REVIEW ARTICLE

CONTENTS

Nowadays and the future of the 3D digital technologies in modern orthodontics

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ABSTRACT

Aim: To investigate the usage trends of different 3D digital technologies in modern orthodontics during the previous eight years to identify their future prospects.

Materials and Methods: A systematic literature search on PubMed revealed 258,059 publications concerning digital technologies in modern orthodontics. Amongst 125 eligible articles, we chose 37 high quality articles. The quality assessment was performed according to the Jadad scale for randomised controlled trials and controlled clinical trial studies.

Conclusions: Our investigation revealed that in the near future, significant changes brought by AI will be implemented into visualization technologies (intraoral scanners and synthesized from CBCT 3D cephalometric landmarks detection), design technologies (3D digital virtual setup software), and different manufacturing technologies such as 3D printers. By fully embracing digital technologies orthodontic clinics and laboratories can digitally replicate their entire operations and ensure a standardized exchange of information along the worldwide orthodontic workflow from diagnostics to therapy. CBCT has a leading position amongst all digital imaging technologies in orthodontics, as it provides a complete and accurate representation of anatomical structures in all three planes. The digital approach improved diagnostic precision, streamlined treatment planning, and eliminated the need for messy and uncomfortable impression materials.

KEY WORDS: orthodontics, modern technologies, digitalization, accuracy, three-dimensional imaging

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INTRODUCTION

Modern orthodontics is undergoing a significant transformation, propelled by the integration of cutting-edge tools, techniques, and technology, leading to a noticeable transition from manual to digital procedures. Over the past 10 years, the creation of new innovative, completely automated, and accelerated prototyping methods has revolutionized the approach to making three-dimensional orthodontic diagnostic measurements. The presented changes must be incorporated within orthodontics to ensure this field harmonizes with the state-of-the-art approach. Simultaneously it is valid to state the added value that the conducted research makes to the existing database of knowledge [1]. Three-dimensional technologies have been widely used in orthodontics for the last ten years. Their implementation has significantly changed approaches for orthodontists. 3D technologies replicate anatomical structures to present three-dimensional anatomy and the bone tissue and soft tissue examination more precisely [2]. In dentistry, 3D-scanning technology increases the accuracy of orthodontic diagnostics in general while 3D-printing technology provides an opportunity to manufacture personalized orthodontic appliances and new changes to traditional manufacturing approaches. The most popular 3D technologies in modern orthodontics are digital vizualization technologies such as: 3D cephalometry, digital models, 3D Photography, CBCT (cone beam computerized tomography), 3D imaging for Indirect-Direct bonding, aligner fabrication, Digital Smile Design, CAD/CAM, Facial 3D WL scans, Intraoral scanning, Orthognathic Surgery 3D Planning—Surgical Splint Manufacturing, Different professional software programs (Invisalign Clincheck Pro, Maestro 3D, Ormco Insignia, 3Shape OrthoAnalyzer) that integrate data and provide 3D volumetric data sets that have a great potential for research and planning in both orthodontics and orthognathics. These methods are better than 2D x-rays or solid records since they are easier to keep, prone to fewer handwriting errors, and provide a 3D evaluation of craniofacial structures [1,2]. The future of digital orthodontics is expected to be significantly spread by 3D technologies as a study into its potential and solutions for current issues continues.

AIM

To investigate the usage trends of different 3D digital technologies in modern orthodontics during the previous eight years to identify their future prospects.

MATERIALS AND METHODS

This systematic review was performed according to the PRISMA statement [3] The framework of this systematic review according to PICO [4] was: Population: orthodontic patients; Intervention: CAD/CAM, scanning oral cavity, 3D cephalometrics, 3D technologies; Comparison: analogue technologies, 3D-printing or no intervention; Outcomes: efficiency and accuracy. The PICO question of this study was as follows: Which 3D technologies are commonly used nowadays and will become the most popular in future orthodontic practice and following clinical trials to get the most accurate diagnostic and manufacturing technologies compared to analogue technologies?

STUDY DESIGN

A systematic literature review approach to gather and analyze relevant literature on 3D technologies usage in orthodontics from 2016 to 2023.

SEARCH STRATEGY

Figure 1 illustrates a systematic literature search conducted on PubMed using keywords "Diagnostics" and "Digital orthodontics" or "Digital technologies" or "CAD" or "CAM", or "3D scanning" or "3D printing" or "clear aligners" or "virtual planning" resulting in the identification of 258,059 publications. These publications were then screened based on inclusion and exclusion criteria, including years 2016-2023, availability of free full text, language (English only), and focus on human subjects.

INCLUSION AND EXCLUSION CRITERIA

The inclusion criteria for selecting studies from the systematic literature search conducted on PubMed using specific keywords included publications between 2016 and 2023, availability of free full text, English language publications, studies focusing on human subjects, and content directly addressing the 3D technology usage in orthodontics for diagnostic accuracy improvements. The following exclusion criteria were applied: abstract and author debates or editorials; lack of effective statistical analysis; papers not related to practical implementations of scanners in orthodontics.

QUALITY ASSESSMENT

According to the PRISMA statements, the evaluation of methodological quality indicates the strength of evidence provided by the study because methodological flaws can result in biases [3]. The quality assessment was performed using the Jadad scale for randomised controlled trials and controlled clinical trials studies [4]. Evaluation of whether the study was randomized, double-blinded with appropriately described methods to determine the risk of bias. Cook criteria were used for quality assessment for those reviews [5].

DATA EXTRACTION

Following the inclusion criteria. titles and abstracts were independently selected by two authors (K.K. and K.S.). The full text of each identified article was then analyzed to verify whether it was suitable for inclusion and amongst 125 eligible articles we chose 37 high-ranked quality articles. Characteristics of the included studies have been presented in Table 1.

REVIEW AND DISCUSSION

Table 1 illustrates study characteristics including the current review from 2016 to 2023, examining the application of 3D technologies in orthodontics. The trend shows steady growth, with elevation from 2019 (4351 publications) and onwards. Results showed a significant increase in publication counts, nearly doubling from 2019 to 2023, indicating an escalation in scholarly activity or an expansion of the discipline. Results show a range of study designs, such as experimental and cohort studies, clinical and comparative studies, systematic reviews, in vitro studies, and cross-sectional studies, and reflect a multidisciplinary approach to comprehending the applications and implications of 3D technologies in orthodontics. As far as sample sizes are concerned, these vary significantly across studies, ranging from small-scale experiments with as few as two participants to larger cohort sizes exceeding 200 individuals, reflecting the diverse scopes and methodologies of the research conducted. Most studies included in this review focus on recent advancements, highlighting the ongoing relevance and evolving nature of research related to 3D technologies.

Figure 1 illustrates a systematic literature search conducted on PubMed. Figure 2 shows the result of the

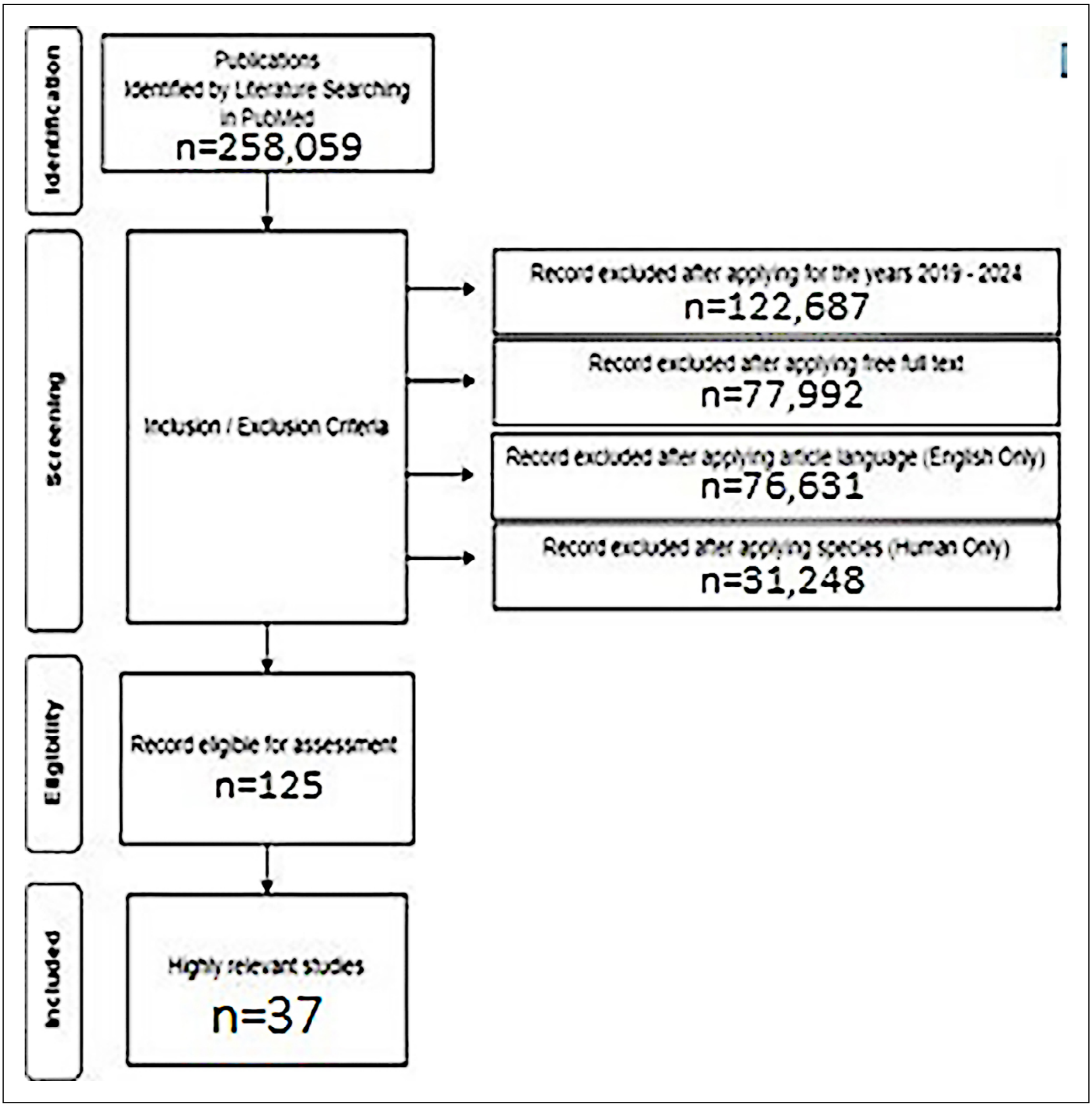

Fig. 1. PRISMA flow diagram.

current review. There was a significant upward surge in publication over the past five years. Table 2 provides a comprehensive overview of the distribution of various 3D diagnostic and manufacturing technologies in orthodontics production, as identified in a systematic literature review. 3D scanning emerges as the most frequently mentioned technology, cited in fourteen instances across multiple studies [19–42]. CAD/CAM follows with five mentions [34-38] while CBCT appears four times [21–24]. Additionally, the review encompasses a diverse range of other 3D diagnostic and manufacturing technologies, collectively referenced 30 times [6–20], [19–23], [28–31], [38–42]. This comprehensive overview underscores the multifaceted application of 3D diagnostic tools in digital orthodontics, providing valuable insights into the evolving landscape of modern diagnostic methods.

Future of digital visualization and photogrammetry: Digital imaging and diagnostics brought significant advancements to orthodontics. CBCT is used to make 3D images with different fields of view (FOVs) of the head in a 1:1 ratio. The virtual head of the patient is attained by the superimposition of digital dental models, CBCT, and facial scanning for diagnosis, treatment

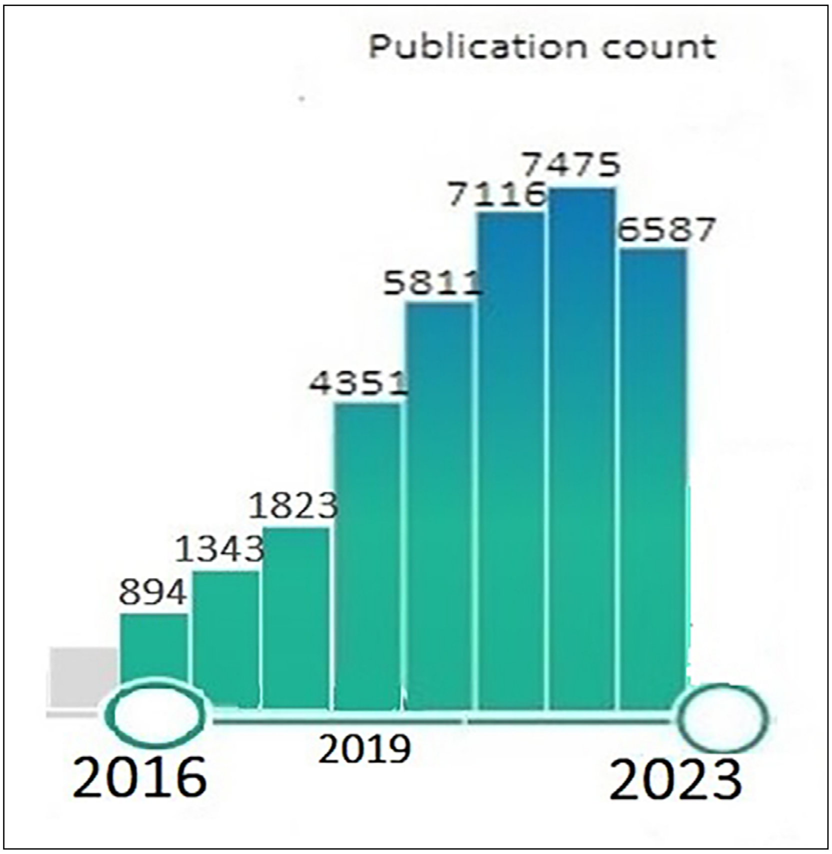

Fig. 2. Publication trend.

plans, and computer-aided design (CAD) and computer-aided manufacturing (CAM) procedures. Software like Dolphin, Anatomage, and 3Shape can be used for diagnosis and treatment planning. Orthodontists have started to utilize 3D CBCT to conquer the insufficiency of 2D radiographic records. A systematic review by Sam et all [20] assessed the reliability of different 3D cephalometric landmarks in CBCT imaging. Their conclusion showed that further research is required to evaluate the reliability of 3D cephalometric landmarks when evaluating 3D craniofacial complexes. Serafin [18] and the authors described their point of view about the accuracy of automated 3D cephalometric landmarks detection, using deep learning compared with manual tracing for cephalometric analysis of 3D medical images. Their conclusion revealed that deep learning algorithms showed excellent accuracy results for automated 3D cephalometric landmarking. In the last two years, promising algorithms have been developed and improvements in landmark annotation accuracy have been made. De Queiroz et all [20] discussed Artificial Intelligence in 3D cephalometrics and evaluated studies that assessed the level of agreement between AI, regardless of system, with the human registration for annotating cephalometric landmarks in digital imaging examinations (2D or 3D). The study conclusion revealed that AI allows to identify landmark placement more precisely on both 2D and 3D images.The study by Jedli´nski et all [19] focused on systematical review and synthesize available controlled trials investigating the accuracy and efficacy of intraoral scanners for orthodontic purposes to provide clinically useful information and to direct further research in this field. The authors' conclusions were next: plenty of data available on the accuracy and efficacy of different scanners. Scanners of the same generation from different manufacturers have almost identical accuracy. Due to those reasons future similar research will not introduce much to orthodontics. The challenge for the coming years is to find new applications of digital impressions in orthodontics. A systematic review by Kustrzycka et all [23] revealed that the substrate type impacts the general accuracy of intraoral scans. The experienced operator influences accuracy, whereas more experienced ones and smaller scan sizes make more accurate scans. A conventional impression technique in a full-arch recording provides the lowest deviation. Angelone et all [24] wrote a systematic review about intraoral scanners, which are routinely used for the reconstruction of 3D dental models for orthodontic treatments and planning and can also be implemented beyond the scope of orthodontic interventions, thus providing alternative diagnostic tools for the detection of oral cavity pathologies/anomalies (e.g., caries, dental wear, periodontal diseases, oral cancer, infections) to traditional methods or available gold standards (e.g., radiographic modalities). They

Table 1. Study Characteristics

Author's	Publication Year	Study Design	Sample Size
Venezia et al. [6]	2023	Observational, retrospective, cross-sectional or comparative study ggff	80
Liu et al. [7]	2021		100
Abu-Arqub et al. [8]	2023		160
Stamm et al. [9]	2022		1
Adel et al. [39]	2021		40
Grassia et al. [40]	2023		4
Schott et al. [41]	2019		31
Beri et al. [42]	2022		45
Patano et al. [10]	2022	Systematic Review	11
Koletsi et al. [11]	2021		7
Shrivastava et al. [12]	2023		6
Baxmann et al. [13]	2023		48
Tartaglia et al. [14]	2020		39
Rossini et al. [15]	2016		35
Torres et al. [16]	2023		4
Desai et al. [17]	2023		4
Serafin et al. [18]	2023		15
de Queiroz et al. [19]	2023		40
Sam et al. [20]	2019		13
Antonacci et al. [21]	2023		16
Jedliński et al. [22]	2021		16
Kustrzycka et al. [23]	2020		13
Angelone et al. [24]	2023		25
Mai.H. et al. [25]	2020		6
Maiet al. [26]	2017		5
Thawri et al. [27]	2023		36
Ishida,Y et al. [28]	2021	In vitro study	2
Hoffman et al. [29]	2022	In vitro study	24
Saccomanno et al. [30]	2022	Survey study	120
Meade et al. [31]	2023	Cohort study	30
Plattner et al. [32]	2023	Clinical Study	40
Felter et al. [33]	2018		16
Choi et al. [34]	2023		1
Bachour et al. [35]	2020		23
Koller et al. [36]	2022		37
Schwärzler et al. [37]	2023		46
Jaber et al. [38]	2021		40

concluded that the differences between the scanners are mainly due to the 3D imaging principle, the different wavelengths used, the image acquisition principle, and the scanner wand. More research is needed to test their performance levels in the context of their differences, which appear to be established only in the case of dental caries. Mai et all [25] reviewed comparisons of the accuracy of mobile device–compatible face scanners for facial digitization with that of systems for professional 3D facial scanning. Overall, mobile device–compatible face scanners did not perform as well as professional scanning systems in 3D facial acquisition, but the deviations were within the clinically acceptable range of <1.5 mm. Significant differences between results when 3D facial scans were performed on inanimate facial objects and when performed on the faces of living

Table 2. Frequency Distribution of technologies in orthodontics

Digital Technologies in Orthodontics	Frequency	Author's
3D diagnostic and treatment technologies	30	[6]–[20], [19]–[23], [28]–[31], [38]–[42].
CAD/CAM	5	[34-38]
Cone-beamed computer tomography (CBCT)	4	[21–24]
Various 3D scanning technologies	14	[19]–[24], [28]–[31], [38]–[42].
Various 3D printing technologies	11	[6], [8–10], [26, 27, 31, 32, 37], [40-41]

participants were found; thus, caution should be exercised when interpreting results from studies conducted on inanimate objects. Network meta-analysis made by Antonacci et all [22] determined the accuracy of various face-scanning technologies in the market, concerning the different dimensions of space (x, y, and z axes). The main attention was paid to the technology types and the best procedures for high-quality scan acquisition. They found out that limiting the movements of the patient and scanner allows for more accurate facial scans with all the technologies involved. Active technologies such as laser scanners, structured light, and infrared structured light have accuracy comparable to static stereophotogrammetry while being more cost-effective and less time-consuming. Beri et all [42] made a study protocol including photogrammetry accuracy with 3D scanning and conventional impression method for craniomaxillofacial defects by using software analysis. This article's conclusion provided an update on defect data acquisition, editing, and design using open-source and commercially available software in digital workflow in modern orthodontics and maxillofacial prosthodontics. A comparative study made by Jaber et all [38] assessed the dimensional accuracy and reliability of dental digital models prepared by direct intraoral scanning and indirect scanning of the plaster models compared to the plaster models as the gold standard. Both direct and indirect scanning techniques are accurate and reliable for digital model preparation and can be considered an alternative to traditional plaster models used in clinical orthodontics diagnostic applications. The intraoral scanning technique can be considered a valid alternative for indirect scanning of the plaster models to prepare digital working models during the digital design and fabrication of orthodontic appliances such as clear aligners.

Designing in modern orthodontics: Three-dimensional scanning and modeling revolutionized how orthodontic information is captured and analyzed. Orthodontists now use intraoral scanners to create virtual 3D models of a patient's teeth, allowing for a detailed examination of tooth positioning, occlusion, and jaw relationships. Hence, these digital models serve as the foundation for treatment planning and facilitate efficient communication among the orthodontic team. With CAD orthodontists can design customized orthodontic appliances, such as clear aligners or lingual braces, using digital models of the patient's teeth. The case report of Choi et all [34] describes the use of the CAD/CAM virtual orthodontic system in a skeletal Class III adult patient undergoing orthognathic surgery and orthodontic treatment with maxillary first premolar extractions to provide treatment effectively while reducing the number of brackets requiring rebonding and shortening the overall treatment time. Conclusions were the following: ideal tooth alignment and occlusion can be achieved by an individualized orthodontic treatment plan and optimal prescriptions of customized brackets using the CAD/CAM virtual orthodontic system. In addition, this system can contribute to efficient orthodontic treatment in surgical cases. However, the evaluation of customized bracket bonding accuracy and additional detailing procedures related to functional occlusion are needed to maximize the advantages of the system. A research study by Adel et all [39] evaluated the accuracy of three different 3D digital model registration software packages for linear tooth movement measurements, regarding a 3D digital virtual setup. Compare and Geomagic software packages consistently showed maximum accuracy in measuring the amount of tooth movement in the maxillary arch compared to the reference standard. Comparison of the software showed the highest agreements in the mandibular arch. None of the three studied software packages showed poor agreement with the Digital Setup across all tooth movement measurements. Buccolingual tooth movements showed the highest agreement amongst linear measurements. Grassia et all [40] in a research study assessed the accuracy (trueness and precision) of orthodontic models obtained from crowded and spaced dentition finalized for the production of clear aligners. Four 3D printers featuring different technologies and market segments were used for this purpose and they concluded that the accuracy of orthodontic models generated for clear aligners can be affected by different 3D printer technologies and anatomical characteristics of dental arches.

Digital manufacturing in orthodontics: After CAD procedures CAM orthodontic appliances are precisely manufactured using 3D printers or milling machines, ensuring a perfect fit for each patient and enhancing treatment efficiency. Venezia et all [6] made a comparative study that evaluated the accuracy of orthodontic models for the production of clear aligners generated with four 3D printers featuring different technologies and belonging to different market segments. They concluded that the accuracy of orthodontic models generated for clear aligners can be influenced by different technologies/market segments of the 3D printers used. An original article by Koller et all [36] investigated the digital construction, the CAD/CAM production, and the intraoral positioning accuracy of custom-manufactured novel 3D CAD/CAM titanium retainers. Based on the results, the present study shows a high level of congruence between the 3D virtual planning and the final intraoral position of the fabricated novel 3D CAD/CAM titanium retainers. A prospective randomized clinical study made by Schwärzler et all [37] compared transfer accuracy and immediate loss rate of hard versus soft transfer trays utilizing a CAD/CAM workflow. Study results concluded the following: CAD/CAM technology for indirect bracket bonding is a reliable method; low rate of immediate loss with both hard and soft resin; soft resin is more favorable than hard resin for accuracy and usability; indirect bonding of molar brackets is less accurate than of incisor brackets. An observation study made by Al Mortadi et all [6] shows how to create a removable orthodontic appliance digitally using an intraoral scan. For the maxillary and mandibular arches, an intraoral scan was performed. The virtual Hawley retainer was created using 3Shape Orthodontics Appliance Designer. It is made up of a base plate and two alloy components, Adam Clasps and Fitted Labial bow. After the alloy components were combined using cold-cured acrylic, the design of the base plate was adjusted to accommodate their insertion. Using computer-aided design (CAD) and computer-aided manufacturing (CAM) technology, this innovative method offers an alternate manufacturing process for removable appliances. The method explained provides a forerunner to digital manufacture of other orthodontic appliances.

Prospectives of digital technologies in orthodontics: As a field, digital orthodontics has changed the game by providing accurate, effective, and patient-friendly tooth alignment treatment methods. Early in the course of treatment, patients benefit from increased comfort and convenience as digital impressions take the place of traditional molds. We noticed that studies focused on CAD/CAM and scanner development and their implementation into solving any challenging aspects of orthodontic diagnosis and therapy aspects. On the other hand, there are plenty of data available about accuracy and efficacy. In future studies, scanners and CAD/CAM technologies should serve only as tools for clinical phenomena observation. The challenge for the coming years is to find new applications of digital impressions and imagining in orthodontics. Additionally, by using virtual simulations, patients and orthodontists may both see the anticipated result, improving communication and guaranteeing that alignment objectives are successfully accomplished. Modern material science and manufacturing techniques have produced smaller, stronger aligners that can precisely apply force to shift teeth into the correct position. Furthermore, the incorporation of functionalities such as SmartTrack technology improves the alignment and consistency of aligner therapy, guaranteeing maximum comfort and effectiveness during the course of treatment. The planning and execution of orthodontic treatments is being completely transformed by artificial intelligence (AI), which provides previously unheard levels of accuracy and efficiency. Artificial intelligence (AI)-powered software platforms may create extremely accurate treatment plans that are customized to each patient's specific dental anatomy and needs by evaluating enormous volumes of patient data and utilizing machine learning algorithms to move teeth into the correct position. Furthermore, the incorporation of functionalities such as SmartTrack technology improves the alignment and consistency of aligner therapy, guaranteeing maximum comfort and effectiveness during the course of treatment. The planning and execution of orthodontic treatments is being completely transformed by artificial intelligence (AI), which provides previously unknown levels of accuracy and efficiency. AI-powered software platforms may create extremely accurate treatment plans that are customized to each patient's specific dental anatomy and treatment goals by evaluating enormous volumes of patient data and utilizing machine learning algorithms. Moreover, AI systems are always learning and changing in response to actual results, which helps them to improve treatment plans and outcomes over time. In addition to increasing the effectiveness of orthodontic treatments, this iterative method gives orthodontists the ability to provide patients with individualized care and achieve better clinical results. The field of orthodontics is constantly developing due to scientific and technical advancements, and straightening teeth has a bright future. With advancements in digital orthodontics, transparent aligner technology, expedited treatment approaches, and AI-powered treatment planning, obtaining a beautiful, straight smile is now more feasible and fun than in the past.

CONCLUSIONS

We conclude that CBCT has a leading position amongst all digital imaging technologies in orthodontics, as it provides a complete and accurate representation of anatomical structures in all three planes. The digital approach improved diagnostic precision, streamlined treatment planning, and eliminated the need for messy and uncomfortable impression materials. Instead of traditional dental impressions, orthodontists use digital scanners to capture accurate 3D images of the patient's teeth and jaw. By fully embracing digital technologies orthodontic clinics and laboratories can digitally replicate their entire operations and ensure a standardized exchange of information along the worldwide orthodontic workflow from diagnostics to therapy. Our investigation revealed that in the near future, significant changes brought by AI will be implemented into visualization technologies (intraoral scanners and synthesized from CBCT 3D cephalometric landmarks detection), design technologies (3D digital virtual setup software), and different manufacturing technologies such as 3D printers. The reproducibility of direct scanning is comparable to indirect scanning although a slight difference can be noticed (0.02 mm).

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CONFLICT OF INTEREST
The Authors declare no conflict of interest

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