International Journal of Community Medicine and Public Health
*Dashti A et al. Int J Community Med Public Health. 2026 Aug;13(8):4665-4678*
https://www.ijcmph.com
pISSN 2394-6032 | eISSN 2394-6040

DOI: https://dx.doi.org/10.18203/2394-6040.ijcmph20262342

**Review Article**

# The 4D virtual patient in digital dentistry: can multimodal data integration and specialty-specific applications pave the road toward dental digital twins?

**Almiqdad Dashti*, Mohammad Reda, Abdulaziz AlAdwani, Ali Shukrallah, Hussain Dashti, Abdullah Alkandari, Ahmad Alsediqi, Anfal Alsanea, Anwar AlMarri, Talal Alawadhi, Khaled Alawadhi, Reem Alkandari, Reem Alotaibi, Bashayer Ghloam, Khadija Alshammari**

Department of Dentistry, Ministry of Health, Kuwait City, Kuwait

**Received:** 27 June 2026
**Revised:** 03 July 2026
**Accepted:** 07 July 2026

***Correspondence:**
Dr. Almiqdad Dashti,
E-mail: almiqdad.dashtii@outlook.com

**Copyright:** © the author(s), publisher and licensee Medip Academy. This is an open-access article distributed under the terms of the Creative Commons Attribution Non-Commercial License, which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

## ABSTRACT

The virtual patient in dentistry represents an integrated digital model rather than a single imaging modality or isolated digital workflow. This structured narrative review examined the principal components, clinical applications, and translational limitations of virtual-patient approaches in dentistry, including intraoral scanning, cone-beam computed tomography, facial scanning, digital photography, jaw-motion tracking, virtual articulation, occlusal analysis, and emerging digital-twin concepts. A literature search of PubMed, Scopus, and Web of Science was conducted, and the evidence was analyzed comparatively according to data source, integration method, specialty-specific application, clinical purpose, and current evidence maturity across periodontics, implant dentistry, prosthodontics, orthodontics, endodontics, pediatric dentistry, and oral and maxillofacial surgery. Overall, the findings suggest that the virtual patient does not represent a uniform level of clinical maturity across dental disciplines. Prosthodontics, implant dentistry, orthodontics, and oral and maxillofacial surgery currently show the strongest clinically anchored applications, particularly for facially driven treatment planning, prosthetically guided implant placement, digital setups, orthognathic simulation, and surgical transfer. By contrast, applications in periodontics, endodontics, and pediatric dentistry remain more focused on diagnosis, monitoring, guided precision, and longitudinal documentation rather than fully predictive digital modelling. Current limitations include registration error, scanner-dependent accuracy, soft-tissue distortion, CBCT artifacts, incomplete dynamic occlusal simulation, software interoperability barriers, and limited evidence linking virtual-patient workflows to long-term clinical outcomes. Future progress will depend on standardized validation studies that assess accuracy, transfer reliability, clinical efficiency, patient communication, and patient-relevant outcomes, while clearly distinguishing virtual-patient modelling from the more ambitious concept of a true dental digital twin.

**Keywords:** Digital dentistry, Virtual patient, Facial scanning, Intraoral scanning, CBCT, Virtual articulation

## INTRODUCTION

Digital dentistry has evolved from isolated computer-aided procedures into a broader clinical ecosystem that includes intraoral scanning, CBCT imaging, CAD/CAM workflows, additive manufacturing, digital planning software, and emerging AI-supported tools. Intraoral scanners are now used beyond conventional CAD/CAM acquisition, with applications extending into diagnosis, patient communication, treatment planning, monitoring,

and specialty-specific digital workflows.[1,2] CBCT provides three-dimensional hard-tissue information for multiple dental indications, but its diagnostic value depends on appropriate parameter selection, artifact control, field of view, image quality, and radiation-dose justification.[1] Additive manufacturing has further expanded digital workflows by enabling the production of models, guides, splints, prosthetic components, and customized dental devices.[3,4] The next conceptual step is not simply the accumulation of more digital records, but their integration into a coherent patient-specific model. The virtual patient is created when datasets such as intraoral scans, facial scans, CBCT records, and other digital information are spatially aligned to represent the patient in a clinically interpretable way.[5] Recent evidence suggests that facial–intraoral scan integration can enhance diagnosis and treatment planning by adding esthetic and functional parameters, although the accuracy of the resulting virtual patient depends on the registration technique used.[5] Automated or AI-supported workflows have also been investigated for creating virtual patients from facial scans, intraoral scans, and CT/CBCT data, indicating a movement toward faster and more reproducible multimodal registration.[6]

The virtual patient is especially relevant because dental treatment decisions often depend on relationships between multiple tissues and functional systems rather than on isolated structures.[7] In restorative and prosthodontic planning, facial and intraoral integration can connect tooth morphology, smile display, occlusal design, and esthetic simulation within one digital environment.[7] In implant and surgical workflows, integrating surface scans, CBCT anatomy, facial information, and planned prosthetic position may help connect diagnosis, treatment simulation, guide fabrication, and clinical transfer.[5] In orthodontics and full-mouth rehabilitation, adding jaw-motion data can extend the virtual patient beyond static anatomy toward a four-dimensional model that incorporates mandibular movement and dynamic occlusal information.[8]

Despite this progress, the virtual patient should not be equated with a true dental digital twin. Patient digital twins have been defined in recent healthcare literature as virtual representations that may support dynamic simulation, monitoring, prediction, and individualized decision-making.[9] However, there is still no universal consensus definition of patient digital twins, and many reported applications remain heterogeneous in purpose, maturity, and clinical implementation.[10] Most current dental workflows therefore remain closer to static or partially dynamic virtual-patient models because they integrate records for diagnosis and planning but rarely include continuous updating, predictive modelling, or closed-loop feedback from the physical patient.[8]

Therefore, a critical synthesis is needed to clarify what the virtual patient currently means in dentistry, how it is constructed, where it is clinically useful, and which limitations still restrict its translation into a true digital-twin model. This review examines the conceptual foundations, data sources, integration strategies, functional extensions, specialty-specific applications, clinical barriers, and future directions of the virtual patient in dentistry. Particular emphasis is placed on distinguishing clinically validated virtual-patient workflows from technologically attractive but insufficiently validated digital-twin claims.

## METHODS

### *Review design and rationale*

This study was designed as a structured comprehensive review examining the development, clinical applications, and limitations of the virtual patient concept in dentistry. The review focused on how different digital data sources are acquired, integrated, and applied across dental specialties to support diagnosis, treatment planning, simulation, procedural transfer, monitoring, and communication. Rather than treating the virtual patient as a single technology, the synthesis considered it as a multidimensional digital framework built from intraoral scans, CBCT data, facial scans, digital photographs, occlusal records, mandibular-motion data, and emerging artificial-intelligence or digital-twin components.

### *Literature search strategy*

A literature search was performed using PubMed/MEDLINE, Scopus, and Web of Science. The search combined terms related to virtual-patient construction, digital dentistry, data integration, and specialty-specific applications. Reference lists of relevant reviews, clinical studies, and technical reports were also screened manually to identify additional sources (Table 1).

### *Eligibility and source selection*

Articles were considered eligible when they addressed a digital workflow, imaging modality, registration method, software-based planning approach, or clinical application directly relevant to construction or use of a dental virtual patient. Eligible studies included original clinical studies, laboratory investigations, validation studies, systematic or scoping reviews, technical reports, and proof-of-concept studies, provided that they contributed meaningful information regarding data acquisition, dataset integration, diagnostic accuracy, treatment planning, simulation, procedural transfer, monitoring, or clinical implementation. Studies were included across dental disciplines when the virtual-patient concept was central to the reported workflow or clinical application. Articles were excluded when they discussed digital dentistry only in general terms without addressing patient-specific data integration, when they focused exclusively on isolated CAD/CAM fabrication without broader virtual-patient relevance, or when they lacked sufficient methodological

or clinical detail. Publications limited to non-dental medical digital twins, general artificial intelligence, or purely technical software development were considered only when they provided concepts directly applicable to dental virtual-patient modelling.

**Table 1: Database-specific electronic search strategies.**

| Database | Search strategy |
|---|---|
| **PubMed** | ("dentistry"(MESH) or "dental informatics"(MESH) or dental or dentistry or oral or orthodontic* or prosthodontic* or periodont* or implant* or endodontic* or pediatric dentistry or paediatric dentistry or "oral and maxillofacial surgery" or orthognathic) and (virtual patient* or digital patient* or "3D virtual patient" or "4D virtual patient" or "dental virtual patient" or "digital twin*" or "dental digital twin" or "patient-specific model*" or "digital workflow*" or "computer-assisted treatment planning") and (intraoral scan* or intraoral scanner* or IOS or "cone-beam computed tomography" or CBCT or "facial scan*" or "3D facial scan*" or stereophotogrammetry or "digital photograph*" or "digital smile design" or "virtual articulator*" or "jaw motion tracking" or "mandibular movement" or "dynamic occlusion" or "scan registration" or superimposition or "data fusion" or "guided implant surgery" or "guided endodontics" or "virtual surgical planning") |
| **Scopus** | Title-abs-key (dental or dentistry or oral or orthodontic* or prosthodontic* or periodont* or implant* or endodontic* or "pediatric dentistry" or "paediatric dentistry" or "oral and maxillofacial surgery" or orthognathic) and title-abs-key ("virtual patient*" or "digital patient*" or "3D virtual patient" or "4D virtual patient" or "dental virtual patient" or "digital twin*" or "dental digital twin" or "patient-specific model*" or "digital workflow*" or "computer-assisted treatment planning") and title-abs-key ("intraoral scan*" or "intraoral scanner*" or IOS or "cone-beam computed tomography" or CBCT or "facial scan*" or "3D facial scan*" or stereophotogrammetry or "digital photograph*" or "digital smile design" or "virtual articulator*" or "jaw motion tracking" or "mandibular movement" or "dynamic occlusion" or "scan registration" or superimposition or "data fusion" or "guided implant surgery" or "guided endodontics" or "virtual surgical planning") |
| **Web of science core collection** | TS=(dental or dentistry or oral or orthodontic* or prosthodontic* or periodont* or implant* or endodontic* or "pediatric dentistry" or "paediatric dentistry" or "oral and maxillofacial surgery" or orthognathic) and TS=("virtual patient*" or "digital patient*" or "3D virtual patient" or "4D virtual patient" or "dental virtual patient" or "digital twin*" or "dental digital twin" or "patient-specific model*" or "digital workflow*" or "computer-assisted treatment planning") and TS=("intraoral scan*" or "intraoral scanner*" or IOS or "cone-beam computed tomography" or CBCT or "facial scan*" or "3D facial scan*" or stereophotogrammetry or "digital photograph*" or "digital smile design" or "virtual articulator*" or "jaw motion tracking" or "mandibular movement" or "dynamic occlusion" or "scan registration" or superimposition or "data fusion" or "guided implant surgery" or "guided endodontics" or "virtual surgical planning") |
| **Embase** | ('dentistry'/exp or 'dental informatics'/exp or dental:ti,AB,KW or dentistry:TI,AB,KW or oral:TI,AB,KW or orthodontic*:TI,AB,KW or prosthodontic*:TI,AB,KW or periodont*:TI,AB,KW or implant*:TI,AB,KW or endodontic*:ti,ab,kw or 'pediatric dentistry':ti,ab,kw or 'paediatric dentistry':TI,AB,KW or 'oral and maxillofacial surgery':TI,AB,KW or orthognathic:TI,AB,KW) and ('virtual patient':TI,AB,KW or 'virtual patients':TI,AB,KW or 'digital patient':TI,AB,KW or 'digital patients':TI,AB,KW or '3D virtual patient':TI,AB,KW or '4D virtual patient':TI,AB,KW or 'dental virtual patient':TI,AB,KW or 'digital twin':TI,AB,KW or 'digital twins':TI,AB,KW or 'dental digital twin':TI,AB,KW or 'patient-specific model':TI,AB,KW or 'patient-specific models':TI,AB,KW or 'digital workflow':TI,AB,KW or 'digital workflows':TI,AB,KW or 'computer-assisted treatment planning':TI,AB,KW) and ('intraoral scan':TI,AB,KW or 'intraoral scans':TI,AB,KW or 'intraoral scanner':TI,AB,KW or 'intraoral scanners':TI,AB,KW or IOS:TI,AB,KW or 'cone beam computed tomography'/exp or 'cone-beam computed tomography':TI,AB,KW or CBCT:TI,AB,KW or 'facial scan':TI,AB,KW or 'facial scans':TI,AB,KW or '3D facial scan':TI,AB,KW or stereophotogrammetry:TI,AB,KW or 'digital photograph':TI,AB,KW or 'digital smile design':TI,AB,KW or 'virtual articulator':TI,AB,KW or 'jaw motion tracking':TI,AB,KW or 'mandibular movement':TI,AB,KW or 'dynamic occlusion':TI,AB,KW or 'scan registration':TI,AB,KW or superimposition:TI,AB,KW or 'data fusion':TI,AB,KW or 'guided implant surgery':TI,AB,KW or 'guided endodontics':TI,AB,KW or 'virtual surgical planning':TI,AB,KW) |

***Synthesis approach***

The evidence was synthesized narratively and organized according to conceptual, technical, and specialty-specific domains. First, the literature was examined to distinguish isolated digital records, integrated virtual patients, 4D virtual patients, and true digital twins. Second, studies were analyzed according to the type of data used,

including the intraoral scanning, CBCT facial scanning, occlusal recording, and mandibular-motion tracking. Third, clinical applications were interpreted across periodontics, implant dentistry, prosthodontics, orthodontics, endodontics, pediatric dentistry, and oral and maxillofacial surgery. The synthesis emphasized comparative interpretation across specialties, with attention to current evidence maturity, clinical relevance, sources of error, registration limitations, workflow complexity, interoperability barriers, and the distinction between virtual-patient modeling and true digital-twin functionality.

## CONCEPTUAL FOUNDATIONS: FROM DIGITAL RECORDS TO THE VIRTUAL PATIENT

Lee et al described the virtual patient as a model created by combining digital diagnostic records such as facial scans, intraoral scans, virtual facebow records, and CBCT data through alignment of shared landmarks or surfaces.[11] This definition is useful because it separates the virtual patient from ordinary digital dentistry: the concept is not simply that records are digital, but that separate datasets are merged into one clinically interpretable patient-specific representation.

In this sense, intraoral scans, CBCT volumes, facial scans, and photographs are only building blocks; they become a virtual patient only when they are spatially integrated and used to support diagnosis, planning, communication, or simulation.

Yuan et al reported that a three-dimensional virtual patient could be created by fusing multiple data formats, including STL, OBJ, PLY, and DICOM files, while a four-dimensional virtual patient required the additional integration of dynamic information such as mandibular movement, occlusal dynamics, temporomandibular joint function, and facial motion.[12]

This distinction is important because most clinical digital workflows remain essentially static: they reproduce anatomy, but they do not fully reproduce function. Therefore, the conceptual shift from a 3D virtual patient to a 4D virtual patient is not just a technical upgrade; it is a movement from anatomical visualization toward functional simulation. Katsoulakis et al defined a healthcare digital twin as a virtual representation that allows dynamic simulation, monitoring, prediction, and feedback based on multimodal data, and they emphasized that a true digital twin requires a connection between the physical person and the virtual replica.[9] This makes the digital twin a more demanding concept than the virtual patient. A virtual patient may integrate records at one point in time, whereas a true dental digital twin would need longitudinal updating, predictive modelling, biologic or functional feedback, and clinically meaningful simulation of treatment response.

Conceptually, then, the virtual patient should be understood as an intermediate stage between fragmented digital records and a mature dental digital twin. It is more sophisticated than isolated IOS, CBCT, or facial scanning, because it attempts to place these datasets into one patient-specific model. However, it is still less advanced than a true digital twin unless it can update dynamically, predict outcomes, and close the feedback loop between the real patient and the digital model. This distinction is essential for avoiding overclaiming and for keeping the review critical rather than promotional (Figure 1).

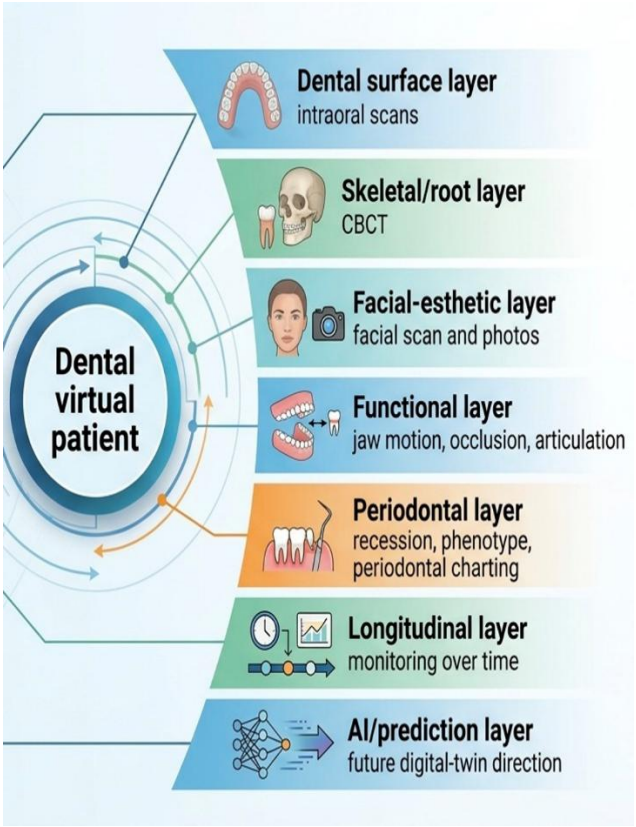



**Figure 1: Multilayer architecture of the dental virtual patient.**

### *Core data sources for constructing the virtual patient*

Joda and Gallucci presented one of the early dental virtual-patient workflows by superimposing intraoral scan data, CBCT data, and extraoral facial-scan data into a single 3D data pool.[13] This established an important principle for the field: the virtual patient does not come from one device, but from the complementary fusion of datasets that capture different tissues and clinical dimensions.

Jindanil et al later reinforced this point by noting that each imaging modality is optimized for a different tissue type and that no single device currently captures all clinically relevant structures accurately.[6] Granata et al described a prosthodontic workflow in which intraoral

scanner, CBCT, and facial-scanner files were superimposed to transfer both intraoral and extraoral clinical information into the virtual environment.[14] This shows why intraoral scans should be viewed mainly as the dentition and occlusal-surface layer of the virtual patient, whereas CBCT contributes skeletal, root, airway, and anatomic-risk information. The facial scan adds the missing extraoral context, allowing the dentition and jaws to be interpreted in relation to lips, smile, facial proportions, and aesthetic display.

**Table 2: Core components of the dental virtual patient.**

| Data sources | Captured information | Main dental applications | Strengths | Main limitations |
|---|---|---|---|---|
| **Intraoral scanning** | Teeth, occlusion, soft-tissue surface | Prosthodontics, orthodontics, implant planning | High surface detail, repeatable | Limited subgingival/deep tissue data |
| **CBCT** | Bone, roots, airway, anatomy | Surgery, implants, endodontics, orthodontics | 3D hard-tissue assessment | Radiation, artifacts |
| **Facial scanning** | Extraoral soft tissues, smile, facial proportions | Prosthodontics, orthodontics, surgery | Esthetic context | Soft-tissue movement/distortion |
| **Jaw-motion tracking** | Mandibular dynamics | Prosthodontics, occlusion, TMD-related planning | Functional data | Device/software variability |
| **Periodontal records** | Pockets, recession, phenotype | Periodontics, maintenance | Disease-monitoring value | Not fully captured by scan alone |

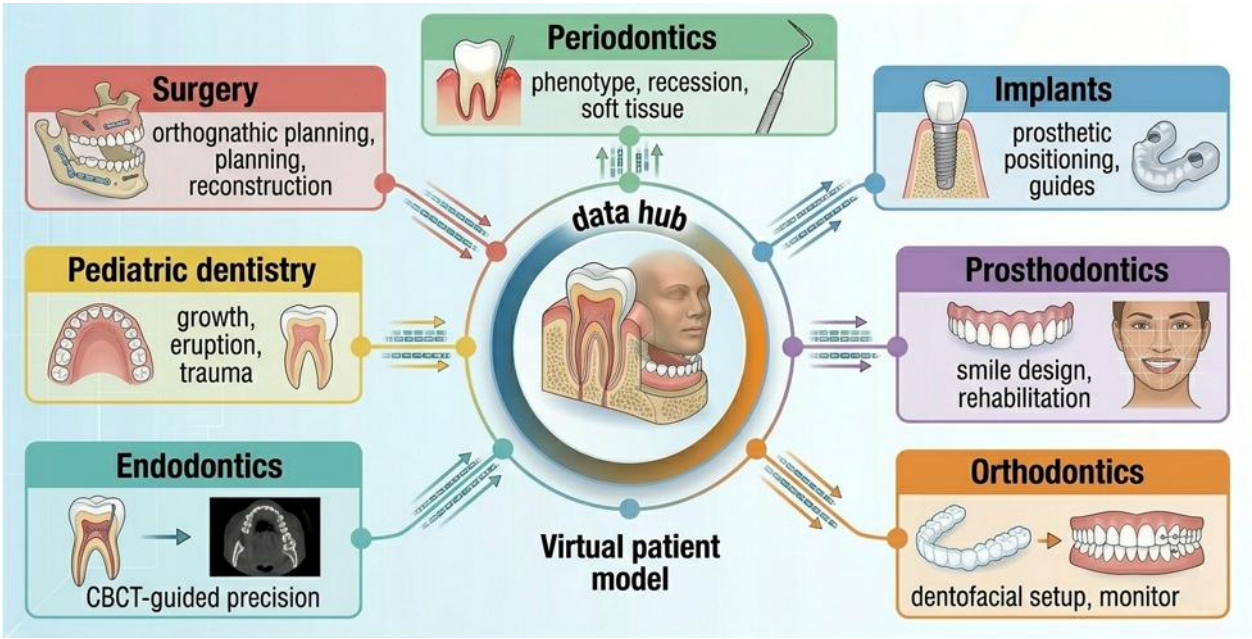



**Figure 2: Specialty-specific clinical translation of the dental virtual patient.**

Lawand et al found that integrating facial and intraoral scans enhanced diagnosis and treatment planning by adding esthetic and functional parameters, but they also showed that the accuracy of this integration depended on the registration technique used.[5] This is important because the data sources themselves are not enough; their clinical value depends on whether the files can be reliably aligned into a coherent patient model. In other words, the virtual patient should not be described merely as "IOS+ CBCT+face scan," but as a validated spatial relationship among these records. Haku-Mizuhara et al extended the data-source concept further by presenting a 4D virtual-patient workflow that combined IOS-derived STL data, facial-scan data, CBCT-derived DICOM data, and jaw-motion tracking data.[8] This addition changes the virtual patient from a static anatomical model into a potentially functional model. Therefore, the core data sources of the virtual patient can be arranged hierarchically: intraoral scanning captures the dentition, CBCT captures hard-tissue anatomy, facial scanning captures extraoral soft-tissue context, and motion or occlusal records begin to capture function (Table 2).

***Data integration, registration accuracy and validation***

Rangel et al reported that fusion of digital dental casts with CBCT scans could be achieved with small surface-matching errors, but they also emphasized that earlier integration methods were limited by radiation exposure, soft-tissue deformation, and time-consuming digital

handling.[15] This is an important starting point because the virtual patient is not validated by the presence of multiple datasets alone; it depends on whether the dentition, skeleton, and soft tissues are transferred into the same coordinate system with clinically acceptable accuracy. Zou et al found that integrating maxillary digital models into CBCT scans was clinically reliable in orthognathic patients, although inter-observer reliability was weaker for the x-coordinate of tooth position.[16] This suggests that registration error is not only a software problem, but also an operator- and direction-dependent problem. The practical implication is that even when a workflow appears accurate overall, specific axes, landmarks, or regions may remain vulnerable to clinically relevant deviation. Pérez-Giugovaz et al described an additively manufactured intraoral scan-body technique to guide the superimposition of facial and intraoral scans when CBCT was not indicated.[17] These approaches indicate that registration accuracy improves when the workflow provides stable reference geometry between datasets, especially when natural facial or dental landmarks are insufficient. Recent validation studies further show that both the facial scanner and the integration method influence the trueness and precision of the resulting 3D virtual patient.[18] Amezua et al similarly investigated how facial scanning method affected the transfer accuracy of a maxillary digital scan into a 3D face scan for a virtual facebow workflow.[19] Taken together, the evidence supports a cautious interpretation: the virtual patient should be treated as an accuracy-dependent clinical model, not as a automatically reliable digital copy of the patient.

## FUNCTIONAL VIRTUAL PATIENT: OCCLUSION, MANDIBULAR MOTION AND DYNAMIC ARTICULATION

Jain and Abduo reported that virtual articulation showed accuracy comparable with conventional articulation for static occlusion, but dynamic occlusal simulation remained less reliable, particularly for mandibular movement tracking and condylar-path reproduction.[20] This distinction is central to the virtual-patient concept because a static model may reproduce tooth position, but it cannot fully represent how the mandible functions during protrusion, laterotrusion, speech, or mastication. The functional virtual patient therefore represents a shift from anatomical visualization toward movement-based treatment planning. Zambrana et al described a workflow in which CBCT data, intraoral surface scans, and target-tracking video were merged to integrate mandibular kinematics into a static virtual patient.[21] Kim et al similarly used target tracking with a three-dimensional facial scanner to transform mandibular movement data into real-time videos of dental cast motion.[22] These approaches suggest that mandibular motion should not be treated as an optional digital accessory, especially in complex rehabilitation, because restorations, occlusal schemes, and anterior guidance are ultimately tested in function rather than in maximum intercuspation alone. Wong King et al, however, reported that no digital method fully replicated articulating paper, and that standalone intraoral scanners tended to underperform during dynamic movements, while systems incorporating jaw tracking produced more accurate dynamic occlusal recordings.[23] This comparison is useful because it shows that digital occlusion is not a single category: static IOS-based articulation, virtual articulators, digital occlusal analyzers, and jaw-tracking-assisted workflows may produce different levels of functional information. Lepidi et al presented the 4D virtual patient as a proof of concept by adding jaw-tracking motion to IOS, CBCT, extraoral scanning, digital facebow transfer, and virtual articulation.[24] The broader implication is that the functional virtual patient remains promising but incompletely validated. It may be highly valuable for full-mouth rehabilitation, implant-supported prostheses, temporomandibular assessment, and occlusal risk evaluation, but its clinical reliability depends on how accurately motion is captured, transferred, and interpreted within the digital workflow. The broader specialty-specific translation of the virtual patient, including its applications in prosthodontics, implant dentistry, orthodontics, periodontics, endodontics, pediatric dentistry, and oral and maxillofacial surgery, is summarized in (Figure 2).

## PERIODONTICS: SOFT-TISSUE ARCHITECTURE, PERIODONTAL PHENOTYPE, AND LONGITUDINAL MONITORING

Caron et al reported in a scoping review of 52 studies that intraoral scanners have been used in periodontology for several diagnostic applications, including gingival thickness, keratinized tissue height, plaque assessment, probing depth, and soft-tissue monitoring.[25] Their review suggested that IOS data were more promising for gingival phenotype and keratinized-tissue assessment than for plaque detection or probing-depth evaluation, where examination bias and visualization limitations remained important. This distinction is clinically important because the periodontal component of the virtual patient should not be reduced to a digital scan of the gingiva; it should integrate soft-tissue morphology with conventional periodontal charting and radiographic bone assessment. Dritsas et al developed and validated a method for quantifying gingival recession by superimposing serial 3D digital dental models, allowing gingival-margin changes to be visualized and measured over time.[26] Kuralt et al found that automated curvature-based analysis increased the precision of recession measurements by improving reproducibility in the selection of cemento-enamel junction and gingival-margin points.[27] Together, these studies suggest that the virtual patient may be particularly valuable in periodontics when the clinical question is longitudinal change rather than one-time diagnosis. Mendoza-Azpur et al described a digital crown-lengthening workflow in which intraoral scanning, digital photographs, CBCT data, and a CAD-CAM surgical guide were merged to support esthetic

periodontal planning.[28] Gonçalves et al later evaluated digitally manufactured periodontal surgical guides for esthetic crown lengthening in a randomized trial, indicating that guided periodontal workflows are moving beyond technical reports toward clinical evaluation.[29] This progression is important because crown lengthening is not only a surgical procedure; it is a periodontal–restorative decision in which gingival margins, bone levels, tooth proportions, smile display, and restorative design must be coordinated. Azhari reported that AI applications in periodontics have been investigated across periapical, bitewing, panoramic, CBCT, and intraoral photographic datasets, with stronger performance for bone-loss measurement and more variable performance for intraoral photographic analysis.[30] This suggests that the periodontal virtual patient is likely to develop in two directions: objective 3D monitoring of soft-tissue architecture and AI-assisted interpretation of periodontal bone and inflammatory status. The current limitation is that these tools still supplement, rather than replace, conventional periodontal examination; their greatest value is in making periodontal change more visible, measurable, and communicable within interdisciplinary planning.

## IMPLANT DENTISTRY: PROSTHETICALLY DRIVEN PLANNING AND PERI-IMPLANT TISSUE VISUALIZATION

Pozzi et al. introduced the “Smiling Scan” technique as a proof-of-concept workflow for creating a virtual dental patient by combining CBCT acquisition during a broad smile with intraoral or extraoral optical surface scanning, with the aim of supporting facially driven, prosthetically guided implant planning and immediate CAD/CAM provisionalization.[31] This is conceptually important because it shifts implant planning from a bone-centered exercise toward a patient-specific model in which implant position is interpreted through the smile, prosthetic envelope, facial esthetics, and surgical anatomy. Pérez-Giugovaz, Sadeghpour, and Revilla-León described a virtual 3D representation of a completely edentulous patient by aligning facial, intraoral, and CBCT scans with an additively manufactured scan body, and they reported that this virtual patient facilitated prosthetically driven implant planning, surgical-guide manufacturing, and interim restoration fabrication.[32]

Compared with the Smiling Scan concept, this workflow is especially relevant to edentulous rehabilitation because it addresses a more difficult registration problem: transferring prosthetic, facial, and radiographic information into a coherent digital patient when stable dentate landmarks are limited or absent. Abad-Coronel et al reviewed digital prosthetically derived surgical guides and reported coronal deviations of 0.44-0.56 mm, apical deviations of 0.64-1.03 mm, angular deviations of 2.03°-2.42°, and vertical deviations of 0.19–0.45 mm.[33] Khaohoen et al synthesized the clinical accuracy of static, dynamic, and robot-assisted implant surgery and reported overall mean deviations of 1.11 mm at the entry point, 1.40 mm at the apex, and 3.51° angularly, with robotic systems tending to show the lowest deviations among computerized approaches.[34] These findings suggest that the virtual patient may improve implant planning, but the final clinical value still depends on accurate dataset acquisition, registration, guide design, manufacturing, and surgical transfer. Overall, implant dentistry is one of the clearest specialty applications of the virtual patient because diagnosis, prosthetic design, surgical planning, and provisional rehabilitation can be linked within one digital environment. However, it is also one of the most accuracy-sensitive applications: even small errors in scan alignment, guide support, template fabrication, or intraoperative execution may compromise the relationship between the planned prosthetic outcome and the final implant position. The strongest interpretation is therefore balanced: the virtual patient supports prosthetically and facially driven implant planning, but it does not eliminate the biological, technical, and transfer-related uncertainties of implant therapy.

## PROSTHODONTICS AND RESTORATIVE DENTISTRY: FACIALLY DRIVEN REHABILITATION AND TREATMENT SIMULATION

Pradíes et al proposed the distinction between analogic and digital virtual patients in prosthodontics, but their scoping review found heterogeneous study designs and insufficient evidence to claim that virtual-patient-related devices consistently improve prosthesis longevity or patient-related outcomes.[35] This is a useful caution for the restorative section: the virtual patient is conceptually attractive because it links face, teeth, occlusion, and prosthetic design, but its value should be judged by whether it improves diagnosis, treatment simulation, communication, and final prosthetic quality rather than by digital sophistication alone. Lin et al described a workflow that integrated facial scanning, virtual smile design, and a static 3D virtual patient to guide CAD-CAM ceramic veneer treatment.[36] Together, these reports suggest that prosthodontics is one of the clearest clinical entry points for the virtual patient because restorative decisions are rarely tooth-only decisions; they depend on the smile frame, lip mobility, incisal display, occlusal plane, vertical dimension, and patient-specific esthetic expectations.

Luniyal et al reported in a randomized trial that patients treated with digital smile design showed higher satisfaction scores than those treated with conventional smile design, and the digital group also showed a higher percentage of excellent restoration fit, occlusion, and esthetics at 3 months.37 Lo Giudice et al, however, showed that digitally planned mock-ups may still differ from the original 3D project, with milled and prototyped mock-ups showing different dimensional behaviors and clinical fit.[38] This comparison is important because digital visualization can improve patient communication, but the

restorative chain remains vulnerable to transfer errors between the virtual design, mock-up, preparation, fabrication, and final delivery. Kaitatzidou et al found in an overview of systematic reviews that digital scans and conventional impressions generally showed no significant differences in accuracy, marginal fit, or internal adaptation for fixed restorations, although conventional impressions performed better for complete-arch fixed prostheses and most included systematic reviews had critically low confidence.[39] Therefore, in prosthodontics and restorative dentistry, the virtual patient should be presented as a planning and communication framework rather than as proof that all-digital treatment is automatically superior. Its strongest current role is in facially driven treatment planning, interdisciplinary communication, and previewing esthetic–functional outcomes, while its main limitation remains the need to validate whether virtual simulations reliably translate into clinically superior restorations.

## ORTHODONTICS: DENTOFACIAL INTEGRATION, TOOTH-MOVEMENT SIMULATION AND TREATMENT MONITORING

Marradi et al reported that orthodontic virtual-patient construction usually depends on superimposing skeletal, dental, and facial soft-tissue datasets, but they also found that available studies were mostly case reports, case series, or single-cohort investigations, with no randomized trials and no accepted gold-standard integration protocol.[40] This makes orthodontics a particularly relevant but still imperfect field for the virtual patient: orthodontic planning cannot rely on teeth alone, because tooth movement must be interpreted in relation to facial esthetics, skeletal pattern, root position, alveolar boundaries, periodontal support, and growth. The orthodontic virtual patient is therefore strongest when it connects the dentition to the face and craniofacial skeleton, rather than functioning as a digital setup isolated from biologic limits.

Sereewisai et al concluded that orthodontic virtual setups showed clinically acceptable accuracy for treatment simulation, particularly in less complex cases, but they also emphasized that actual outcomes may differ from simulations because of segmentation errors, software limitations, appliance mechanics, biologic constraints, and patient compliance.[41] This distinction is central to the review: a virtual setup is not a prediction of certainty, but a planning hypothesis. In orthodontics, the virtual patient should therefore be framed as a tool for visualizing options, communicating objectives, and estimating movement requirements, not as proof that planned tooth movement will be fully achieved. Stucki and Gkantidis found that serial 3D model superimposition could be useful for assessing tooth movement over time, but the evidence was heterogeneous and reliable recommendations were mainly possible for selected maxillary reference areas such as the medial two-thirds of the third rugae and adjacent posterior palatal regions.[42]

This is important because orthodontics adds a longitudinal dimension to the virtual patient. Unlike many restorative or implant workflows that focus on a single planned endpoint, orthodontics requires repeated comparison between planned, achieved, and biologically tolerated movement over months or years. Pandian et al reported that optimized and conventional invisalign attachments did not differ significantly for most evaluated movements and that none of the attachment designs produced the full movement predicted by ClinCheck.[43] Sangalli et al reviewed dental monitoring as a remote orthodontic monitoring system, reflecting the growing use of AI-supported follow-up during orthodontic care.[44] Together, these findings support a cautious interpretation: orthodontics may be one of the specialties closest to a dynamic virtual-patient model, but current systems still require clinician interpretation, biological judgment, and careful distinction between simulated movement, monitored tracking, and actual treatment response.

## ENDODONTICS: TOOTH-SPECIFIC DIGITAL DIAGNOSIS AND GUIDED PRECISION

Rosen et al identified 22 studies evaluating higher-level diagnostic efficacy of CBCT in endodontics, but only 2 had a low risk of bias, and the authors concluded that evidence for CBCT influencing decision-making and treatment outcomes remained predominantly methodologically weak.[45] This is important for the virtual-patient concept because endodontics contributes a highly detailed tooth-level layer, but CBCT should still be interpreted as an indication-specific diagnostic tool rather than a routine digital requirement for every case.

Zubizarreta-Macho et al reported in a systematic review and meta-analysis that computer-aided navigation techniques achieved a root-canal location success rate of 98.1%, with no significant difference between static and dynamic navigation, and with higher odds of success than conventional freehand access.[46] In this context, guided endodontics represents one of the clearest examples of a small-scale virtual-patient workflow: CBCT provides internal anatomy, intraoral scanning provides the external tooth and arch surface, and digital planning translates both into a clinically executable access path. Jonaityte et al noted that dynamic navigation may overcome some limitations of static guides because it allows real-time modification of the drilling path, posterior application, and treatment within the same appointment.[47] Langaliya et al, however, found that evidence for dentin preservation with dynamic navigation was based on only two studies, even though both suggested greater precision, efficiency, and tooth-structure preservation than freehand access.[48] This comparison suggests that guided endodontics is promising, but its strongest current justification is in complex anatomy, pulp canal

obliteration, calcified canals, retreatment, and high-risk access rather than routine endodontic cases.

Pul and Schwendicke reported that AI showed high pooled sensitivity and specificity for detecting periapical radiolucencies, but they also emphasized that most studies tested model accuracy rather than fully developed clinical software systems.[49] Setzer et al similarly described growing AI applications in endodontics for detecting periapical lesions, fractures, resorptions, and outcome prediction, while stressing limitations related to dataset quality, transparency, generalizability, and clinical implementation.[50] Therefore, the endodontic virtual patient should be framed as a precision-diagnosis and guided-treatment environment, not yet as a fully predictive digital twin of pulpal or periapical disease behavior.

## PEDIATRIC DENTISTRY: GROWTH, ERUPTION, TRAUMA AND THE CHANGING VIRTUAL PATIENT

Liczmanski et al found that intraoral scans in mixed dentition were clinically tolerable compared with conventional alginate-derived models, but they also emphasized that pediatric scanning must cope with saliva, mobile soft tissues, partially erupted teeth, eruption spaces, appliances, and behavior-related challenges.[51] This makes pediatric dentistry conceptually different from adult virtual-patient workflows: the child's virtual patient is not a stable anatomical model, but a changing record of growth, eruption, exfoliation, and developing occlusion. Okamoto et al reported that mixed-dentition space analysis using digital models showed clinically insignificant differences compared with plaster-model analysis and produced fewer inter-examiner differences.[52] This suggests that the pediatric virtual patient may be useful not only for visualization, but also for structured monitoring of arch-length discrepancy, eruption guidance, and interceptive treatment planning. However, this value remains dependent on repeated accurate records, because eruption and growth can change the diagnostic baseline faster than in adult restorative or implant patients. Van Gorp et al showed that pediatric dentists' diagnostic performance in dental-trauma cases remained limited with both two-dimensional and CBCT imaging, and they concluded that CBCT use in pediatric traumatology required proper training.[53] This is important because trauma is one of the strongest pediatric indications for a richer virtual-patient record, especially when root fracture, luxation injury, resorption, or apical pathology is suspected. At the same time, CBCT should not be treated as a routine component of the pediatric virtual patient, because radiation exposure and interpretation quality remain central constraints.

A recent systematic review and meta-analysis on AI in pediatric dentistry reported promising diagnostic performance for tasks such as mesiodens detection, early childhood caries detection, tooth numbering, and root-development estimation, but the included applications varied widely in data source, task definition, and validation level.[54] Assiry et al extend this discussion by showing that AI applications in pediatric and special care dentistry span diagnostic imaging, three-dimensional imaging, interceptive orthodontics, teledentistry, predictive analytics, pain assessment, behavior management, behavior modeling, and ethical considerations.[55] They also emphasize that AI is currently most developed for diagnostic imaging and caries detection, while evidence for children with special health care needs remains limited and seldom validated. Therefore, the pediatric virtual patient may eventually combine longitudinal IOS records, radiographs, growth-related data, trauma follow-up, behavior-related information, and AI-supported interpretation. For now, however, its most defensible role is as a longitudinal monitoring and communication tool rather than a fully predictive model of growth, eruption, behavior, or disease progression.

## ORAL AND MAXILLOFACIAL SURGERY: ORTHOGNATHIC PLANNING, GUIDES, SPLINTS AND CRANIOFACIAL RECONSTRUCTION

Alkhayer et al reported that virtual planning in orthognathic surgery generally achieved average translational discrepancies below 2 mm in both the maxilla and mandible, while also noting that CBCT combined with intraoral scan data was the most frequently used imaging protocol.[56] This supports the surgical value of the virtual patient because orthognathic planning requires the integration of skeletal deformity, dental occlusion, facial asymmetry, and planned jaw movements in three dimensions rather than relying on isolated cephalometric or cast-based information. Lee et al found in a systematic review and meta-analysis that virtual surgical planning showed a 0.54-mm smaller difference between planned and actual jaw positions than conventional planning, and that virtual planning with custom surgical guides showed a 1.20-mm smaller difference.[57]

However, the same review found that operative-time reduction was not statistically significant, suggesting that the main current advantage of virtual surgical planning is accuracy of transfer rather than guaranteed surgical efficiency. This distinction is important because the surgical virtual patient is only clinically meaningful when the digital plan can be transferred predictably through splints, guides, plates, or navigation. Olejnik et al reported that 3D soft-tissue simulations in orthognathic surgery showed whole-face mean errors ranging from 0.27 to 2.9 mm, with larger inaccuracies often occurring around the lips, chin, and paranasal regions depending on the osteotomy pattern.[58]

This finding highlights a critical limitation: skeletal repositioning may be planned with reasonable precision, but facial soft-tissue response remains less predictable. Therefore, the surgical virtual patient should be used for communication and expectation-setting, but soft-tissue predictions should not be presented to patients as exact postoperative forecasts.

Kotecha et al found that patient-specific implants for post-traumatic orbital reconstruction tended to improve orbital volume restoration and reduce operative duration in some included studies, but meta-analysis did not show statistically significant superiority over conventional implants.[59] Yousif et al reported high pooled success for 3D-printed patient-specific implants in maxillofacial reconstruction, although the evidence base remained small and workflow standardization was still needed.[60] Overall, oral and maxillofacial surgery shows one of the strongest translations of the virtual patient from diagnosis to execution, but its maturity depends on transfer accuracy, soft-tissue prediction limits, and stronger outcome-based validation (Table 3).

**Table 3: Specialty-specific applications of the virtual patient in dentistry.**

| Specialty | Virtual-patient application | Main clinical value | Current maturity | Key limitation |
|---|---|---|---|---|
| **Periodontics** | Recession monitoring, phenotype assessment, crown-lengthening planning | Longitudinal soft-tissue assessment | Emerging | Limited integration with full periodontal charting |
| **Implant dentistry** | Prosthetically driven implant planning, guides, full-arch workflows | Implant positioning and prosthetic emergence | Relatively mature | Transfer and registration errors |
| **Prosthodontics** | Smile design, full-mouth rehab, virtual articulation | Esthetic-functional simulation | Relatively mature | Simulation-to-delivery discrepancies |
| **Orthodontics** | Digital setup, facial integration, treatment monitoring | Dentofacial planning and movement tracking | Moderate | Predicted movement≠ achieved movement |
| **Endodontics** | CBCT-based diagnosis, guided access | Precision in complex anatomy | Selective but strong | Not routine for all cases |
| **Pediatric dentistry** | Growth, eruption, trauma monitoring | Longitudinal developmental tracking | Emerging | Changing anatomy and radiation concerns |
| **Surgery** | Orthognathic planning, splints, guides, reconstruction | Surgical simulation and transfer | Relatively mature | Soft-tissue prediction uncertainty |

## FROM VIRTUAL PATIENT TO DENTAL DIGITAL TWIN

Drummond et al defined patient digital twins as multidimensional, patient-specific replicas that inform clinical decisions, and they distinguished simulation twins from monitoring twins.[10] This distinction is useful for dentistry because the current virtual patient is usually closer to a simulation model than a true continuously updated twin. In most dental workflows, IOS, CBCT, facial scans, and jaw-motion records are integrated to support diagnosis or planning at a specific time point, but they rarely maintain a live feedback loop with the real patient. Sun et al described healthcare digital twins as evolving models supported by technologies such as sensors, IoT, big data, artificial intelligence, and simulation, with potential applications in real-time monitoring, dynamic analysis, prediction, and personalized treatment.[61] This means that the dental digital twin should not be defined merely as a 3D virtual patient. A true dental twin would require longitudinal data updating, prediction of treatment response, and feedback from the actual patient into the model, such as monitored tooth movement, occlusal wear, periodontal change, peri-implant tissue behavior, or postsurgical healing. Elsayed et al. reviewed digital twin technologies in endodontics and reported that current applications included CBCT-driven anatomical replicas, infrared thermography for nickel–titanium instrument monitoring, simulation-based education, and guided procedures, but they concluded that the evidence remained preliminary and limited by small samples, lack of standardized protocols, and absence of multicenter trials.[62] Salvi et al similarly found in dental informatics that IoT and digital twin implementations in dentistry remained largely conceptual or pilot-stage, despite growing interest in AI, connected devices, and digital convergence.[63] Together, these findings suggest that dentistry has strong components for digital twinning, but not yet a mature, validated digital-twin ecosystem. Therefore, the virtual patient should be presented as the necessary foundation for the dental digital twin, not as its synonym. The virtual patient integrates anatomy, esthetics, occlusion, and sometimes function; the digital twin should go further by updating over time, learning from patient-specific data, simulating alternative treatments, and refining predictions after clinical feedback. This distinction protects the review from technological overclaiming and gives the manuscript a stronger critical message: dentistry is moving toward digital twins, but most current evidence still supports

integrated virtual-patient modeling rather than fully adaptive, predictive, closed-loop digital twinning.

## LIMITATIONS, CLINICAL BARRIERS AND FUTURE RESEARCH PRIORITIES

Lawand et al reported that techniques for aligning facial and intraoral scans still vary across workflows, including retracted facial scans, extraoral scan bodies, and perioral intraoral scans.[5] This matters because the virtual patient is highly dependent on registration accuracy; even small distortions in facial–intraoral alignment may compromise diagnosis, prosthetic design, esthetic planning, or surgical simulation. Yuan et al found that construction of a 4D dynamic virtual patient was feasible, but the available workflows differed substantially in devices, software, registration methods, file formats, applications, and reported accuracy.[12] This heterogeneity creates a major translational barrier because clinicians cannot easily compare systems or know which workflow is accurate enough for a specific decision. The limitation is especially important for dynamic functions such as mandibular motion, occlusion, and facial movement, where error may arise not only from image acquisition but also from motion capture, data transfer, and interpretation. Tengku Alang et al emphasized that medical digital twins require interoperability across heterogeneous healthcare data systems and that frameworks such as HL7 and DICOM are important but still insufficient for seamless medical-data integration.[64] This issue is directly relevant to dentistry because virtual-patient workflows often depend on proprietary scanners, closed software ecosystems, incompatible file formats, and incomplete transfer of metadata.

A virtual patient may therefore look visually complete while still being fragmented at the data level, especially when IOS, CBCT, facial scans, jaw-motion records, AI outputs, and laboratory CAD files do not communicate transparently. Burr et al identified broader healthcare digital-twin barriers related to data quality, consent, privacy, cybersecurity, equity, model validation, infrastructure, and human factors.[65] These concerns are not peripheral to dentistry; they become more important as virtual-patient workflows move from isolated planning files toward longitudinal, AI-supported, cloud-based, or digital-twin systems. The main research priority is therefore not simply to create more impressive virtual models, but to validate clinically meaningful workflows, define acceptable error thresholds for different applications, test whether virtual-patient planning improves outcomes, and develop transparent standards for data governance, interoperability, and patient communication.

## CONCLUSION

The virtual patient marks a shift from isolated digital records toward an integrated, patient-specific model that combines dental, skeletal, facial, periodontal, occlusal, and functional information for diagnosis and treatment planning. Current evidence supports its clinical value mainly in implant dentistry, prosthodontics, orthodontics, and oral and maxillofacial surgery, where data integration can improve visualization, simulation, communication, and procedural transfer. In periodontics, endodontics, and pediatric dentistry, its role is still more focused on diagnosis, monitoring, guided precision, and longitudinal documentation. Future research should move beyond impressive digital visualization and determine whether virtual-patient workflows genuinely improve accuracy, efficiency, communication, treatment outcomes, and patient-specific decision-making.

*Funding: No funding sources*
*Conflict of interest: None declared*
*Ethical approval: Not applicable*

## REFERENCES

1. Fontenele RC, Gaêta-Araujo H, Jacobs R. Cone beam computed tomography in dentistry: Clinical recommendations and indication-specific features. J Dent. 2025;159:105781.
2. Alrehaili RS, Almuzaini S, Alrajhi J, Dashti A, Alsuroor O, Alzahrani F, et al. Teledentistry in the Era of Digital Dentistry: Clinical Applications, Patient Experience, and Equity-Oriented Policy Implications. Cureus. 2025;17:e100137.
3. Caussin E, Moussally C, Le Goff S, Fasham T, Troizier-Cheyne M, Tapie L, et al. Vat Photopolymerization 3D Printing in Dentistry: A Comprehensive Review of Actual Popular Technologies. Materials (Basel). 2024;17(4):950.
4. Khalil AS, Alrehaili RS, Alenazi S, Alfawzan F, Alobaidi R, Alshami A, et al. How Accurate is the Fit of Additive 3D-Printed Implant-Supported Restorations and Partial Coverage Posterior Restorations? A Systematic Review. J Pioneering Med Sci. 2025;14(9):12-22.
5. Lawand G, Tohme H, Azevedo L, Martin W, Gonzaga L, Nassif M, et al. Techniques and accuracy for aligning facial and intraoral digital scans to integrate a 3-dimensional virtual patient: A systematic review. J Prosthet Dent. 2026;135(3):484-504.
6. Jindanil T, Burlacu-Vatamanu OE, Baldini B, Meyns J, Meewis J, Fontenele RC, et al. Automated orofacial virtual patient creation using two cohorts of MSCT vs. CBCT scans. Head Face Med. 2025;21:21.
7. Shuto T, Mine Y, Tani A, Taji T, Murayama T. Facial Scans in Clinical Dentistry and Related Research: A Scoping Review. Cureus. 2025;17(4):e81662.
8. Haku-Mizuhara K, Tanabe G, Kadempour A, Mirafzali S, Yotsuya M, Yamaguchi S. Development of a 4-dimensional virtual patient in motion: A digital concept. J Prosthet Dent. 2026;135(1):47-53.

9. Katsoulakis E, Wang Q, Wu H, Shah J, Ranjbar K, Noguchi T, et al. Digital twins for health: a scoping review. NPJ Digit Med. 2024;7:77.
10. Drummond D, Gonsard A. Definitions and Characteristics of Patient Digital Twins Being Developed for Clinical Use: Scoping Review. J Med Internet Res. 2024;26:e58504.
11. Lee JD, Nguyen O, Lin YC, Poon CY, Huang YF, Chen CC, et al. Facial scanners in dentistry: An overview. Prosthesis. 2022;4(4):664-78.
12. Yuan Y, Liu Q, Yang S, Li H, Wang Y, Zhang L, et al. Four-dimensional superimposition techniques to compose dental dynamic virtual patients: A systematic review. J Funct Biomater. 2023;14(1):33.
13. Joda T, Gallucci GO. The virtual patient in dental medicine. Clin Oral Implants Res. 2015;26:725-6.
14. Granata S, Giberti L, Vigolo P, Stellini E, Di Fiore A. Incorporating a facial scanner into the digital workflow: A dental technique. J Prosthet Dent. 2020;123(6):781-5.
15. Rangel FA, Maal TJJ, Bronkhorst EM, Breuning KH, Schols JGJH, Berge SJ, et al. Accuracy and reliability of a novel method for fusion of digital dental casts and cone beam computed tomography scans. PLoS One. 2013;8(3):e59130.
16. Zou B, Kim JH, Kim SH, Lee C, Kim YJ, Kim HJ, et al. Accuracy of a surface-based fusion method when integrating digital models and the cone beam computed tomography scans with metal artifacts. Sci Rep. 2022;12:8034.
17. Pérez-Giugovaz MG, Park SH, Revilla-León M. Three-dimensional virtual representation by superimposing facial and intraoral digital scans with an additively manufactured intraoral scan body. J Prosthet Dent. 2021;126(4):459-63.
18. Ntovas P, Revilla-León M, Barmak AB, Att W, Özcan M, Kois JC, et al. Accuracy of 3-dimensional virtual patient representation using different digital integration techniques and four facial scanners: A clinical validation study. J Prosthet Dent. 2026;135(4):561.e1-10.
19. Amezua X, Iturrate M, Garikano X, Pradíes G, Solaberrieta E. Analysis of the influence of the facial scanning method on the transfer accuracy of a maxillary digital scan to a 3D face scan for a virtual facebow technique: An in vitro study. J Prosthet Dent. 2022;128(5):1024-31.
20. Jain M, Abduo J. Accuracy of static and dynamic occlusion simulation of virtual articulation compared with a conventional articulator: A systematic review. J Prosthet Dent. 2026.
21. Zambrana N, Sesma N, Fomenko I, Revilla-León M, Kois JC, Att W, et al. Jaw tracking integration to the virtual patient: A 4D dynamic approach. J Prosthet Dent. 2024;131(3):370-4.
22. Kim JE, Park JH, Moon HS, Shim JS, Lee JY. Complete assessment of occlusal dynamics and establishment of a digital workflow by using target tracking with a three-dimensional facial scanner. J Prosthodont Res. 2019;63(1):120-4.
23. Wong King C, Chuy V, Laran A, Fages M, Bertholon A, Ducret M, et al. In vitro comparison of digital occlusal analyzers and articulating paper in static and dynamic occlusion. J Dent. 2026;164:106215.
24. Lepidi L, Kim BC, Giberti L, Chen Z, Li J, Revilla-León M, et al. The 4D virtual patient: A proof of concept in digital dentistry. J Prosthet Dent. 2025;134(6):1442-5.
25. Caron T, Decup F, Grosgogeat B, Chacun D. The relevance of intraoral scanner (IOS) for periodontal diagnosis: A scoping review. J Dent. 2025;160:105824.
26. Dritsas K, Halazonetis D, Ghamri M, Antonarakis GS, Christou P. Accurate gingival recession quantification using 3D digital dental models. Clin Oral Investig. 2023;27(4):1697-705.
27. Kuralt M, Gašperšič R, Fidler A. The precision of gingival recession measurements is increased by an automated curvature analysis method. BMC Oral Health. 2021;21:505.
28. Mendoza-Azpur G, Cornejo H, Villanueva M, Paredes C, Rios K, Mayta-Tovalino F, et al. Periodontal plastic surgery for esthetic crown lengthening by using data merging and a CAD-CAM surgical guide. J Prosthet Dent. 2022;127(4):556-9.
29. Gonçalves V, De Almeida Malzoni CM, Santos JC dos, Rios D, De Souza Batista VE, De Lima Lucas BL. Predictability of periodontal surgical guides manufactured by digital flow in clinical crown lengthening: A randomized trial. J Esthet Restor Dent. 2025;37:2125.
30. Azhari A. Accuracy of artificial intelligence applications in periodontics: a thematic narrative review. Front Dent Med. 2026;7:1729825.
31. Pozzi A, Arcuri L, Moy PK. The smiling scan technique: Facially driven guided surgery and prosthetics. J Prosthodont Res. 2018;62:514-7.
32. Pérez-Giugovaz MG, Sadeghpour M, Revilla-León M. Virtual 3-dimensional representation of a completely edentulous patient for computer-aided static implant planning. J Prosthet Dent. 2023;129:384-90.
33. Abad-Coronel C, Vandeweghe S, Vela Cervantes MD, Cobo-Vázquez C, Álvarez-Novoa C, Agustín-Panadero R, et al. Accuracy of implant placement using digital prosthetically-derived surgical guides: A systematic review. Appl Sci (Basel). 2024;14(17):7422.
34. Khaohoen A, Powcharoen W, Sornsuwan T, Wongsirichat N, Sirintawat N, Chaisuparat R, et al. Accuracy of implant placement with computer-aided static, dynamic, and robot-assisted surgery: a systematic review and meta-analysis of clinical trials. BMC Oral Health. 2024;24:359.
35. Pradíes G, García-Naranjo AM, Martínez-Rus F, Martínez de Fuentes R, Romeo-Rubio M. EPA Consensus Project Paper: Shifting from the 'Analogic Virtual Patient' to the 'Digital Virtual

Patient' in Prosthodontics. A Scoping Review. Eur J Prosthodont Restor Dent. 2023.
36. Lin WS, Harris BT, Phasuk K, Liao YJ, Morton D. Integrating a facial scan, virtual smile design, and 3D virtual patient for treatment with CAD-CAM ceramic veneers: A clinical report. J Prosthet Dent. 2018;119(2):200-5.
37. Luniyal C, Shukla AK, Priyadarshi M, Singh S, Gupta A, Kumar A, et al. Assessment of patient satisfaction and treatment outcomes in digital smile design vs. conventional smile design: A randomized controlled trial. J Pharm Bioallied Sci. 2024;16(1):S669.
38. Lo Giudice A, Ortensi L, Farronato M, Lucchese A, Lo Giudice R, Pantaleo G, et al. The step further smile virtual planning: milled versus prototyped mock-ups for the evaluation of the designed smile characteristics. BMC Oral Health. 2020;20:165.
39. Kaitatzidou A, Chalazoniti A, Faggion CM, Tsintsadze N, Kourtis S. Digital scans versus conventional impressions in fixed prosthodontics: An overview of systematic reviews. J Prosthet Dent. 2025;134(6):2156-64.
40. Marradi F, Staderini E, Zimbalatti MA, Spagnuolo G, Galli M, Gracco A, et al. How to obtain an orthodontic virtual patient through superimposition of three-dimensional data: A systematic review. Appl Sci (Basel). 2020;10(15):5354.
41. Sereewisai B, Chintavalakorn R, Santiwong P, Ratanaporncharoen C, Thiradilok S. The accuracy of virtual setup in simulating treatment outcomes in orthodontic practice: a systematic review. BDJ Open. 2023;9:41.
42. Stucki S, Gkantidis N. Assessment of techniques used for superimposition of maxillary and mandibular 3D surface models to evaluate tooth movement: a systematic review. Eur J Orthod. 2020;42:559-70.
43. Muthuswamy Pandian S, Subramanian AK, Vaiid N. Comparison of efficacy and accuracy of tooth movements in optimized and conventional attachments of clear aligners - A systematic review and meta-analysis. J Oral Biol Craniofac Res. 2025;15:1123-33.
44. Sangalli L, Alessandri-Bonetti A, Dalessandri D. Effectiveness of dental monitoring system in orthodontics: A systematic review. J Orthod. 2023.
45. Rosen E, Goldberger T, Beitlitum I, Tsesis I, Taschieri S, Rosenberg E, et al. Diagnosis efficacy of cone-beam computed tomography in endodontics—A systematic review of high-level-evidence studies. Appl Sci (Basel). 2022;12(2):938.
46. Zubizarreta-Macho Á, Castaño SV, María Montiel-Company J, Mena-Álvarez J, Cabanillas-Balsera D, Martín-González J, et al. Effect of computer-aided navigation techniques on the accuracy of endodontic access cavities: A systematic review and meta-analysis. Biology (Basel). 2021;10(3):212.
47. Jonaityte EM, Bilvinaite G, Drukteinis S, Peciuliene V, Skliutas E, Zaleckas L, et al. Accuracy of dynamic navigation for non-surgical endodontic treatment: A systematic review. J Clin Med. 2022;11(12):3441.
48. Langaliya A, Kritika S, Shah A, Jain S, Patel S, Patel N, et al. Does dynamic navigation system preserve more dentine? – A systematic review. BMC Oral Health. 2024;24:678.
49. Pul U, Schwendicke F. Artificial intelligence for detecting periapical radiolucencies: A systematic review and meta-analysis. J Dent. 2024;147:105104.
50. Setzer FC, Li J, Khan AA. The Use of Artificial Intelligence in Endodontics. J Dent Res 2024;103:853–862.
51. Liczmanski K, Stamm T, Sauerland C, Rüther J, Wiechmann D, Lübberink G, et al. Accuracy of intraoral scans in the mixed dentition: A prospective non-randomized comparative clinical trial. Head Face Med. 2020;16:11.
52. Okamoto A, Karibe H, Tanaka S, Kawakami T, Fujita Y. Reliability of mixed dentition space analysis using a digital model obtained from an optical impression: A preliminary study. BMC Res Notes. 2024;17:12.
53. Van Gorp G, Maes A, Lambrechts M, Politis C, Jacobs R, Willems G, et al. Is use of CBCT without proper training justified in paediatric dental traumatology? An exploratory study. BMC Oral Health. 2023;23:270.
54. Karamüftüoğlu N, Üçpunar BY, Birben İ, Aksoy S, Korkmaz Y. Artificial intelligence in pediatric dentistry: A systematic review and meta-analysis. Children (Basel). 2026;13(2):152.
55. Assiry AA, Alrehaili RS, Mahnashi A, Alharthi A, Alotaibi S, Alshammari F, et al. How is artificial intelligence transforming the intersection of pediatric and special care dentistry? A scoping review of current applications and ethical considerations. Prosthesis. 2025;7(4):119.
56. Alkhayer A, Piffkó J, Lippold C, Danesh G. Accuracy of virtual planning in orthognathic surgery: A systematic review. Head Face Med. 2020;16:34.
57. Lee YJ, Oh JH, Kim SG. Virtual surgical plan with custom surgical guide for orthognathic surgery: Systematic review and meta-analysis. Maxillofac Plast Reconstr Surg. 2024;46:39.
58. Olejnik A, Verstraete L, Croonenborghs TM, Verhelst PJ, Politis C. The accuracy of three-dimensional soft tissue simulation in orthognathic surgery—A systematic review. J Imaging. 2024;10(5):119.
59. Kotecha S, Ferro A, Harrison P, Patel M, Praveen P. Orbital reconstruction: A systematic review and meta-analysis evaluating the role of patient-specific implants. Oral Maxillofac Surg. 2023;27(2):213-26.
60. Yousif E, Abdalla M, Jumaa H, Al-Saadi S, Al-Mutairi K, Alharthi A, et al. 3D-printed patient-specific implants in maxillofacial reconstruction: A systematic review and meta-analysis of clinical

outcomes and workflow efficiency. Cureus. 2025;17:e98224.
61. Sun T, He X, Li Z. Digital twin in healthcare: Recent updates and challenges. Digit Health. 2023;9:20552076221149651.
62. Elsayed EI, Galadari R, Alharmoodi R. Digital twin technologies in endodontics: Current evidence, challenges, and future perspectives. Digit Dent J. 2026;3:100051.
63. Salvi S, Vu G, Gurupur V, Li X, Wang H, Zhang Y, et al. Digital convergence in dental informatics: A structured narrative review of artificial intelligence, Internet of Things, digital twins, and large language models with security, privacy, and ethical considerations. J Dent Inform. 2025.
64. Alang TAIT, Lee YY, Tan TS. Medical Digital Twin Technology for Interoperability: Challenges and Opportunities. Biomed Eng Comput Biol. 2026;17:11795972261431928.
65. Burr CD, Qian S, Winter P, Chico T, Rangel Smith C, Wagg D, et al. Realising the digital twin: a thematic review and analysis of the ethical, legal, and social issues for digital twins in healthcare. AI Soc. 2026;41(5):5243-67.

**Cite this article as:** Dashti A, Reda M, AlAdwani A, Shukrallah A, Dashti H, Alkandari A, et al. The 4D virtual patient in digital dentistry: can multimodal data integration and specialty-specific applications pave the road toward dental digital twins?. Int J Community Med Public Health 2026;13:4665-78.