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Impact of 3D imaging techniques and virtual patients on the accuracy of planning and surgical placement of dental implants: A systematic review

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Abstract

Aim: The integration of advanced technologies, including three-dimensional (3D) imaging modalities and virtual simulations, has significantly influenced contemporary approaches to preoperative planning in implant dentistry. Through a meticulous analysis of relevant studies, this review synthesizes findings related to accuracy outcomes in implant placement facilitated by 3D imaging in virtual patients.

Methods: A comprehensive literature search was conducted across relevant databases to identify relevant studies published to date. The inclusion criteria were studies utilizing 3D imaging techniques, virtual patients, and those focusing on the accuracy of dental implant planning and surgical placement. The selected studies were critically appraised for their methodological quality.

Results: After a rigorous analysis, 21 relevant articles were included out of 3021 articles. This study demonstrates the versatility and applicability of these technologies in both *in vitro* and *in vivo* settings. Integrating Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM), cone bean computed tomography (CBCT), and advanced 3D reconstruction methodologies showcases a trend toward enhanced precision in implant planning and placement. Notably, the evaluation parameters varied, encompassing distances, discrepancies, and deviations in the implant placement. The ongoing integration of systems such as dynamic navigation systems, augmented reality, and sophisticated software platforms shows a promising trajectory for the continued refinement of virtual reality applications in dental implantology, providing valuable insights for future research and clinical implementation. Moreover, using stereolithographic surgical guides, virtual planning with CBCT data, and 3D-printed templates consistently demonstrates enhanced precision in dental implant placement compared to traditional methods.

Conclusion: The synthesis of the available evidence underscores the substantial positive impact of 3D imaging techniques and virtual patients on dental implant planning and surgical placement accuracy. Utilizing these technologies contributes to a more personalized and precise approach that enhances overall treatment outcomes. Future research directions and potential refinements to the application of these technologies in clinical practice should be discussed.

Keywords

three dimensional, CBCT, virtual reality, precision, dental implants

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Introduction

Advances in technology have revolutionized various fields of medicine and dentistry, with the field of dental implantology being no exception. Dental implants have emerged as a primary solution for the replacement of missing teeth because of their durability, esthetics, and functionality. The success and accuracy of dental implant placement depend on meticulous treatment planning and precise surgical execution. In recent years, three-dimensional (3D) imaging techniques and virtual patient simulations have emerged as powerful tools for enhancing the accuracy of dental implant planning and surgical placement.[1,2] The increasing prevalence of dental implant procedures has resulted in an increased incidence of complications. These complications manifest in diverse forms, from restorative challenges attributable to suboptimal placement to potential harm to collateral structures such as nerves and adjacent teeth. It is imperative to note that a judiciously placed implant significantly mitigates the likelihood of encountering these complications.[3] However, the pivotal determinants of the success and precision of dental implant placement reside in meticulous treatment planning and execution of surgical procedures.

The accuracy of planning and surgical placement of dental implants is crucial to ensure successful outcomes and long-termm patient stability.[4] Accurate planning allows clinicians to thoroughly assess a patient's oral and maxillofacial anatomy and identify any potential challenges or complications that may arise during the procedure.[5] By examining the quality and quantity of available bone, proximity to vital structures such as nerves and sinuses, and the position of adjacent teeth, clinicians can develop an appropriate treatment strategy that minimizes the risk of complications.[6] Accurate planning also facilitates the selection of the optimal implant size, shape, and angulation, considering factors such as the patient's esthetic preferences and functional requirements.[7] Moreover, precise surgical placement of dental implants is vital for osseointegration, the process through which the implant fuses with the surrounding bone.[8] Misalignment or improper placement of implants can lead to mechanical and biological complications such as implant failure, bone loss, and soft tissue problems. The precise location of the implant is crucial to optimize load distribution and facilitate appropriate functionality, thus playing a pivotal role in the overall durability and reliability of the implant.[9] Moreover, the achievement of favorable esthetic outcomes primarily relies on the optimization of algorithms that are specific to the stages of pro-implant and implant procedures. Additionally, the design and technological execution of future prosthetic restorations play a crucial role in this regard.[10] Accurate placement allows for the creation of harmonious and esthetically pleasing restorations, thus enhancing patient satisfaction and confidence in their new smile.

In recent years, technological advancements have brought about transformative changes in various domains of medicine and dentistry, with dental implantology being a notable example.[11] The convergence of virtual engineering and the digitization of dental information have heralded a novel and innovative trajectory for diagnosing and treating dental conditions. The integration of computer-based implant-guided surgery has emerged as a solution to the limitations inherent in traditional surgical planning methods. This technological leap has substantially enhanced the precision of implantation procedures, ushering in the era of minimally invasive surgery.[12,13] In the field of dental implantology, conventional treatment planning usually utilizes two-dimensional (2D) imaging techniques, including panoramic, and periapical radiographs.[14] While these conventional techniques offer valuable insights, they exhibit constraints in faithfully representing the 3D anatomy of the oral and maxillofacial regions.[15] This deficiency introduces challenges in visualizing crucial anatomical structures, including nerves, sinuses, and adjacent teeth, potentially leading to complications during implant placement.[15] Advanced imaging technologies such as cone beam computed tomography (CBCT) and computer-aided design/computer-aideded manufacturing (CAD/CAM), have facilitated precise implant planning. Moreover, these technologies have enabled the production of implant surgical guides through 3D printing, thereby enhancing the overall efficacy of dental implant procedures.[16] Augmented reality (AR) has progressively been applied in dental implant surgery, marking another dimension of technological integration. Nevertheless, the level of improvement in accuracy that can be achieved by integrating a dynamic navigation system with AR technology is currently unknown and requires further investigation.[17]

In addition to 3D imaging, virtual patient simulation has gained popularity in dental implantology.[18] Virtual patient simulations involve the creation of 3D models that simulate the patient's anatomy and allow the clinician to virtually plan and perform implant surgery.[19] This technology provides a platform for clinicians to assess the feasibility of implant placement, evaluate surrounding structures, determine the optimal implant size and angulation, and virtually place implants in a simulated environment.[20] The integration of 3D imaging techniques and virtual patient simulations offers several advantages. Accurate visualization of the anatomy allows clinicians to identify potential challenges and develop appropriate treatment strategies prior to surgery.[21] The ability to virtually plan and simulate implant surgery helps minimize intraoperative complications, reduce surgical time, and improve patient outcomes.[22] Furthermore, it serves as an invaluable tool for patient communication, as clinicians can visually demonstrate the treatment plan and discuss the expected patient outcomes.

The use of 3D imaging modalities such as CBCT and CAD/CAM technology has significantly enhanced the ability to visualize and comprehend the intricate 3D anatomy of the oral and maxillofacial regions. This new clarity is instrumental in overcoming the limitations associated with traditional 2D imaging methods, thereby enabling more accurate treatment planning. Moreover, incorporating virtual patient models allows meticulous preoperative simulations, offering practitioners a dynamic and interactive platform for evaluating and refining surgical approaches. Consequently, amalgamation of 3D imaging and virtual patient technologies facilitates precise implant planning and improves surgical placement accuracy, ultimately advancing the field of dental implantology. This systematic review aimed to evaluate the impact of 3D imaging techniques and virtual patients on the accuracy of planning and surgical placement of dental implants.

Materials and methods

This systematic review and meta-analysis adhered to the guidelines outlined by the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) criteria.[23] The protocol used for this systematic review was registered at the International Platform of Registered Systematic Review and Meta-Analysis Protocols (INPLASY) (2023110097)

Literature search

The search strategy was established according to the participants, intervention, comparators or controls, and outcome framework.[24] Population/participants: dental implants. Intervention: 3D imaging. Comparison or control: other imaging techniques. Outcomes: accuracy and virtual reality. Different databases such as ScienceDirect, Web of Sciences, PubMed, GoogleScholar, and Scopus were searched using different keywords such as “3D imaging”, “3-dimensional imaging”, “3D Digital dentistry”, “CAD/CAM imaging”, “Virtual patients”, “Virtual environment”, “Virtual reality”, “Simulation”, “Dental Implants”, and “Dental fabrication” (see Supplemental Table 1).

Inclusion criteria

The evaluation encompassed studies that necessitated the integration of digital tools, such as intraoral scanners, CAD/CAM systems, or 3D imaging techniques. The research was anticipated to prioritize measurements of the outcome, including prosthesis fabrication accuracy, implant placement accuracy, marginal fit, occlusal discrepancies, and other relevant metrics assessing precision. Incorporating a wide range of topics, potential research inquiries pertain to dental materials, software applications, or hardware components related to the field of digital dentistry. Eligible studies included randomized controlled trials (RCTs), cohort studies, case-control studies, observational studies, retrospective studies, prospective studies, and in vitro studies that investigated the use of 3D imaging and virtual patient technologies in dental implant planning and placement. Only articles published in English were included in the present study. Studies published up to 2023 in peer-reviewed journals were included.

Exclusion criteria

To ensure the inclusion of pertinent research examining the effects of 3D imaging techniques and virtual patients on the precision of dental implant planning and surgical placement, the exclusion criteria were established. Studies were excluded if they did not specifically focus on 3D imaging or virtual patients in the context of dental implant planning and placement. Additionally, articles lacking sufficient methodological rigor, such as those with a high risk of bias or inadequate sample size, were excluded to maintain the quality and reliability of the synthesized evidence. Studies published in languages other than English were excluded to facilitate a comprehensive data extraction and synthesis. Case series, case reports, and reviews were excluded.

Study selection and assessment

We created and implemented a standardized data extraction form to maintain data accuracy and address potential errors. Any inconsistencies or contradictions between the two autonomous reviewers were addressed through dialogue and agreement. A third reviewer was consulted if consensus was not reached.

Data extraction

Information retrieval was performed for the selected studies that met the inclusion criteria. The data-extraction protocol encompasses several essential components. Initially, demographic characteristics were documented (author’s details, country, study design, and sample size (patients/implants)). Moreover, 3D technology is used, along with the characteristics of virtual reality (hardware, software, methodology duration, evaluation time, and evaluation items). In addition, the characteristics of the accuracy assessment (techniques used to measure accuracy, dental implant position, and marginal fit measurements) were extracted. The protocol also aimed to capture the edentation type, and limitations or potential biases identified were also reported.

Quality assessment

The in vitro studies were assessed for methodological quality using the CONSORT scale (14 items; for items, see Appendix 1) for the included studies.[25,26] Conversely, non-in vitro studies were appraised using the Mixed Methods Appraisal Tool (Appendix 2), and their quality scores were computed following the method outlined byCharette, McKenna.[27] Studies were categorized as either low quality (score ≤ 3) or high quality (score > 3) based on their responses to “yes” (1 point) or “no” (0 points).[28]

Data analysis

This systematic review incorporated articles through a qualitative analysis. The PRISMA checklist served as the framework for systematically reviewing relevant literature, and a systematic step-by-step approach was employed to select articles.

Results

Literature searched

Extensive examination of the scientific literature was performed using multiple electronic databases. All research articles included in this study were previously published in reputable, peer-reviewed academic publications. After rigorous analysis, 3021 relevant articles were included. Subsequently, 470 duplicate articles were identified and excluded from analysis. The remaining 2551 publications were meticulously examined their titles and abstracts, revealing that 2504 articles were not pertinent to the scope of our study and were consequently excluded. Subsequently, the remaining 47 articles were subjected to comprehensive scrutiny, leading to the removal of 26 articles for various reasons (Figure 1). Tables 1, 2, and 3 offer a detailed overview of the 21 remaining publications, highlighting their key characteristics and features.

General characteristics

Most of the studies were conducted in Germany,[29–33] followed by China,[34–37] the USA,[38–40] Switzerland,[41,42]

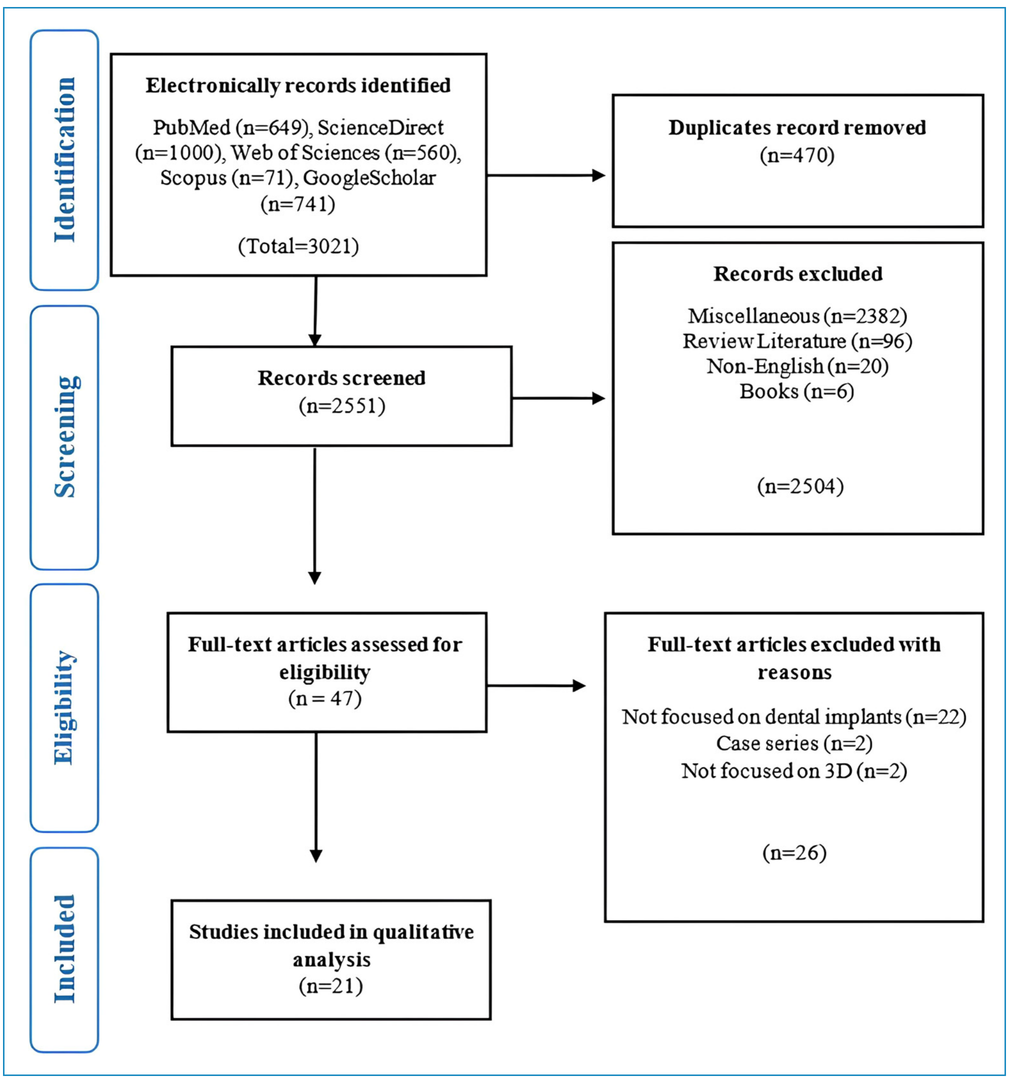

Figure 1. PRISMA flow chart.

Poland,[43] Saudi Arabia,[44] Italy,[45] Albania,[46] Greece,[47] Korea,[48] and Hungary.[49] In terms of study design, the majority of the studies followed an *in vitro* design, except six studies that followed retrospective[32,45,48] and RCT[34,40,46] designs. The minimum number of patients was 10,[30,31] and the maximum number of patients was 120.[35] Meanwhile, 5 was the minimum number of implants used in a study,[38] and the maximum number of implants was 250.[29] Most studies used the CBCT scan method, four studies used computed tomography (CT),[38,43–45] and two used CBCT and intraoral scans.[33,47] The included studies documented several categories of 3D technology (Table 1).

Virtual reality and accuracy measurements

Table 2 presents a comprehensive overview of the various methods, hardware, software, and evaluated items used in dental implant planning in different studies. The most frequently used method among these studies is coDiagnostiX.[29–31,49] In addition, a registration method without specifying hardware was used,[38] and Digital Imaging and Communications in Medicine (DICOM) data with NobelGuide software was used for slice-collimation.[43] Moreover, surgical guides and Mimics, Materialise NV for deviation analysis,[39] the Chair-side Economical Restoration of Esthetic Ceramic (CEREC) AC system, and GALILEOS Implant software for measuring discrepancies between visualized 3D surface and CBCT data.[32] Other studies utilized various hardware and software combinations, such as the 64-channel helical CT system with Materialize Interactive Medical Image Control System (MIMICS) software (Materialize, Leuven, Belgium), Geomagic Freeform Plus software,[45] AR-based dynamic navigation system, and Innooral System with coDiagnostiX software version 10.4.[49] The evaluated parameters varied across studies and included the distances between planned implants and actual osteotomies, deviation analysis, angular and linear measurements, apical and angular deviations, and implant length and deviation (Table 2).

The accuracy measurement techniques employed in these studies varied according to the specific requirements of each study, including the use of surgical guide templates, stereolithography (STL/SLA) files, CAD/CAM, and other methods tailored to the implant types and models under investigation. However, the most frequently employed accuracy method across studies is the use of STL/SLA files for accuracy measurements.[30,31,34,37,39–41,44,47,49] These studies utilized STL files for techniques such as surgical guide templates, STL registration, automated Hausdorff distance function, CAD/CAM, and the superimposition of STL files for accuracy measurements. Additionally, Ku and Lee[48] used SLA and superimposition of CBCT for accuracy evaluation, whereas STL was also used for tooth visualization.[33] Accuracy analysis systems were used for the mandibular implant assessment[36] (Table 2).

Outcomes

The specifications of edentation types are often overlooked in most studies. However, three studies, namely,[34,38,39] provided detailed information on the edentation type, particularly focusing on complete and partial edentation.[29,32,41,46,49] These studies have shed light on the significant differences observed in entrance point, apical point, and angulation deviation, as evidenced by the findings summarized in Table 3.

Interestingly, the implementation of advanced 3D technologies, such as CBCT and CAD/CAM, has been found to greatly enhance the precision and reliability of dental implant placement. Furthermore, utilizing 3D imaging allows for more accurate preoperative planning, leading to optimal implant placement with improved anatomical fit and reduced risk of complications.[29] Virtual simulations enable clinicians to anticipate potential challenges and customize treatment plans to individual patient anatomy, resulting in improved implant stability and long-term success rates. These technologies have shown remarkable outcomes, as highlighted in Table 3, and have also brought significant improvements to the field.

Patients generally perceive treatment outcomes positively, as these technologies provide enhanced visualization and communication of treatment plans,[43] fostering a clearer understanding of proposed procedures and minimal exposure to radiation.[31] By allowing patients to preview outcomes and actively participate in decision-making processes, these tools often lead to increased satisfaction and confidence in treatment outcomes as it prove to be more accurate.[48] Furthermore, the precision enabled by 3D imaging can result in improved treatment accuracy and reduced complications,[33] contributing to enhanced long-term oral health and overall quality of life for patients. Likewise, dynamic navigation systems have demonstrated superior implant placement accuracy compared to static systems, primarily due to their real-time tracking capabilities and ability to account for intraoperative anatomical variations.[36]

However, it is important to acknowledge the limitations of these previous studies. These limitations include relatively small sample sizes, variations in study design, and the need for further clinical implementation to validate these promising findings. Despite these limitations, no major adverse events or complications have been reported in relation to the planning and accuracy of 3D planned surgery for dental implants, which supports the notion that these technologies improve precision and reliability. Nonetheless, future research efforts should address the noted limitations to further enhance the clinical implementation of these innovative techniques.

Table 1. General characteristics of the included studies.

	Demographic characteristics					
Study ID	Country	Study design	Sample size (patients)	Sample size (implants)	Scan method	3D technology used
Sarment et al.[38]	USA	In vitro	NA	5	CT	CAD/CAM
Nickenig and Eitner[29]	Germany	In vitro	102	250	CBCT	3D planning software
Wojciechowski et al.[43]	Poland	In vitro	26	NA	CT	3D reconstruction
Nickenig et al.[30]	Germany	In vivo	10	23	CBCT	3D planned surgical guide template
Nickenig and Eitner[31]	Germany	In vitro	10	23	CBCT	3D planned surgical guide template
Turbush and Turkyilmaz[39]	USA	In vitro	NA	150	CBCT	SLA
Ritter et al.[32]	Germany	Retrospective	16	NA	CBCT	Wax-ups based on 3D surface models
Kernen et al.[41]	Switzerland	In vitro	NA	34	CBCT	D-temp
Moiduddin et al.[44]	Saudi Arabia	In vitro	NA	NA	CT	Medical modeling software Mimics®
Tarsitano et al.[45]	Italy	Retrospective	34	NA	CT	CAD/CAM
Tallarico et al.[46]	Albania	RCT	30 (Test = 15, Control = 15)	Test = 49, Control = 41	CBCT	Intraoral digital impression
Tang et al.[37]	China	In vitro	19	32	CBCT	Digital registration method
Schneider et al.[42]	Switzerland	In vitro	NA	48	CBCT	CAD/CAM
Lee et al.[40]	USA	RCT	30	NA	CAD/CAM	Digital scanning technique
Vasoglou et al.[47]	Greece	In vitro	NA	35	CBCT and intraoral scans	SLA
Ku et al.[48]	Korea	Retrospective	34	89	CBCT	3D printer (Dentium, Suwon, Korea)

(continued)

Table 1. Continued.

Study ID	Demographic characteristics				Scan method	3D technology used
	Country	Study design	Sample size (patients)	Sample size (implants)		
Kivovics et al.[49]	Hungary	In vitro	NA	48	CBCT	Flashforge Hunter Digital Light Processing 3D printer
Zhang et al.[34]	China	RCT	14	79	Photogrammetric imaging	CAD
Riad-Deglow et al.[33]	Germany	In vitro	NA	Tooth visualization (AR TOOTHi) = 23, AR SCREWS-i = 23, Conventional freehand technique (FHT-I) = 23	CBCT and intraoral scans	3D intraoral scan
Pei et al.[36]	China	In vitro	NA	80	CBCT	NA
Sun et al.[35]	China	In vitro	120	116	CBCT	i-CAT 3D imaging system

CAD/CAM: computer-aided design/computer-aided manufacturing; CBCT: cone bean computed tomography; CT: computed tomography; i-CAT: computerized axial tomography; NA: not available; SLA: stereolithography.

Table 2. Techniques used for virtual reality and accuracy measurements.

	Virtual reality		Accuracy measurement		
Study ID	Hardware/format	Software/method	Evaluated items	Technique	Implant type
Sarment et al.[38]	NA	Registration method	Distances between planned implants and actual osteotomies	SLA	Jaws
Nickenig and Eitner[29]	NA	coDiagnostiX	NA	Surgical guide templates	Mandibular
Wojciechowski et al.[43]	DICOM	NobelGuide software	Slice-collimation = 10 × 0.75 mm, slice-thickness = 0.75 mm	Multiple reconstructions	Maxilla and mandible
Nickenig et al.[30]	DICOM-size	coDiagnostiX	Tip-distance, base-distance, divergence of implant axis	Surgical guide templates	Lower jaws
Nickenig and Eitner[31]	NA	coDiagnostiX	Tip-distance, base-distance, divergence of implant axis	Surgical guide templates	Lower jaws
Turbush and Turkyilmaz[39]	Surgical guides	Mimics; Materialize NV	Deviation analysis	SLA	Mandibular
Ritter et al.[32]	CEREC AC system	Implant planning software (GALILEOS)	Differences between the 3D surface data visualization and the corresponding CBCT data	NA	Mandibular, maxilla and teeth
Kernen et al.[41]	NA	Med-3D system	Coronal and apical deviations	STL	CAMLOG SCREW-LINE Implants
Moiduddin et al.[44]	NA	NA	Deviation analysis	STL	Reconstruction plate
Tarsitano et al.[45]	A 64-channel helical CT system	MIMICS software	Error was calculated	Automated computation of the Hausdorff distance function within the simulation software, along with the superimposition of STL files	Mandibular
Tallarico et al.[46]	NA	NA	Deviation analysis	Computer assisted, template based implant placement techniques	

(continued)

Table 2. Continued.

	Virtual reality			Accuracy measurement	
Study ID	Hardware/format	Software/method	Evaluated items	Technique	Implant type
Tang et al.[37]	NA	NA	Deviation analysis	STL registration	Not specified
Schneider et al.[42]	NA	Planning software (SimPlant/ Facilitate, Materialise)	Deviation analysis	CAD/CAM	Lower jaws
Lee et al.[40]	NA	NA	Marginal fits	STL	Single
Vasoglou et al.[47]	DICOM	NA	Angular and linear measurements	SLA	Maxilla and Mandible
Ku et al.[48]	NA	Computer-guided surgery	Apical and angular deviations	SLA and superimposition of CBCT	Not specified
Kivovics et al.[49]	AR-based dynamic navigation and Innooral System	coDiagnostiX software, version 10.4	Angular, coronal, and apical global deviation	STL	Callus Pro implants
Zhang et al.[34]	PG-STL	Reverse engineering software program	Deviation analysis	STL	Jaws
Riad-Deglow et al.[33]	Hololens2	AR technology	Deviation angle and horizontal measurement	STL	Self-drilling mini-implants
Pei et al.[36]	Implant Precision Systems, Digital healthcare	Dynamic navigation system	Implants deviation analysis	Accuracy analysis systems	Mandibular
Sun et al.[35]	DICOM	Planning software (Nobel Clinician, Nobel Biocare, Sweden)	Implant length and deviation	NA	Pterygoid implant

AR: augmented reality; CAD/CAM: computer-aided design/computer-aided manufacturing; CBCT: cone bean computed tomograpy; CT, computed tomography; DICOM: Digital Imaging and Communications in Medicine; NA: not available; STL/SLA: stereolithography.

Table 3. Outcomes.

Study ID	Edentation type	Accuracy outcomes (mean deviation)			Conclusion	Limitations
		Entrance point/coronal	Apical point	Angulation		
Sarment et al.[38]	Complete	1.5 mm	2.1 mm	NA	Implant placement benefits from a stereolithographic surgical guide	NA
Nickenig and Eitner[29]	Partially	NA	NA	NA	Virtual planning with CBCT data and surgical templates ensures a reliable preoperative assessment of implant size, placement, and potential anatomical complications	NA
Wojciechowski et al.[43]	Unspecified	NA	NA	NA	Double-scan CT allows for precise virtual dental implant placement planning, guiding the implantation procedure	NA
Nickenig et al.[30]	Unspecified	NA	NA	4.8° for 3D and 9.8° for free-hand method	The precision of implant placement is markedly elevated when employing virtual planning based on CBCT data and surgical templates, surpassing the accuracy achieved through free-hand insertion by a significant margin	Study design, free-hand implementation was not carried out in clinical setting
Nickenig and Eitner[31]	Unspecified	NA	0.6 mm in the lateral/medial direction and 0.9 mm in the anterior/ posterior direction	4.2°	This alternative matching technique offers a dependable means for postoperative assessment of variations in the position and axis of implants, comparing the planned versus actual placement while minimizing the radiation exposure to the patient	NA
Turbush and Turkyilmaz[39]	Complete	1.18 mm ($p < 0.01$)	1.44 mm ($p > 0.01$)	2.2° ($p > 0.01$)	Stereolithographic surgical guides are a dependable option for accurate implant placement	NA

(continued)

Table 3. Continued.

Study ID	Edentation type	Accuracy outcomes (mean deviation)			Conclusion	Limitations
		Entrance point/coronal	Apical point	Angulation		
Ritter et al.[32]	Partially	NA	NA	NA	The alignment of 3D surface and CBCT data for dental implant planning is reliable and achieves sufficient accuracy	NA
Kernen et al.[41]	Partially	NA	$p < 0.001$	$p < 0.001$	Using 3D-printed templates that are generated by aligning a surface scan with CBCT can lead to enhanced accuracy in implant placement	NA
Moiduddin et al.[44]	Unspecified	0.1167 / −0.0841		NA	Focus should be on implant design techniques	NA
Tarsitano et al.[45]	Unspecified	The accuracy evaluation study found an average mean error of 1 mm in reconstructions			CAD/CAM microvascular reconstruction offers excellent reproducibility	The “best fit” superimposition tool may underestimate errors in overlapping complex 3D meshes
Tallarico et al.[46]	Partially	NA	NA	Test = 1.98, Control = 2.25	Surgical templates without metallic sleeves showed superior vertical and angular dimension accuracy compared to conventional templates with metallic sleeves	Small sample size
Tang et al.[37]	Unspecified	-0.03 ± 0.38 mm	-0.03 ± 0.57 mm	$0.60 \pm 2.94°$	The digital registration method is accurate for clinical applications, showing comparable precision to the radiographic procedure in assessing implant position	NA
Schneider et al.[42]	Unspecified	NA	NA	Nonsignificant difference ($p = 0.67$)	CAIPP protocols exhibited lesser variations regardless of the tooth gap size	Implementing these findings in an actual clinical setting, however, results in a more accurate determination of implant positions

(continued)

Table 3. Continued.

Study ID	Edentation type	Accuracy outcomes (mean deviation)			Conclusion	Limitations
		Entrance point/coronal	Apical point	Angulation		
Lee et al.[40]	Unspecified	NA	NA	NA	The digital scanning method proved to be more effective than the traditional impression technique when it came to single implant-supported restorations	NA
Vasoglou et al.[47]	Unspecified	NA	NA	Nonsignificant difference ($p > 0.01$)	A 3D-designed and manufactured precision surgical guide incorporates CBCT and intraoral scanning data for accurate mini-implant placement	NA
Ku et al.[48]	Unspecified	NA	$p < 0.001$	$p = 0.001$	The flapless approach in computer-guided surgery exhibits enhanced precision in implant placement	Study design, heterogeneity to the surgeons and tooth position
Kivovics et al.[49]	Partially	$p > 0.001$	$p > 0.001$	$p > 0.001$	AR dynamic navigation showed comparable implant positioning accuracy to static CAIS, surpassing the precision of the free-hand approach	In order to stabilize the models during surgery, the AR-based system was restricted to tracking only the drill
Zhang et al.[34]	Complete	NA	NA	0.432°	Photogrammetric imaging of full-arch implant-supported prostheses exhibited clinically acceptable accuracy	Photogrammetric imaging precision was not assessed, and traditional splinted impressions still fall short in accurately capturing intraoral implant positions
Riad-Deglow et al.[33]	Unspecified	$p < 0.001$	$p < 0.001$	$p < 0.001$	Using AR technology for orthodontic self-drilling mini-implant placement improves precision and reduces complications compared to traditional free-hand methods. AR	Study design, small sample size

(continued)

Table 3. Continued.

Study ID	Edentation type	Accuracy outcomes (mean deviation)			Conclusion	Limitations
		Entrance point/coronal	Apical point	Angulation		
					TOOTH, in particular, exhibits superior accuracy in aligning planned and placed implants, outperforming AR SCREWS and conventional approaches	
Pei et al.[36]	Unspecified	NA	$p = 0.17$	UT group 2.16°, RW group 1.53°	The implementation of reflective wafers led to more streamlined registration and calibration processes in comparison to U-shaped tube	Sampling error and navigation accuracy variations can occur among models and patients due to patient movement, mouth opening, limited visualization, and the influence of blood and saliva
Sun et al.[35]	Unspecified	In nearly 90% of planned implants, a strong correlation with the sinus cavity was noted, with implants lacking a sinus connection showing longer lengths	NA	83.2°	Approximately 90% of virtually planned implants were closely associated with the sinus cavity, and those without a sinus relationship showed longer lengths	NA

AR: augmented reality; CAD/CAM: computer-aided design/computer-aided manufacturing; CAIS: Computer-Assisted Image Guidence; CAIPP: Computer-Assisted Implant Planning and Template-guided Placement; CBCT: cone bean computed tomography; CT: computed tomography; NA: not available.

Table 4. Quality assessment of *in vitro* studies.

	Items														
Study ID	1	2a	2b	3	4	5	6	7	8	9	10	11	12	13	14
Sarment et al.[38]	Y	Y	Y	Y	Y	N	N	N	N	N	Y	N	N	N	N
Nickenig and Eitner[29]	Y	Y	Y	Y	Y	N	N	N	N	N	Y	N	N	N	N
Wojciechowski et al.[43]	Y	Y	Y	Y	Y	N	N	N	N	N	Y	N	N	N	N
Nickenig et al.[30]	Y	Y	Y	Y	Y	N	N	N	N	N	Y	Y	Y	N	N
Nickenig and Eitner[31]	Y	Y	Y	Y	Y	N	N	N	N	N	Y	Y	N	N	N
Turbush and Turkyilmaz[39]	Y	Y	Y	Y	Y	N	N	N	N	N	Y	N	N	Y	N
Kernen et al.[41]	Y	Y	Y	Y	Y	N	N	N	N	N	Y	Y	N	Y	N
Moiduddin et al.[44]	N	Y	Y	Y	Y	N	N	N	N	N	N	N	N	Y	N
Tang et al.[37]	Y	Y	Y	Y	Y	N	N	N	N	N	Y	N	N	N	N
Schneider et al.[42]	Y	Y	Y	Y	Y	Y	N	N	N	N	Y	Y	Y	Y	N
Vasoglou et al.[47]	Y	Y	Y	Y	Y	N	N	N	N	N	Y	Y	Y	Y	N
Kivovics et al.[49]	Y	Y	Y	Y	Y	Y	N	Y	N	N	Y	Y	Y	Y	N
Riad-Deglow et al.[33]	Y	Y	Y	Y	Y	Y	N	Y	N	N	Y	Y	Y	Y	N
Pei et al.[36]	Y	Y	Y	Y	Y	N	N	N	N	N	Y	Y	Y	Y	N
Sun et al.[35]	Y	Y	Y	Y	Y	N	N	N	N	N	Y	N	N	Y	N

N: no; Y: yes.

Quality assessment

In vitro studies

The examined 15 studies encompassed essential components, such as abstract, introduction, intervention, outcome, statistical method, and results (items 1–4, 10, and 11). A comprehensive analysis of 12 studies was extended to explore trial limitations (item 12), while 9 explicitly disclosed details about their funding sources (item 13). Notably, three studies uniquely addressed aspects such as sample size calculation for the specimens (item 5) or the accessibility of the full trial protocol (item 14). Details regarding the procedure utilized to produce the chosen sequence (item 7) were absent in most studies, with only two studies providing this detail. Furthermore, none of the studies provided specifics regarding the blinding of examiners or information about the researcher responsible for generating random allocation (items 8 and 9), as shown in Table 4.

Non-*in vitro* studies

Non-*in vitro* studies, including RCTs and retrospective studies, showed good quality (score ≥ 3) in the domain of 2.1 to 2.5, except for the 2.4 domain for RCTs, while retrospective studies showed good quality in the 3.2, 3.3, and 3.5 domains (Table 5).

Discussion

The adoption of advanced methodologies is on the rise in orthodontics and prosthodontics, contributing to the digitization of treatments. In particular, using aligners, digital dental models, and increased accessibility to CBCT images enables improved and highly individualized treatment planning in these fields.[11] The integration of advanced technologies in dentistry has heralded a paradigm shift in treatment approaches, with 3D imaging and virtual simulations emerging as pivotal tools in preoperative planning.[50] By meticulously synthesizing the included studies, we

Table 5. Quality assessment of the non-*in vitro* studies (MMAT).

Study ID	Study design	Items					Score
		2.1	**2.2**	**2.3**	**2.4**	**2.5**	
Tallarico et al.[46]	RCT	Y	Y	Y	Can't tell	Y	4
Lee et al.[40]	RCT	Y	Y	Y	Can't tell	Y	4
Zhang et al.[34]	RCT	N	Y	Y	Can't tell	Y	4
		3.1	**3.2**	**3.3**	**3.4**	**3.5**	
Ritter et al.[32]	Retrospective	Can't tell	Y	Y	N	Y	3
Tarsitano et al.[45]	Retrospective	Can't tell	Y	Y	N	Y	3
Ku et al.[48]	Retrospective	Can't tell	Y	Y	N	Y	3

MMAT: Mixed Methods Appraisal Tool; N: no; RCT: randomized controlled trial; Y: yes.

navigated the nuanced landscape of the benefits and challenges of these innovative modalities. Our examination encompasses the efficacy of 3D imaging in enhancing precision during implant planning, the role of virtual patients in simulating surgical scenarios, and overall implications for implant placement accuracy. In addition, we scrutinized the existing gaps in the literature, highlighting areas for further research and potential refinements in applying these technologies to dental implantology.

In the present study, CBCT was the most commonly used scanning technique for dental implants and generated precise images. Our findings align with the findings of other studies that concluded that the measurements obtained through CBCT were notably smaller than those from the model scanner, intraoral scanner, and control, with a significant difference ($p < 0.001$).[51] Moreover, several prior investigations have employed CBCT to assess the 3D placement of implants postsurgery and to evaluate the precision of surgical templates and implant navigation systems[52–54] and as a most used procedure may be due to several compelling reasons. First, CBCT provides 3D images with high resolution and precision, offering a comprehensive and detailed view of oral and maxillofacial structures.[55] This superior imaging capability thoroughly assesses the anatomical features relevant to dental implant placement, including bone density, morphology, and proximity to the vital structures. The efficiency of CBCT is also noteworthy, as it enables quick and convenient image acquisition with minimal radiation exposure compared with traditional CT scans.[56] This feature is particularly advantageous in dental settings where minimizing radiation exposure is a priority. Furthermore, CBCT allows precise treatment planning by facilitating accurate measurements and assessments of the available bone volume. Visualizing the site in three dimensions aids in determining the optimal implant size, orientation, and angulation, contributing to the overall success and longevity of dental implants.[57] The widespread adoption of CBCT can also be attributed to its noninvasive nature and enhanced patient comfort. With its ability to capture detailed images in a single scan, CBCT reduces the need for multiple imaging sessions, streamlines the diagnostic process, and enhances the overall patient experience.[55]A comprehensive meta-analysis assessing the precision of computer-aided implant planning and transfer unveiled that the mean error for implant placement was 1 mm at the entry point (with a maximum of 6.5 mm) and 1.2 mm apically (with a maximum of 7 mm), accompanied by an average angular deviation of 3.8° (up to 25°). Notably, reduced deviation was observed when employing static surgical guidance, particularly with a single surgical template and increased fixation pins.[58] Computer-guided implant placement demonstrates a noteworthy level of accuracy and meticulous execution. Nevertheless, it is crucial to acknowledge that errors in CBCT imaging, planning, and the surgical transfer process may potentially result in substantial and clinically unacceptable deviations.[58]

A present study highlights the efficacy of computer-aided implant planning in improving accuracy and virtual reality (Table 3). Other studies have also highlighted the accuracy of computer-aided implants; for instance, in another analysis the accuracy of implant placement using computer-aided static navigation systems demonstrated superior results (6.02 ± 3.71) compared to manual implant placement (9.26 ± 3.62).[59,60] AR devices can potentially project a virtual planning image onto the surgical field, contrasting the planned and actual surgical scenarios.[59] The efficacy of computer-aidedd implant planning in enhancing accuracy compared to traditional methods can be attributed to its ability to provide detailed 3D reconstructions of the oral and maxillofacial structures. These computer aided approaches offer meticulous preoperative evaluations by utilizing advanced technologies such as stereolithographic surgical guides, virtual planning based on CBCT data, and 3D-printed templates, enabling precise assessment of implant size, placement, and potential anatomical complications.[61] The use of computer-guided techniques allows for comprehensive visualization and analysis of the implant site, facilitating optimal positioning and orientation of the implant.[62] These methods often involve static surgical guidance, reducing variability and enabling a more standardized approach. Overall, the digitalization of implant planning minimizes the margin of error associated with traditional free-hand methods, leading to improved accuracy and ultimately enhancing the success and longevity of dental implant procedures. Our findings are in line with other study findings and revealed the linear disparity in three dimensions between the intended and actual implant positions was determined to be 0.97 ± 0.37 mm at the cervical and 1.13 ± 0.36 mm at the apical regions. Furthermore, the angular deviation between the planned and placed implants exhibited a variance of $3.42 \pm 2.12°$.[16] In evaluating factors influencing implant placement accuracy, statistically significant differences were observed in cases involving tissue-supported implant guide, implant diameter, and implant length.[48] Similarly, dynamic computer-aidedd implant surgery achieves an accuracy within a clinically acceptable range and exhibits potential for clinical implementation. However, there is a need for more comprehensive reporting of patient-centered outcomes and socioeconomic benefits. Currently, there is a need for more scientific data on dynamic navigation in the existing literature, with only a limited number of studies focusing on its application in edentulous patients.[63,64] Moreover, artificial intelligence (AI) can play a crucial role by enhancing efficiency of these 3D technologies. Enables automated detection and segmentation of more relevant anatomical structures with higher precision. In addition, AI can aid dentists in the selection of the most suitable implant parameters and surgical techniques. Future research endeavors should prioritize the exploration of dynamic navigation surgery in the context of edentulism and provide detailed data on its accuracy for a more thorough understanding of its clinical implications.

Moreover, there can be certain challenges in the clinical implementation of 3D imaging and virtual simulation. For instance, the initial acquisition and later maintenance cost of the equipment, trained professionals in the particular field are required to run these equipment, and most importantly, the integration of these technologies into the pre-existed clinical workflow. These challenges can be overcome by the development of cost-effective and user-friendly imaging systems. In-service training programs for the professional can be helpful in understanding and running these technologies and for integration, multidepartmental approach should be followed between dental professionals, engineering staff, and software developers. Furthermore, the included studies did not highlight the ethical or legal considerations associated with 3D imaging and virtual simulation.

The study demonstrates several strengths and limitations. One notable strength lies in the comprehensive synthesis of available studies, providing a holistic overview of the current landscape in this rapidly evolving field. Incorporating diverse 3D imaging modalities and virtual simulations enhances the depth of analysis, allowing a nuanced understanding of their collective impact on accuracy. In addition, the systematic approach employed in this review contributes to the robustness of the findings. However, limitations include potential heterogeneity in the study designs and methodologies across the reviewed literature, which may affect the comparability of the results. Furthermore, the temporal aspect of technological advancements may introduce variations in the relevance of older studies to contemporary practices. Despite these limitations, this review offers valuable insights into the current state of 3D imaging and virtual technologies in dental implantology, paving the way for future research and clinical applications.

Conclusions

This study underscores the transformative role of advanced technologies in modern dentistry. The integration of 3D imaging, virtual simulations, and computer-aidedd techniques has significantly enhanced the precision and individualization of implant procedures. These findings revealed a notable improvement in implant placement accuracy facilitated by these technologies, leading to more informed preoperative planning and a reduced margin of error. However, it is crucial to acknowledge variations in the study methodologies, the need for further investigation of long-termm outcomes, and potential limitations. As technology continues to evolve, the synthesis of current evidence emphasizes the promising trajectory of 3D imaging and virtual approaches in revolutionizing the field of dental implantology with implications for improved patient outcomes and clinical practice.

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Appendix 1 List of Items (CONSORT Scale)

Item 1: Structured abstract.
Items 2a and 2b are related to the introduction:
Item 2a: Scientific background and rational explanation.
Item 2b: Introduction should have specific objectives and hypotheses.
Items 3 to 10 are related to methodology:
Item 3: Intervention for each group.
Item 4: Completely defined, prespecified primary and secondary measures of outcome.
Item 5: Sample size determination.
Item 6: Method used to generate the random allocation sequence.
Item 7: Mechanism used to implement the random allocation sequence.
Item 8: Who generated the random allocation sequence.
Item 9: If done, who was blinded after assignment to intervention and how.
Item 10: Statistical methods used to compare groups for primary and secondary outcomes.
Item 11: For each primary and secondary outcome, results for each group and the estimated size of the effect and its precision (e.g. 95% confidence interval).
Item 12: Trial limitations.
Item 13: Sources of funding and other support, the role of funders.
Item 14: Where the full trial protocol can be accessed.

Appendix 2 Question (MMAT)

2.1	Is randomization appropriately performed?
2.2	Are the groups comparable at baseline?
2.3	Are there complete outcome data?
2.4	Are outcome assessors blinded to the intervention provided?
2.5	Did the participants adhere to the assigned intervention?
3.1	Are the participants representative of the target population?
3.2	Are measurements appropriate regarding both the outcome and intervention (or exposure)?
3.3	Are there complete outcome data?
3.4	Are the confounders accounted for in the design and analysis?
3.5	During the study period, is the intervention administered (or exposure occurred) as intended?