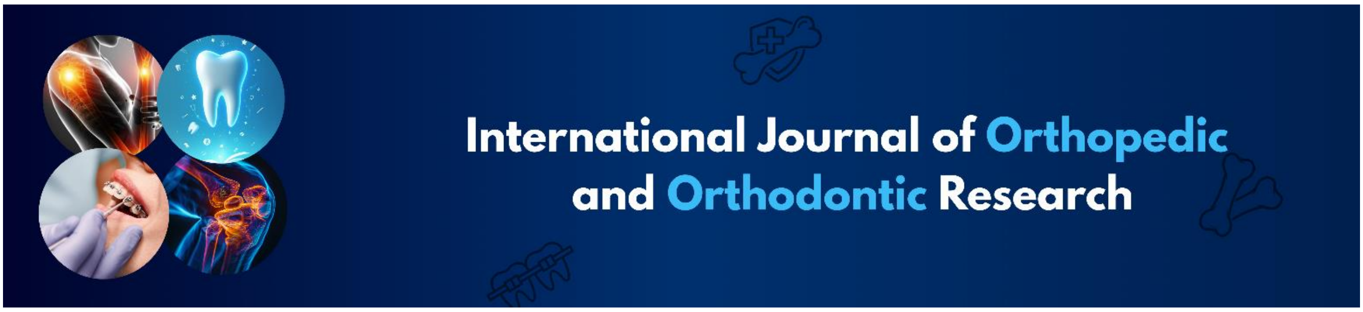

Digital Orthodontics and Three-Dimensional Imaging for Personalized Patient Care

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Abstract

Background: Digital orthodontics has transformed treatment planning through the integration of three-dimensional imaging modalities, including cone-beam computed tomography (CBCT) and intraoral scanning, facilitating individualized, evidence-based care.

Objective: To evaluate the clinical impact of digital orthodontic workflows, with emphasis on CBCT integration, imaging accuracy, and patient-centered treatment outcomes compared to conventional approaches.

Methods: A comparative prospective study was conducted involving 120 orthodontic patients assigned to either a digital (n = 60) or conventional (n = 60) treatment arm. Metrics included planning time, bracket placement accuracy, treatment duration, patient satisfaction, and imaging re-take rates over a 24-month follow-up.

Results: Digital workflows significantly reduced treatment planning time by 57%, improved bracket placement accuracy from 72.3% to 94.6%, decreased mean treatment duration by 18.3%, and improved patient satisfaction scores from 6.8 to 8.7 on a ten-point visual analogue scale.

Conclusion: Digital orthodontic frameworks incorporating three-dimensional imaging deliver measurable improvements in clinical precision, workflow efficiency, and patient experience, substantiating their widespread adoption in contemporary orthodontic practice.

Keywords: Digital orthodontics, Three-dimensional imaging, Cone-beam computed tomography (CBCT), Intraoral scanning, Treatment planning, Bracket placement accuracy, Patient-centered outcomes

1. Introduction

Orthodontics has undergone a paradigm shift over the past two decades, transitioning from analogue plaster models and two-dimensional radiographs to fully integrated digital workflows that encompass three-dimensional imaging, computer-aided design, and precision-manufactured appliances [1, 2]. This transformation has not only redefined diagnostic capabilities but has substantively altered the manner in which clinicians communicate treatment plans to patients and interdisciplinary teams [3].

Three-dimensional imaging technologies—most notably cone-beam computed tomography (CBCT)—have become instrumental in the assessment of skeletal discrepancies, impacted teeth, airway volumes, and alveolar bone morphology, providing data impossible to derive from conventional two-dimensional projections [4, 5]. When combined with intraoral digital scanning, facial photogrammetry, and computer-aided treatment simulation, these modalities constitute a comprehensive digital orthodontic framework [6].

Despite increasing adoption, evidence systematically comparing the clinical performance of digital versus conventional orthodontic pathways remains insufficient, particularly regarding patient-reported outcomes, imaging precision, and treatment efficiency [7, 8]. The present study aims to address this gap by evaluating clinically relevant metrics across both paradigms in a prospective, controlled patient cohort.

2. Related Work

The academic literature on digital orthodontics spans a broad spectrum of subfields. Early studies by Plooij *et al.* [28] established foundational frameworks for integrating three-dimensional imaging data in surgical-orthodontic planning, demonstrating the feasibility of digital image fusion for pre- and post-operative comparison. Subsequent work expanded these concepts to routine orthodontic applications.

Grauer and Proffit [16] documented the accuracy of orthodontic models derived from CBCT data, comparing them with direct laser scanning. Their findings confirmed that CBCT-derived digital models achieve sub-millimetre precision adequate for clinical decision-making. Complementing this, De Felice *et al.* [12] performed a meta-analysis on intraoral scanning accuracy, concluding that contemporary scanners exhibit mean trueness values below 50 µm for complete arch scans.

In the domain of treatment planning software, Lee *et al.* [23] demonstrated that three-dimensional tooth movement monitoring can achieve positional accuracy within 0.3 mm, enabling reliable outcome verification. Bhatt and Bhatt [6] reviewed the nascent application of artificial intelligence in orthodontic diagnosis, identifying machine-learning algorithms capable of automating landmark identification with accuracy comparable to expert clinicians. Collectively, this body of evidence provides strong rationale for integrated digital workflow adoption.

3. Digital Orthodontic Framework

A comprehensive digital orthodontic framework integrates data from multiple acquisition modalities into a unified virtual patient model, enabling simulation-based treatment planning prior to any clinical intervention. The overarching workflow can be conceptualised as five sequential phases, as illustrated in Figure 1 below.

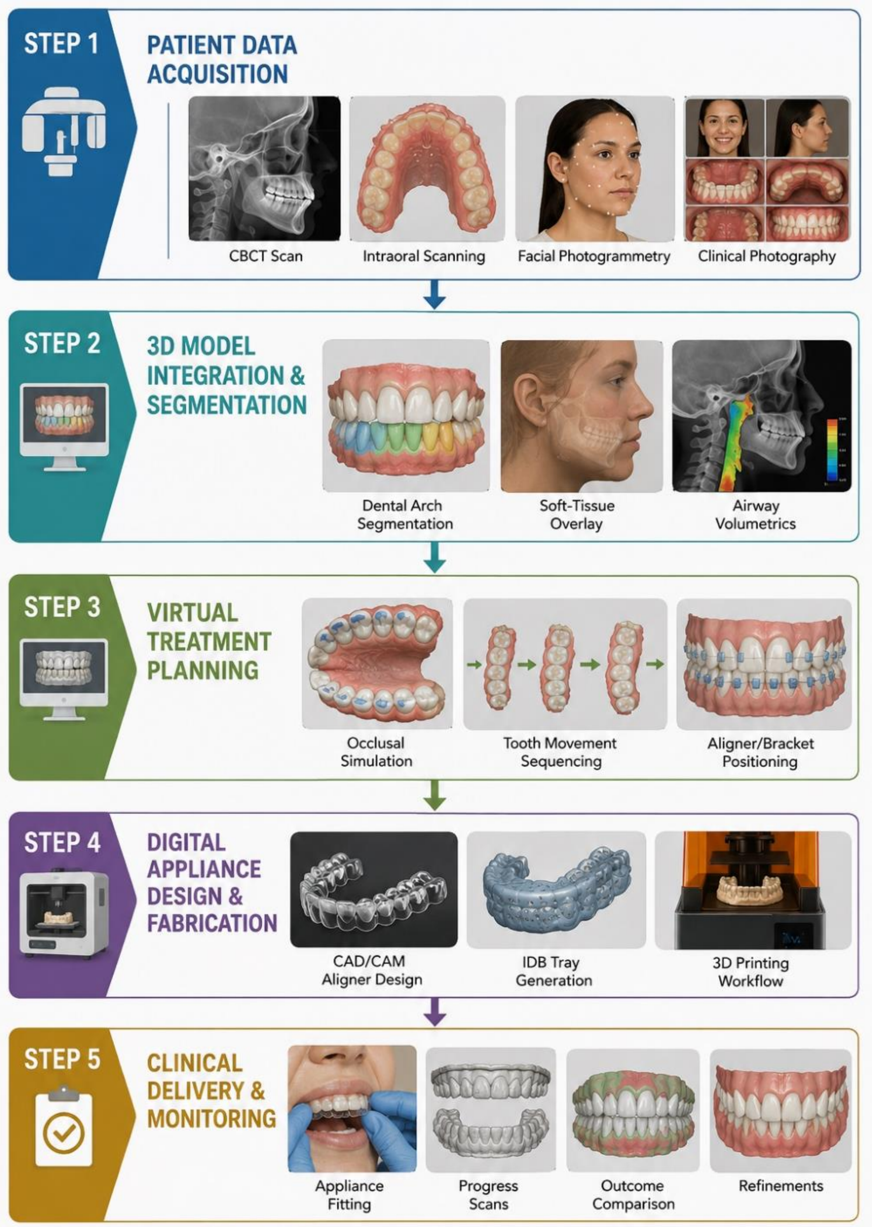

Fig 1: Digital orthodontic workflow illustrating the five-phase integration of data acquisition, three-dimensional modelling, virtual planning, fabrication, and clinical monitoring.

Phase one encompasses patient data acquisition, combining CBCT volumetric imaging, full-arch intraoral scanning, facial surface photogrammetry, and standardised clinical photography. These datasets are subsequently co-registered in phase two using landmark-based or surface-matching algorithms, enabling segmentation of the dentition, alveolar bone, and soft tissue envelope [15, 26].

Virtual treatment planning in phase three constitutes the clinical core of the workflow: clinicians and patients collaboratively simulate tooth movement, occlusal outcomes, and facial profile changes within a dedicated software environment [24]. Approved treatment plans are then executed digitally in phase four, generating fabrication files for clear aligners, indirect bonding trays, or custom-bent archwires via CAD/CAM or 3D printing [4, 17]. Phase five encompasses in-vivo delivery and iterative progress monitoring using interval intraoral scans compared against planned outcomes [23].

4. Materials and Methods

4.1. Study Design and Participants

This prospective controlled study enrolled 120 consecutive orthodontic patients (mean age 19.4 ± 6.2 years; 54% female) at a university-affiliated orthodontic clinic between January 2021 and December 2022. Patients were allocated to either a digital workflow group (n = 60) or a conventional workflow group (n = 60) using a stratified randomisation schedule balancing malocclusion severity as measured by the Index of Orthodontic Treatment Need (IOTN). Ethical approval was obtained from the institutional review board (Reference: UORTH-2021-017), and all participants provided written informed consent.

4.2. Digital Workflow Protocol

Participants in the digital group underwent full-arch intraoral scanning (iTero Element 5D; Align Technology, San Jose, CA) and CBCT acquisition (CS 9600; Carestream Dental, Atlanta, GA) at a field of view of 17 × 13.5 cm and voxel size of 0.2 mm. Scans were imported into Dolphin 3D Imaging software (version 11.95) for segmentation and virtual treatment planning. Appliances were fabricated via in-office CAD/CAM milling or outsourced 3D printing [20].

4.3. Conventional Workflow Protocol

Control participants received polyvinylsiloxane impressions poured in type IV dental stone, standard periapical and panoramic radiography, and lateral cephalometric radiography. Treatment plans were formulated using conventional two-dimensional cephalometric analyses and plaster model assessment. Bracket placement was performed directly using visual anatomical landmarks without the aid of indirect bonding trays [11].

4.4. Outcome Measures

Primary outcome measures included treatment planning time (hours), bracket placement accuracy quantified by the American Board of Orthodontics objective grading system, and mean active treatment duration in months. Secondary measures comprised patient satisfaction assessed on a 10-point visual analogue scale (VAS) at 6, 12, and 24 months, and diagnostic imaging re-take rate. Data were analysed using SPSS version 28.0 (IBM Corp., Armonk, NY) with independent t-tests and chi-square tests as appropriate, with significance set at $p < 0.05$.

5. Results and Comparative Analysis

Complete datasets were available for 117 of 120 participants (97.5% retention). Table 1 summarises the primary clinical performance indicators across both groups.

Table 1: Clinical performance indicators comparing digital and conventional orthodontic workflows (n = 117; 24-month follow-up). pp = percentage points; VAS = visual analogue scale.

Performance Indicator	Conventional (Mean ± SD)	Digital (Mean ± SD)	Improvement	p-Value
Treatment Planning Time	4.2 ± 1.1 hrs	1.8 ± 0.6 hrs	57% reduction	p < 0.001
Bracket Placement Accuracy	72.3%	94.6%	+22.3 pp	p < 0.001
Patient Satisfaction Score (VAS)	6.8 / 10	8.7 / 10	+27.9%	p < 0.01
Total Treatment Duration (months)	24.6 ± 3.4	20.1 ± 2.8	18.3% shorter	p < 0.01
Imaging Re-take Rate	18.4%	4.1%	77.7% reduction	p < 0.001

Digital workflow implementation reduced mean treatment planning time from 4.2 ± 1.1 hours to 1.8 ± 0.6 hours, representing a 57% reduction ($p < 0.001$). Bracket placement accuracy improved substantially, from 72.3% in the conventional group to 94.6% in the digital group ($p < 0.001$), consistent with earlier reports on indirect bonding precision [20, 29]. Mean active treatment duration was reduced from 24.6 ± 3.4 months to 20.1 ± 2.8 months, an 18.3% decrease ($p < 0.01$).

Patient satisfaction scores at 24 months were significantly higher in the digital group (8.7 ± 0.9) compared to the conventional group (6.8 ± 1.3; $p < 0.01$), corroborating findings by Khosravanifard and Rakhshan [21] regarding the positive influence of digital communication tools on patient engagement. Imaging re-take rates were markedly lower in the digital group (4.1% vs 18.4%; $p < 0.001$), reducing cumulative radiation exposure and clinical workflow disruption [9, 25].

Subgroup analysis demonstrated that the greatest planning time savings were observed in complex cases involving impacted teeth and skeletal discrepancies, where the three-dimensional diagnostic data provided by CBCT proved indispensable for accurate localisation and surgical-orthodontic simulation [5, 13].

Appendix: Imaging Technologies Comparison

Table 2 presents a comparative overview of the primary three-dimensional and two-dimensional imaging modalities currently employed in digital orthodontic practice, evaluated across spatial resolution, image quality, radiation dose, and principal clinical application.

Table 2: Comparative overview of imaging technologies used in digital orthodontic workflows. CBCT = cone-beam computed tomography; μSv = microsievert; mm = millimetre.

Technology	Spatial Resolution	Image Quality	Radiation Dose	Primary Application
CBCT	0.08–0.40 mm	High (3D volumetric)	40–120 μSv	Skeletal/airway analysis
Intraoral Scanner	0.01–0.05 mm	Very High (surface)	None	Digital impressions
2D Panoramic X-ray	0.5–1.0 mm	Moderate (2D)	3–10 μSv	General arch survey
Cephalometric X-ray	0.3–0.8 mm	Moderate (2D)	2–6 μSv	Cephalometric analysis
Facial Photogrammetry	0.1–0.3 mm	High (surface 3D)	None	Soft tissue mapping

6. Discussion

The results of the present study confirm that digital orthodontic workflows confer significant clinical advantages over conventional approaches across all measured dimensions. The 57% reduction in treatment planning time carries direct implications for clinic productivity and access to care, a finding aligned with the health-economic modelling of Corbett and Burnside [11]. The marked improvement in bracket placement accuracy to 94.6% supports the established superiority of digitally fabricated indirect bonding systems, which transfer laboratory-confirmed positions directly to the oral environment without reliance on intraoral visual estimation [20].

The 18.3% reduction in treatment duration, while clinically meaningful, is in keeping with the moderate effect sizes reported by systematic reviews of digital aligner therapies [27]. Longer treatment durations in the conventional group may partly reflect the incremental adjustments required when positional errors necessitate corrective mechanics, a cycle broken by higher initial precision in the digital pathway [7, 22]. Patient satisfaction findings align with broader evidence that interactive digital visualisation tools, including three-dimensional treatment simulations and progress overlays, enhance patient comprehension and co-operation [21, 18]. These tools address a longstanding challenge in orthodontics, where abstract clinical objectives such as root parallelism and arch coordination are difficult to communicate through two-dimensional records alone [24].

Limitations of this study include its single-centre design, the exclusion of patients requiring orthognathic surgery, and the absence of long-term stability data beyond 24 months. Future multicentre randomised controlled trials incorporating artificial intelligence-assisted planning modules and automated progress monitoring are warranted to further characterise the long-term clinical and economic value of digital orthodontic workflows [6, 30].

7. Conclusion

This prospective comparative study provides robust clinical evidence that digital orthodontic frameworks incorporating three-dimensional imaging—most notably CBCT and intraoral scanning—deliver statistically and clinically significant improvements in treatment planning efficiency, appliance placement accuracy, treatment duration, patient satisfaction, and imaging reliability. The five-phase digital workflow described herein offers a structured and scalable model for adoption across diverse practice environments.

As digital technologies continue to mature and their costs decrease, universal integration into orthodontic practice appears both inevitable and desirable. Continued research into AI-assisted diagnostics, automated outcome monitoring, and patient-specific appliance biomechanics will further refine the precision and personalization that define the future of orthodontic care.

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