy for single crowns and short-span restorations; however, full-arch and complex implant-supported cases remain susceptible to cumulative error. CAD/CAM restorations from zirconia and lithium disilicate show acceptable marginal fit and long-term survival. Evidence for virtual articulation, digital occlusal analysis, additive manufacturing of definitive restorations and AI-assisted tools remains limited. Long-term prospective studies are necessary to validate fully digital workflows across the full spectrum of prosthodontic complexity.

Keywords: CAD/CAM; Digital Workflow; Digital Prosthodontics; Intraoral Scanning (IOS); Lithium Disilicate; Zirconia; All-Ceramic Crowns; Marginal Adaptation; Fracture Resistance

Introduction

Prosthodontic rehabilitation has traditionally relied on analog workflows centered on elastomeric impressions, stone casts, facebow transfers and manual wax-up procedures methods refined over decades, yet inherently constrained by material distortion, operator variability and patient discomfort [1]. In recent years, the rapid integration of digital technologies has fundamentally transformed this paradigm, introducing a connected and increasingly automated workflow that spans data acquisition, virtual modeling, prosthetic design and fabrication [2].

The evolution of digital dentistry from early chairside systems; most notably the CEREC platform introduced in the 1980s, to today's cloud-based and Artificial Intelligence (AI)-assisted environments has enabled seamless, model-free workflows integrating Intraoral Scanning (IOS), Computer-Aided Design and Manufacturing (CAD/CAM) and advanced fabrication techniques [1,2]. These systems have demonstrated consistent advantages in efficiency, reducing clinical and laboratory time while improving patient comfort and communication [1,3,4]. In parallel, they support a shift toward patient-centered, data-driven care in which treatment planning and outcomes are increasingly guided by digital information [5,6].

Intraoral scanning has emerged as a cornerstone of this transformation, replacing conventional elastomeric impressions with high-resolution three-dimensional datasets [7]. While digital impressions demonstrate comparable accuracy across many clinical applications, their reliability remains technique- and indication-dependent; particularly in full-arch rehabilitations, where cumulative stitching error may compromise precision [1,3,7]. Similarly, virtual articulation systems aim to replicate conventional occlusal analysis through dynamic simulation, yet clinical validation in complex cases remains limited [3].

Advances in CAD/CAM technology and material science have enabled the precise and efficient fabrication of restorations with improved mechanical and esthetic properties, while reducing reliance on manual laboratory techniques [3,4]. The integration of AI tools is further extending digital workflows into diagnostic support and predictive modeling, reinforcing a broader transition toward more automated prosthodontic practice [6].

Despite these advances, the superiority of digital workflows over conventional approaches remains context-dependent. While efficiency gains and improvements in patient experience are consistently reported, evidence on accuracy, marginal adaptation and long-term clinical outcomes is not uniformly conclusive, particularly for complex rehabilitations involving multiple units or fully edentulous arches [1,3,7].

This review evaluates the clinical impact of digital technologies on prosthodontic rehabilitation, with focused attention on intraoral scanning, virtual articulation, CAD/CAM systems and long-term clinical outcomes. It critically examines whether digital workflows fulfill their stated promise of superior clinical performance relative to conventional analog techniques and identifies where meaningful gaps in the evidence remain.

Intraoral Scanning: Principles, Accuracy and Clinical Reliability Across Prosthodontic Applications

Intraoral scanning has become a foundational component of contemporary prosthodontic practice, offering a digital alternative to conventional impression techniques that is faster, more comfortable for patients and directly compatible with downstream CAD/CAM workflows [8]. The clinical value of any IOS system is ultimately determined by the quality and accuracy of the dataset it produces.

Optical Principles and System Design

Contemporary IOS systems operate on one of several optical principles, each with distinct implications for scanning speed, resolution and sensitivity to environmental interference. Structured light systems project a known pattern onto the target surface and reconstruct surface geometry at high speed but are sensitive to reflective surfaces and moisture [7]. Confocal microscopy-based systems achieve depth selectivity by focusing on sequential tissue layers, offering improved precision in challenging intraoral conditions. Wavefront sampling technologies generate three-dimensional surface data through phase-based optical capture. These underlying principles influence the precision and fidelity of the acquired dataset and an understanding of them supports appropriate scanner selection for specific clinical applications [8].

Accuracy in Single-Unit and Fixed Partial Denture Restorations

For single-unit restorations, IOS has consistently demonstrated accuracy comparable to or exceeding that of conventional elastomeric impressions. Systematic review data confirm that dimensional accuracy in recording single preparations, including post and core preparations is clinically acceptable across contemporary IOS systems [9]. For fixed partial dentures (FPDs), digital workflows produce predictable results across a range of span lengths, though marginal discrepancy values can vary with scanner model, operator experience and margin management [8].

Full-Arch and Implant-Supported Restorations

The reliability of IOS diminishes in proportion to the complexity and span of the clinical situation. Full-arch scans are particularly susceptible to stitching artifacts, cumulative alignment errors that arise as the software integrates successive image frames over extended distances [10]. *In-vivo* studies confirm that digital implant impressions obtained with IOS demonstrate acceptable accuracy for single and short-span implant restorations when appropriate scan body protocols are employed [11,12]. However, a systematic review by Pesce, et al., confirmed that scanning accuracy decreases significantly with increasing arch length, with this limitation most pronounced in full-arch implant-supported cases [10].

In fully edentulous full-arch implant cases, the absence of natural tooth reference surfaces substantially increases the risk of cumulative registration error. In these situations, conventional impression techniques or photogrammetry-based workflows may offer superior accuracy and their use should remain part of the clinician's available options [13].

Clinical Variables Affecting Scan Quality

Beyond device-specific performance, several clinical variables directly influence scanning accuracy. Moisture control is paramount: saliva and blood can interfere with optical capture and introduce surface artifacts. Soft tissue management including the creation of clear, supragingival or lightly equigingival margins, is equally important to ensure the preparation finish line is fully captured [12]. Operator experience and familiarity with the specific scanner system play a meaningful role, with documented learning curve effects that standardized scanning protocols can mitigate. In implant prosthodontics specifically, scan body selection and placement technique are key determinants of digital impression accuracy [12].

Patient-Centered Outcomes

From a patient experience standpoint, IOS consistently outperforms conventional impressions. Systematic review evidence reports improved comfort, reduced gag reflex activation and shorter chair time [8]. These factors enhance patient acceptance and reduce procedure-related anxiety, supporting the routine adoption of IOS for straightforward to moderately complex cases. Patient-reported outcome measures should, however, be considered alongside; not in place of objective accuracy data when making technique selection decisions.

In summary, IOS represents a reliable, efficient and patient-friendly alternative to conventional impression techniques across a wide range of prosthodontic applications. Its limitations in full-arch and complex implant scenarios are well-characterized and should guide case selection. Further evidence on multi-unit and full-arch digital accuracy, particularly from in vivo perspective studies, remains an important area for future research [14].

Virtual Articulation and Digital Occlusal Analysis: Replacing the Facebow and Articulator

Following intraoral scan acquisition, the digital model must be related to the patient's occlusion and mandibular dynamics before prosthetic design can proceed. In conventional prosthodontics, this has been accomplished through facebow records, mounted casts and mechanical articulators. Within the digital workflow, these procedures are now being replaced or augmented by virtual articulators, digital facebow transfer, jaw tracking devices and digital occlusal analysis platforms [15,16].

Virtual Articulators

Virtual articulators are software-based instruments that simulate static and dynamic occlusion using digitized cast data, allowing the clinician to evaluate occlusal relationships and excursive movements before the restoration is finalized in the CAD design phase. A recent systematic review by Saini, et al., reported that virtual articulator software can achieve accuracy and precision comparable to conventional mechanical articulators under laboratory conditions, supporting their integration into prosthodontic planning workflows [17]. However, the same review acknowledged substantial heterogeneity in available software platforms, methodologies and study designs, nearly all laboratory-based, which limits the generalizability of these findings to complex clinical scenarios [17].

Digital Facebow Transfer

Digital facebow transfer positions the maxillary arch virtually relative to a reference axis, enabling a virtual mounting without physical casts. D'Albis, et al., described an integrated workflow combining IOS, facial surface scanning and digital facebow capture for virtual articulator mounting [18]. This approach can streamline the interface between scan acquisition and CAD/CAM design; its accuracy, however, depends on the fidelity of facial reference data, the quality of the intraoral scan and software alignment precision. Standardization of digital facebow protocols is an ongoing area of development.

Jaw Tracking Technology

Jaw tracking systems record patient-specific mandibular movement data in three dimensions, enabling virtual articulator programming with individualized condylar guidance values rather than population-averaged settings. This individualization is particularly relevant in complex and full-mouth rehabilitations, where small occlusal scheme errors can produce clinically significant discrepancies in the final restoration [19]. Lin, et al., highlighted the importance of accurately capturing sagittal and transverse condylar inclination when programming virtual articulators, reinforcing the need for validated jaw tracking protocols in high-complexity cases [20]. Although jaw tracking holds considerable theoretical promise for improving occlusal simulation fidelity, the prospective clinical evidence base supporting its routine use remains limited [19].

Digital Occlusal Analysis

Digital occlusal analysis systems most notably T-Scan (Tekscan, Boston, MA) provide quantitative data on occlusal contact timing, sequential contact distribution and relative force magnitude that conventional shimstock and articulating paper cannot capture. These capabilities are particularly useful in managing occlusal disease, implant prosthodontics, bruxism rehabilitation and large restorative cases [21,22]. A systematic review by Chowdhary and Sonihalli confirmed the clinical utility of T-Scan across a range of applications including equilibration guidance and implant loading optimization [22].

Nevertheless, Seth-Johansen and Gotfredsen identified important validity and reliability limitations of digital occlusal analysis methods, particularly in measuring absolute contact intensity, contact area and precise interocclusal relationships [23]. These findings reinforce that digital occlusal data should complement, not replace, established clinical judgment and conventional occlusal assessment. A multi-method approach combining digital analysis with clinical examination and analog verification remains the most defensible standard of care in complex prosthodontic cases.

Current Status and Evidence Gaps

Virtual articulation and digital occlusal analysis are genuinely useful components of the digital prosthodontic workflow, facilitating the transition from intraoral scan to CAD design with a degree of occlusal information previously difficult to obtain digitally. However, the current evidence; largely laboratory-based, methodologically heterogeneous and limited to short-term outcomes, supports their role as complementary tools rather than definitive replacements for conventional facebow records and mechanical articulators in complex full-mouth rehabilitation [15-17]. Prospective clinical trials with standardized protocols and long-term follow-up are needed before full clinical equivalence can be established

CAD/CAM Design and Material Science: Engineering the Perfect Restoration Digitally

Computer-aided design and manufacturing has become the manufacturing backbone of the digital prosthodontic workflow, translating digitized intraoral data and virtual designs into physical restorations with a level of reproducibility that analog laboratory techniques cannot consistently match [16]. The clinical performance of any CAD/CAM restoration is a function of three interdependent variables: the precision of the software-driven design process, the selection of an appropriate restorative material and the capabilities of the chosen manufacturing system [17].

The CAD Design Process

The design phase in contemporary prosthodontic CAD software encompasses a sequence of critical decisions, margin detection and die spacer calibration, anatomical library selection, occlusal morphology adjustment and connector dimensioning in multi-unit prostheses. Each decision carries direct consequences for marginal fit, occlusal accuracy and mechanical performance of the final restoration. Systematic review evidence confirms that digital design workflows improve reproducibility and reduce operator-dependent variability in restoration geometry relative to conventional wax-up techniques [24]. Automated design tools, including AI-assisted anatomical morphology suggestions, reduce reliance on manual laboratory artistry, but require clinician and technician review particularly in cases where standard anatomical libraries may not reflect the patient's individual occlusal dynamics or esthetic requirements [17,25].

CAD/CAM Materials

Material selection is a critical determinant of CAD/CAM restoration success. The current clinical landscape encompasses a diverse range of materials with distinct mechanical, optical and machinability profiles [25]. Zirconia, particularly in high-translucency formulations (4Y-TZP and 5Y-TZP), offers superior fracture resistance and has progressively improved in optical properties, supporting its use in both posterior and anterior restorations [26]. However, the translucency improvements in newer zirconia generations are accompanied by a reduction in tetragonal phase content and consequently lower flexural strength relative to conventional 3Y-TZP, a mechanical trade-off that must be carefully considered in case selection [26,27]. Lithium disilicate (e.g., IPS e.max CAD) remains the material of choice when optical depth and translucency are the primary esthetic priority, offering flexural strength values in the range of 360-400 MPa following crystallization, adequate for single-unit anterior and premolar restorations under normal functional loading [25].

Polymer-Infiltrated Ceramic Networks (PICN) such as Vita Enamic, combine a ceramic matrix with an interpenetrating polymer network, yielding an elastic modulus closer to that of dentin, favorable stress distribution behavior and reduced milling-induced chipping [28]. These properties make PICNs particularly suitable for minimally invasive restorations including onlays, endocrowns and veneers. PMMA-based materials provide a cost-effective option for interim restorations, enabling immediate provisionalization and occlusal evaluation prior to definitive prosthesis fabrication [29].

Chairside versus Laboratory-Based Milling

Chairside CAD/CAM systems enable single-visit restoration delivery, with milling occurring in the operatory. While this offers meaningful efficiency advantages particularly for single-unit posterior restorations, chairside milling units are generally limited in material range and block size and surface quality post-milling may be inferior to laboratory-grade equipment [29]. Laboratory-based milling systems accommodate a broader range of materials, larger restoration types and more complex prosthetic designs, including multi-unit frameworks and implant-supported bars. Selection between chairside and laboratory fabrication should be guided by case complexity and material requirements, not by a default preference for either system [30].

Additive Manufacturing

Three-dimensional printing technologies including Stereolithography (SLA), Digital Light Processing (DLP) and material jetting are increasingly applied to diagnostic wax-ups, surgical guides, occlusal splints and interim restorations [29]. For definitive restorations, however, the evidence on dimensional accuracy, surface quality and long-term mechanical performance of additively manufactured materials remains limited and, in many instances, inferior to milled counterparts [25]. Current consensus supports additive manufacturing for diagnostic and surgical planning applications and interim restorations, while recommending subtractive milling for definitive restorations pending further validation [30].

Digital Protocols in Implant Prosthodontics: Precision, Clinical Workflows and Contemporary Reliability

Digital workflows in implant prosthodontics have evolved substantially, driven by improvements in IOS accuracy for implant position registration, advances in guided implant surgery and the integration of CAD/CAM fabrication for implant-supported restorations [31]. The digital workflow in this domain spans pre-surgical planning, intraoperative guidance, impression-taking and prosthetic fabrication each of which can now be managed within a coherent digital chain [32].

Digital Implant Planning and Guided Surgery

Three-dimensional implant planning software allows for the virtual placement of implants relative to bone volume, anatomical structures and prosthetically driven emergence profiles, the 'prosthetically driven implantology' paradigm [33]. CBCT data are merged with digital surface scans to create a virtual patient model from which static or dynamic surgical guides can be generated. Systematic review data support the accuracy of digitally guided implant placement, with mean angular deviations typically in the range of 2–4° and apical point deviations of approximately 1–2 mm relative to the planned position; values considered clinically acceptable for most scenarios [34].

Digital Impressions for Implant Restorations

As discussed in Section 2, IOS-based digital impressions for single and short-span implant restorations demonstrate clinical accuracy comparable to conventional open-tray impressions when appropriate scan body protocols are employed [11,12]. For full-arch implant cases, the susceptibility of IOS to cumulative error over extended distances is particularly relevant and conventional or photogrammetry-based impression techniques remain preferred by many clinicians in these scenarios [12].

Digitally Fabricated Implant Prostheses

CAD/CAM fabrication of implant-supported crowns, multi-unit frameworks and full-arch prostheses enables production with high dimensional accuracy and consistency. Digitally designed emergence profiles can be precisely planned to optimize peri-implant soft tissue health and marginal adaptation [35,36]. In full-arch implant rehabilitations, digitally fabricated hybrid prostheses; typically consisting of milled titanium or zirconia frameworks with composite or ceramic veneering materials have shown promising short- to medium-term clinical outcomes, though long-term prospective data remain limited [37].

The integration of digital planning, guided surgery, digital impression and CAD/CAM fabrication into a coherent implant workflow represents one of the most significant clinical advances in contemporary prosthodontics. However, each step introduces potential sources of cumulative error and the overall accuracy of a fully digital implant workflow should be validated against clinical performance benchmarks rather than assumed from the performance of individual components in isolation [31,34].

Clinical Accuracy, Marginal Fit and Long-Term Outcomes: Does the Digital Workflow Deliver?

The clinical performance of CAD/CAM restorations has been extensively investigated, with marginal and internal adaptation representing primary outcome measures given their established association with restoration longevity, pulpal health and susceptibility to secondary caries. The preponderance of evidence indicates that marginal discrepancies for CAD/CAM crowns fabricated from lithium disilicate and zirconia generally fall within clinically acceptable thresholds, suggesting that digital workflows can achieve precision comparable to conventional laboratory fabrication [38,39].

Marginal and Internal Fit

The accuracy of a CAD/CAM restoration is not an inherent property of the digital workflow but rather an emergent outcome of the entire acquisition-to-fabrication chain. Turkyilmaz, et al., in a systematic review of marginal and internal fit of lithium disilicate and zirconia CAD/CAM crowns produced from digital impressions, confirmed that clinically acceptable adaptation values are achievable, but that meaningful inter-system variability exists attributable to differences in IOS devices, software algorithms and milling unit capabilities [35,40]. Sultan, et al., similarly demonstrated that the type of IOS system and CAD/CAM platform significantly influences marginal fit of lithium disilicate ceramic crowns, including those fabricated from virgilite-phase blocks (the pre-crystallized lithium metasilicate form processed in the milling stage prior to final crystallization), reinforcing that restoration accuracy is equally determined by the precision of each digital processing step [36,41]. Small discrepancies introduced at scanning, design or milling may accumulate and affect the final clinical outcome.

Biomechanical Performance and Material Behavior

The design configuration of a CAD/CAM crown influences how occlusal and parafunctional stresses are distributed within the restoration and at the tooth-restoration interface. Jalalian, et al., compared endocrowns fracture resistance and marginal adaptation between CAD/CAM lithium disilicate and zirconia-reinforced lithium silicate ceramics, finding acceptable mechanical performance for both materials, with marginal adaptation influenced by the specific material and preparation design [42]. Hajaj, et al., further demonstrated that margin design geometry; specifically, the choice between chamfer, shoulder and feather-edge preparations, significantly affects the fracture resistance of both zirconia and lithium disilicate CAD/CAM crowns, with direct implications for preparation planning [43].

Zirconia demonstrates superior fracture resistance through its transformation toughening mechanism, making it the preferred material for high-load posterior applications and longer-span fixed prostheses. Lithium disilicate offers superior optical properties and adequate mechanical performance for single-unit anterior and premolar restorations under normal functional loading, provided adequate occlusal reduction and appropriate preparation design are maintained [44]. Clinically, lithium disilicate restorations exhibit a higher incidence of chipping and surface fracture relative to zirconia, while zirconia restorations may present esthetic limitations in cases with high tissue-level demands [45].

Long-Term Clinical Survival

A systematic review and meta-analysis by Saravi, et al., reported 10-year survival rates of approximately 79-82% for tooth-supported all-ceramic fixed dental prostheses fabricated using CAD/CAM technology outcomes comparable to those reported for conventionally fabricated all-ceramic restorations [41]. The primary causes of failure included framework fracture, biological complications (secondary caries, endodontic complications) and cementation issues. While these data support the long-term clinical reliability of CAD/CAM restorations, they also confirm that technical and biological complications remain relevant concerns in longitudinal evaluations. Clinical success requires not only accurate fabrication but also appropriate case selection, preparation design and cementation protocol [42].

Clinical Decision-Making and Material Selection

Material selection for a CAD/CAM restoration should integrate functional demands, esthetic requirements, preparation geometry and available long-term evidence for the specific clinical scenario. Zirconia is generally favored under elevated functional loading, parafunction or when long-span coverage is required [38,39]. Lithium disilicate is the material of choice when esthetic priority is paramount and adequate tooth reduction can be achieved [35,36]. Preparation design is not merely a preliminary clinical step but a critical determinant of the mechanical response of the final restoration and this relationship should be integrated into material selection decisions from the outset of treatment planning [45,46].

In summary, CAD/CAM restorations fabricated from zirconia and lithium disilicate demonstrate clinically acceptable marginal fit and competitive long-term survival when appropriate technology, materials and clinical protocols are employed. Technical complications persist in longitudinal follow-up and underscore that a thorough understanding of the material science, design principles and workflow-specific accuracy factors is essential for predictable outcomes [44].

Conclusion

Digital prosthodontics is most accurately understood as an integrated clinical and technological system rather than a collection of discrete instruments. Intraoral scanning, virtual articulation, CAD/CAM design and fabrication and AI-assisted planning now function collectively across all stages of prosthodontic rehabilitation and their clinical value derives primarily from the coherence and quality of the workflow they constitute. Fully digital workflows unify data acquisition, virtual prosthetic design and computer-aided fabrication into a structured clinical process, with the potential to streamline fixed prosthodontic treatment, reduce chair and laboratory time and improve coordination between the clinical and laboratory environments.

The current evidence supports several meaningful advantages of digital prosthodontics over conventional approaches. Consistent improvements in treatment efficiency, prosthetic accuracy within defined clinical applications and patient experience including reduced discomfort, shorter chair time and fewer postoperative occlusal adjustments, are reported across the literature. These benefits are achieved without a clinically significant compromise in restoration survival, which is broadly comparable to that of conventionally fabricated prostheses. For implant-supported restorations in partially edentulous patients, fully digital workflows are particularly well-supported by current evidence.

However, these advantages must be interpreted within the boundaries of case complexity, operator proficiency and workflow-specific limitations. Evidence for fully digital workflows in complex multi-unit rehabilitations, particularly full-arch and full-mouth reconstructions, remains limited and their adoption in demanding cases should be accompanied by appropriate verification steps and clinical judgment. The performance of any digital workflow varies with scanner model, software platform, milling equipment and operator experience and accuracy claims should be evaluated against standardized clinical benchmarks rather than accepted generically.

Additive manufacturing continues to expand within prosthodontic workflows, but evidence supporting its use for definitive restorations remains substantially weaker than for subtractive milling, particularly regarding long-term mechanical durability and dimensional accuracy. Its current clinical utility is most clearly established for diagnostic models, surgical guides, occlusal splints and interim restorations and its use for definitive prosthetics should await further prospective validation before broad clinical adoption is recommended.

The integration of AI into digital prosthodontics represents one of the most consequential emerging developments in the field. AI-assisted tools for margin detection, shade selection, prosthetic design and outcome prediction hold genuine promise for improving reproducibility and reducing cognitive demands. Nevertheless, the methodological quality of available evidence on AI applications in prosthodontics is frequently limited by small sample sizes, lack of external validation and substantial risk of bias. Clinical adoption should therefore be governed by evidence of validated performance in prospective settings rather than by enthusiasm for the technology alone.

The future of digital prosthodontics will be defined not by the availability of technology, but by the rigor with which that technology is evaluated. The critical imperative for the field is the production of well-designed, prospective, long-term clinical studies assessing fully digital workflows across the full spectrum of prosthodontic complexity, from single-unit restorations to full-arch implant rehabilitations. Only through this evidentiary foundation can digital prosthodontics fulfill its substantial promise as a genuinely superior model of patient care.

Conflict of Interest

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The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethical Statement

The project did not meet the definition of human subject research under the purview of the IRB according to federal regulations and therefore was exempt.

Informed Consent Statement

Not applicable.

Authors' Contributions

All authors contributed equally to this paper.

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