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Evaluation of The in Vitro Studies on Marginal and Internal Fit Accuracies of Additive Manufactured Single-Unit Crowns: A Systematic Review

[1]Collins Chike Obi, BDS, University of Benin Teaching Hospital, Benin City, Edo State, Nigeria

[2]Gift Alumhense Orukpe, BDS, University of Benin Teaching Hospital, Benin City, Edo State, Nigeria

[3]Okelue Edwards Okobi, MD, MS., Family Medicine, Medficient Health Systems, Laurel, Maryland, USA

Corresponding Author: Okelue Edwards Okobi, MD, MS., Family Medicine, Medficient Health Systems, Laurel, Maryland, USA

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Abstract

Digital dentistry has witnessed significant advancements in recent years, providing increasingly reliable techniques for tooth shape recording and treatment planning. Dissimilar to conventional approaches, the novel digital methods enable instant and seamless sharing of data via electronic connections to dental laboratories. Usually, restorations that include fillings are directly placed while indirect and extensive restorations, including bridges, onlays, and crowns are done using different materials such as lithium disilicate. The increased use of advanced dental technologies can be attributed to the cost reduction of impression materials, enhanced patient experience, and accurate and effortless scanning and capturing of affected regions. Further, digital scanners manufactured 3D models enable the prevention of possible challenges related to the traditional gypsum models. In restoration production, the Standard Tessellation Language (STL) files generated using scans are vital to the creation of 3D models for CAD/CAM software. Often subtractive milling and stereolithography additive manufacturing are the preferred methods for the fabrication of models; however, this systematic review has focused on the additive method owing to its aptitude to handle undercuts and intricate shapes, which are challenging to the subtractive method due to limited machine axes, as well as challenges of errors linked to variations in bur diameters during milling. Though indirect model scanning for CAD/CAM manufacturing is considered a viable alternative, it may result in errors due to impression materials and gypsum models' impressions. Therefore, direct digitalization is considered an increasingly precise option as it bypasses the requirement for scanning and fabrication of models. The increasing interest in anesthetic materials employed in restorations has been linked to the observed advancements in technology, which has additionally led to the use of zirconia and lithium disilicate materials. Advanced machines like IPS e.max have been used to broaden the restoration methods and materials' scope.

Moreover, the restoration's fit precisions have a significant impact on the success and survival rates, and this makes the comprehension of possible marginal gaps and inaccuracies important. Therefore, the main objective of this systematic review is to assess the fit accuracy of single-unit crowns manufactured through additive manufacturing (AM) in comparison to computer-aided design/computer-aided manufacturing (CAD/CAM) and other traditional methods. In terms of accuracy, AM manufacturing techniques are similar to CAD/CAM and conventional methods. To realize the study objective, an in-depth search was conducted on Scopus, Web of Sciences, PubMed, and Cochrane databases for literature published between 2000 and 2025. The literature selection process, quality assessment, and data extraction were undertaken by two independent reviewers. In the end, 12 studies met the set inclusion criteria and were reviewed. The systematic review disclosed that there were no significant differences in the fit of accuracy (both internal and marginal) for CAD/CAM and AM methods, as well as the accuracy and trueness of measurements. Consequently, AM was observed to have a better marginal fit than the various conventional techniques, despite having a comparable internal fit to other techniques.

Keywords: Additive Manufacturing (AM), 3D Printing, Crowns, Fixed Prostheses, Marginal Fit, Internal Fit, computer-aided design/computer-aided manufacturing (CAD/CAM)

Introduction

Technological advancements in 3D printing and AM manufacturing have significantly affected the field of dentistry. For instance, in dentistry, the workflows, especially fixed prosthodontics, have continuously shifted towards digitization and automation [1, 2]. Normally, the digital workflow commences with the digitization of the oral soft and hard tissues using intra-oral scanners, followed by the use of CAD software in restoration designing and CAM in restoration manufacturing. Thus, technological advancements have resulted in the development of additive manufacturing (AM) and subtractive manufacturing techniques, which are the two widespread technologies. Thus, AM entails a broader array of methods for the creation of objects on a layer-by-layer basis, each layer employing distinctive materials and methods. Among the widely used AM techniques are digital light processing (DLP), polyjet 3D printing (PJP), stereo-lithography (SLA), direct metal laser sintering (DMLS), selective laser sintering (SLS), and fused deposition/filament modeling (FDM/FFM) [3]. Regardless of these distinctive methods, SLA has turned out to be the most used additive manufacturing method. SLA utilized ultraviolet laser scanners in the curing of photopolymer resin materials. On the other hand, Srinivas et al. maintain that DLP makes use of the traditional sources of light in the polymerization of resin material and has been acknowledged to improve the accuracy of the restorations while also enabling faster printing durations in comparison to both the conventional and milling techniques [4]. Nevertheless, in dentistry, AM is used in the manufacture of dental restoration frameworks, obturators, metal copings, orthodontic models, stents, and prosthodontic models

[5]. Such advancements have considerably reduced the durations of conventional fabrication processes while additionally facilitating physical parts manufacturing from the 3D models as an aspect of the efficient digital workflow, which reduces the overall costs in the long run, even as to permits faster fabrication of increasingly intricate structures [4]. Nonetheless, AM technology's limitations are attributable to the existence of aptly established techniques, including CAD/CAM. Such conventional techniques often entail prostheses and appliance fabrications done through milling concrete blocks into tailored dimensions and shapes and material removal.

The development of various CAD/CAM techniques has made it feasible to effectively produce wax patterns from different castable materials, thereby overcoming different limitations linked to conventional methods, such as wax-up procedures. CAD/CAM systems that include Everest Systems, Precident DCS Systems, and CORiTEC Systems have indicated capabilities in frameworks million from different materials [6]. Moreover, CAD/CAM methods are preferred for several reasons, including manufacturing of high-quality and uniform restorations using commercially available material blocks, standardizing the process of restoration shaping, and effectively reducing the manufacturing-associated costs, alongside labor and time [7]. Furthermore, such systems have been found to improve accuracy as they eliminate processes that include casting, waxing, and investing [8]. The automatic detection of margin along with the simple restoration designs, in comparison to the traditional manual waxing, additionally supports the increased use of CAD/CAM technologies [9]. Nevertheless, CAD/CAM techniques also present several challenges, including the observation that the scanning systems' finite resolutions might bring about faintly rounded edges, thereby leading to internal inaccuracies. In many instances, these inaccuracies adversely affect the incisal and occlusal edge contacts and have additionally been acknowledged to affect the marginal fit [8]. Other notable limitations include the faster advances in technology, printing materials limitations, and the unavailability of a printer with the capability to handle all types of materials [3, 4].

In AM, accuracy is considered an important factor, especially with regard to dental applications. As such, Bae et al. conducted a comparison between AM and subtractive manufacturing in terms of the manufacturing of tailored distal occlusal inlays and disclosed that AM had better accuracy levels than subtractive manufacturing [5]. Bae et al. utilized SLA and SLS for AM and zirconia milling and wax for subtractive manufacturing. The difference in accuracy levels was found to vary between 3 µm and 13 µm, without any statistically significant difference between SLA and SLS [5]. Similar studies have reported significant inaccuracies in AM that accrue during the manufacturing process [10, 11]. In their study, Silva et al. made use of dry human skulls to develop tomographic images produced using 3D printing (3DPTM) and SLS [10]. Consequently, in their study, Wan Hassan et al. scanned and printed various dental casts for orthodontic applications, and conducted a comparison of tooth dimensions through the use of digital calipers [11]. Despite realizing approvable tolerance levels and successfully ascertaining their purposes in the final printed products, the marginal fit has turned out as a major determinant of fixed prostheses longevity and prognosis.

The marginal gap, which refers to the vertical distance that exists between the preparation margin of the tooth and the restoration's cervical margin, is tasked with ensuring the success and longevity of restorations [2-5]. Thus, according to Reich et al., though various clinical studies have accepted a marginal gap threshold of 100 μm, it should not be more than 120 μm [12]. Inaccuracies in the internal and marginal fits often result in various complications that include secondary caries and marginal inflammations [13]. Similarly, the internal gap, which refers to the distance (perpendicular) between the internal interface of the restoration and the axial wall of the tooth is important [14].

The adoption of digital workflows has enabled the fabrication of restorations through the use of contemporary technologies that include CAD/CAM, which have, in turn, enabled the attainment of accuracy levels comparable to traditional techniques. Various studies that have assessed the marginal fit and internal fits of restorations manufactured using CAD/CAM and various traditional techniques have disclosed that the marginal fit is a major determinant of the success and longevity of metallic ceramic crowns [15]. The exposure to various luting materials is increased by marginal discrepancies and this leads to cement dissolution alongside micro-leakages [16].

Still, studies focusing on CAD/CAM restorations using traditional fabricated metallic copings and metallic crowns have often experienced difficulties attributable to differences in sample sizes, types of systems, and measurement techniques. Consequently, various studies have disclosed bigger internal and marginal gaps for CAM and CAD/CAM ceramic restorations in comparison to the traditional PFM crowns [16, 17]. Nonetheless, various studies have additionally noted that CAD/CAM restorations offer improved marginal fits with [17, 18]. Such disclosures have underlined the significance of ongoing assessment of AM technologies that seek to realize enhanced or comparable fit accuracy to traditional methods.

Furthermore, according to the study by Akbar, Omar, and Al-Tarakmah, the fit accuracy of restorations has a direct influence on the clinical outcomes, which makes the identification and tackling of potential inaccuracies imperative [19]. Cyclic fatigue may increase as a result of the influence of designs and preparation materials on the marginal gaps [20]. The objective of this study is to evaluate the fit accuracy of single-unit crowns manufactured through additive manufacturing (AM) in comparison to computer-aided design/computer-aided manufacturing (CAD-CAM) and other traditional methods. Through an in-depth synthesis of extant studies, this systematic review will offer vital insights and information on the fit of accuracy and the clinical implication of the AM and CAD/CAM technologies.

Materials and methods

This systematic review entailed the performance of a thorough, in-depth, and detailed review of the extant literature on different virtual databases, including Scopus, Web of Sciences, PubMed, Embase, and Google Scholar, for studies focusing on AM and CAD/CAM manufacturing of single-unit crowns and provisional restorations, and published between 2010 and 2024. The studies selected and included in this systematic review included prospective cohort studies, systematic reviews, multi-center investigations, and health assessment studies. Various duplicate studies were additionally pinpointed through matching studies that had comparable population years. Furthermore, different MeSH terms and keywords were employed in the literature search, including additive manufacturing, single-unit crowns, internal fit accuracy, marginal fit accuracy, prosthodontics, three-dimension (3D) printing, and computer-aided design/computer-aided manufacturing (CAD-CAM) designs. The in-depth literature search performed on diverse virtual databases yielded a total of 1217 references.

Inclusion and exclusion criteria for studies

The selection of pertinent studies, and the removal of duplicates, was performed based on a three-phase process. The first phase entailed the review of titles and abstracts of the selected studies, whereas the second phase entailed the exclusion of studies perceived as inappropriate to the study. The last phase entailed the performance of a thorough evaluation of the full texts of every reference to verify their pertinence to this study. Therefore, three independent reviewers were assigned to screen the reference, and potential disagreements on inclusion or exclusion were resolved through consensus and discussions.

Still, the inclusion criteria targeted original studies, including crossover design studies, randomized controlled trials (RCTs), and prospective cohort studies. Further, studies published between 2010 and 2025 were included, as per the inclusion criteria. Also, the included studies had to be originally published in English language and original scientific study published in reputable journals. Lastly, the included studies were those that examined the fit of accuracy of single-unit crowns manufactured using AM and CAD/CAM methods.

Contrariwise, these systematic review’s exclusion criteria included sponsored clinical trials, opinion pieces, editorials, and narrative reviews. Inaccessible and irrelevant studies, and those with inappropriate methodologies, were also excluded, resulting in the exclusion of 1258 references. Moreover, data drawn from the included studies comprised general attributes like authors' names, publication year, study design and methodology, demographic data, and follow-up information. The main findings of every included study was also accurately documented.

Result

Identification and screening of studies

For this systematic review, the process of literature selection was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). Thus, the in-depth literature search conducted in different databases yielded 1271 references. In this regard, 768 references were from PubMed, 457 references were obtained from Scopus, and the other 46 references were obtained from Cochrane. Consequently, the 1271 references identified from the databases were subjected to screening, which resulted in the elimination of 239 duplicates and 84 references found ineligible through automation. Additionally, 163 references were excluded for different reasons, including not being aligned with the objectives of this systematic review and animal-based studies. The study exclusion criteria also encompassed studies published in non-English language and non-peer-reviewed journals. Editorials, secondary studies, dissertations, scoping reviews, non-academics authored studies, and opinion pieces were also excluded. As such, 785 eligible references were further subjected to screening conducted by three independent reviewers, which resulted in the exclusion of an additional 284 references. Thus, the researchers sought to retrieve the remaining 501 references and were unable to retrieve 305 references. Therefore, only 196 references were assessed for eligibility, out of which additionally 171 references were excluded for a myriad of reasons following the full-text screening, including; miscellaneous (72 references); in vivo studies (50 references), and not related to the topic under study (49 references). Finally, 25 studies satisfied the set inclusion criteria and were included and subsequently reviewed. The study selection and inclusion process has been shown in the PRISMA flow diagram in Figure 1 below.

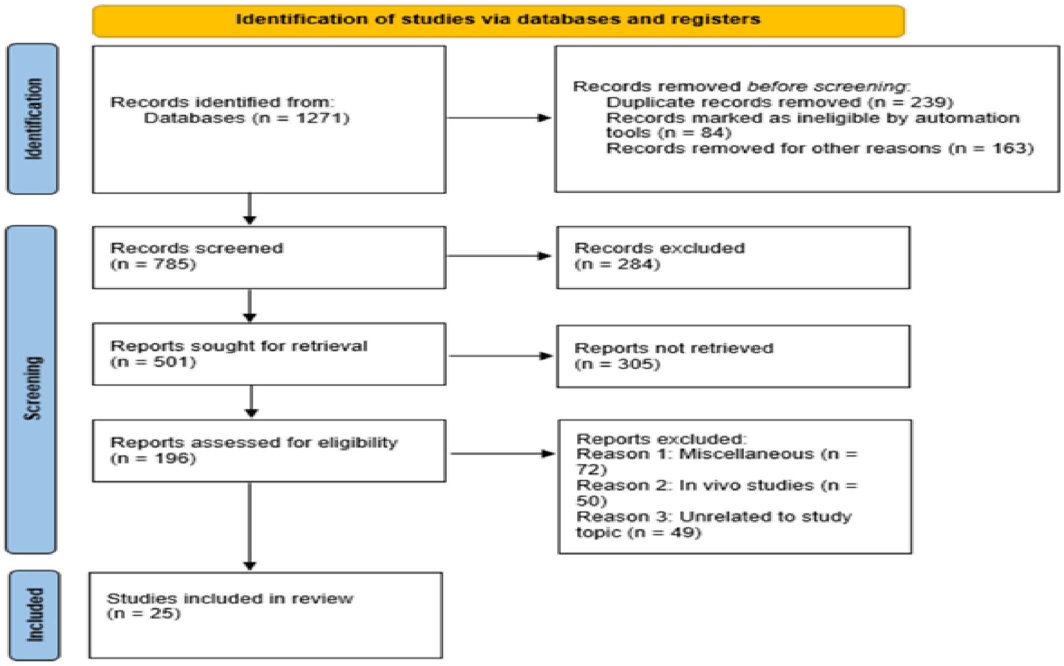

Figure 1: PRISMA flow diagram indicating the study selection process for this systematic review.

Table 1: Summary of the studies included in this systematic review

Study/year/citation	Study design	Findings
Gupta et al. 2025 [26]	In vitro	CAD-CAM method provided significant accuracy levels with regard to the marginal fit of endocrown designs, even as the variations in fit were influenced by the differences in designs.
Padrós et al. 2020 [28]	In vitro	Dental restorations fabricated using CAD-CAM methods presented greater marginal accuracy and mechanical properties compared to those manufactured using conventional methods.
Frasheri et al. 2022 [31]	Retrospective	The findings have indicated that gold crowns fabricated using 3D methods had excellent longevity of over 10 years, attributable to factors that included superior fit accuracy and material stability.
Habib et al. 2020 [32]	In vitro	The findings showed that the crown-disclosing agents offered a thinner film than cement, emphasizing the significance of the accuracy of the cementation techniques.
Aboelenen et al. 2020 [35]	In vitro	The study disclosed that monolithic zirconia crowns that are cemented using bioactive cements portrayed greater marginal fit alongside reduced micro-leakages than glass ionomer cements.
Akın, Toksavul, and Toman 2015 [37]	Randomized controlled clinical trial	The findings indicated that all-ceramic crowns manufactured using the AM method had higher marginal adaptation in addition to maintaining clinical performance over a two-year duration.
Tsirogiannis, Reissmann, and Heydecke 2016 [42]	Meta-analysis	The findings showed that digitally manufactured complete-coverage ceramic crown restorations had superior marginal fit than conventional impressions.
Sulaiman 2020 [43]	Meta-analysis	The findings have indicated that advancements in digital dentistry materials improved the adaptability and durability of provisional restorations.
Lerner et al. 2021 [45]	In vitro	The study has disclosed that 3D-printed zirconia crowns had comparable accuracy and trueness to milled zirconia crowns, despite the existence of minor variations.
Abualsaud and Alalawi 2022 [48]	In vitro	The findings disclosed that milled zirconia crowns had greater accuracy and marginal fits than 3D-printed crowns.
Kakinuma et al. 2022 [50]	In vitro	3D-printed and milled resin-composite crowns had comparable accuracy levels, with minor variations in definite parameters

Mohajeri et al. 2021 [51]	In vitro	3D printed provision restorations demonstrated superior marginal fit compared to fabricated chairside provisions.
Chou et al. 2021 [54]	In vitro	3D-printed metal crowns demonstrated superior internal fit than the conventional casting techniques.
Khanlar et al. 2023 [56]	In vitro	AM-manufactured provisional crowns had minimal marginal discrepancies that were similar to conventional methods.
Son et al. 2019 [57]	In vitro	Differences in marginal and internal fit evaluation techniques significantly impacted the reported fit accuracy levels in fixed dental prostheses.
Peng et al. 2020 [58]	In vitro	3D-fabricated single-unit crowns had the most consistent internal fit and marginal integrity, even as 3D-printed crowns indicated variations with regard to quality dependent on the printing method used.
Ishida and Miyasaka 2016 [60]	In vitro	The results indicated that 3D-printed dental crowns and restoration patterns had exceptional dimensional accuracy.
Al Deeb et al. 2019 [63]	In vitro	The findings showed that AM, CAD-CAM, and 3D methods resulted in the realization of greater marginal integrity alongside compressive strength in fixed dentures compared to the conventional methods.
Park et al. 2016 [70]	In vitro	The findings have disclosed provisional restorations fabricated using digital methods portrayed superior fit and accuracy than those manufactured using conventional methods.
Li et al. 2023 [72]	In vitro	The findings indicated that single-unit crowns fabricated using the stereolithography method demonstrated acceptable precision levels, especially in internal adaptation, making the method a promising fabrication method for zirconia crowns.
Hasanzade et al. 2023 [77]	In vitro	The study findings indicated significant variability concerning adaptation between two printers, underlining the aptitude of 3D printers to positively impact the quality of single-unit crowns and provisional restorations.
Elrashid et al. 2019 [79]	In vitro	CAD/CAM-manufactured lithium disilicate ceramic crowns were found to have a higher marginal accuracy compared to the conventional methods.
Zimmermann, Ender, and Mehl 2020 [81]	In vitro	Contemporary intraoral scanners were found to generate higher local accuracy and were considered suitable for the fabrication of single-unit crowns and provisional restorations.
Neves et al. 2014 [87]	In vitro	CAD/CAM fabricated lithium disilicate crowns indicated greater marginal fit compared to crowns manufactured using heat-pressing methods.
Bosch, Ender, and Mehl, 2014 [88]	In vitro	CAD/CAM manufacturing produced increasingly accurate crowns and provisional restorations with minimal discrepancies.

Quality assessment of the included studies

The selection process resulted in 13 studies meeting the inclusion criteria for this systematic review, even as 82% of the entries were positively reported. Thus, Items 1–4, and 10 which included abstract, introduction, intervention, statistical methods, and outcomes, were satisfactorily reported in all 13 studies. 10 studies offered discussions of the limitations (Item 12) in addition to reporting the results accurately based on the confidence intervals (Item 11). Seven studies additionally mentioned their funding sources (Item 13), even as Ten studies reported their sample size calculations (item 5). Still, five studies offered details on the trial protocol accessibility (item 14), while eight studies provided details regarding blinding to deter prospective operator-based biases (item 9). However, none of the studies provided a discussion associated with randomization (items 6-8).

Study characteristics

All 25 studies reviewed were in vitro studies, with all having been published between 2014 and 2025, making their results and findings increasingly generalizable and pertinent to this study. Furthermore, 11 studies assessed the marginal fits and accuracy of single crowns [26, 28, 35, 45, 48, 54, 57, 58, 72, 77-79] while 14 studies evaluated internal fits [37, 45, 48, 50, 54, 56-58, 60, 63, 70, 72, 77, 88]. Further, of the 25 included studies, 7 evaluated digital and traditional methods of manufacturing dental crowns and fixed prostheses [42, 50, 56, 63, 79, 81, 88], even as 6 studies focused on evaluating the material properties and longevity of materials used in the fabrication of the dental crowns [31, 32, 53, 58, 60, 87]. Also, three of the included studies evaluated the clinical implications of AM and CAD/CAM-manufactured single-unit crowns and fixed prostheses [37, 51, 70]. Additionally, based on this study's objectives, the relevant data drawn from the 25 included studies have been discussed using diverse sub-headings. Further, for effective assessment and measurement of the discrepancies, 9 studies made use of micro-computed tomography scanners, even as the other 4 made use of silicon replica methods, digital microscopes, and electronic digital calipers.

Discussion

Assessment of the single crowns' internal and marginal fit accuracy

The evaluation of single crowns' internal and marginal fit accuracies has often been a key challenge to researchers. Despite the traditional methods being widely validated for the performance of such assessments, they have also portrayed certain limitations, including the provision of a restricted number of measurement points for every restoration and being method-sensitive. This might bring about inadequate representation and inaccuracies in the circumferential fit of the crown [21, 22]. Regardless of such disadvantages, traditional techniques have been widely employed in prosthodontics, and have enabled comparisons with alternative methods. Nevertheless, the use of fingers to set crowns, which is a widespread dental clinic practice, is not only inconsistent but also contributes significantly to inaccuracies. Moreover, the cementation is often followed by the sectioning of the crown to enhance the measurements' validity; however, ascertaining equal measurement points throughout the diverse methods is still unrealizable. In the last four decades, there has been an increased use of divergent dental impression materials across the world, for the accurate transfer of shapes of teeth from patients to dental laboratories. For clinicians and dentists, such materials are indispensable, given that they facilitate the design and manufacture of prosthetics that include bridges, dentures, and crowns [23]. Precise impressions have ascertained stability alongside accurate restorations even as advanced and novel digital technologies, including digital scanners, have significantly transformed dentistry by eradicating the requirement for impression materials [24]. The digital scanners produce high-quality and accurate records of implants, teeth, and gingivae, in addition to enhancing the restoration's longevity by ensuring internal fit [25]. Nonetheless, challenges that include casting errors, distortions, and transportation-associated damages found in conventional impressions may be reduced and minimized through the use of intraoral scanners. Digital scanners enable rescanning precise regions to enhance accuracy without having to retake the impressions. Thus, realizing accuracy in closely situated margins and subgingival remains a key challenge, with the high costs and difficulties associated with recording deeper subgingival preparations being some of the notable limitations.

Systematic review findings

This study reviewed 13 in vitro studies that examined the marginal fit accuracies of single-unit crowns printed using AM and CAD/CAM printing methods. In this regard, this systematic review has disclosed the existence of higher levels of heterogeneity, which necessitates the application of the random-effects model. Further, statistical analyses conducted in different studies have indicated that AM methods presented greater marginal fit accuracies in comparison to the CAD/CAM methods, even though the differences in accuracy levels between the two methods were not statistically significant [26 -28]. The findings have also emphasized that the accuracy of the marginal fit of single-unit crowns is mainly influenced by aspects that include the manufacturing method used and material type. Accuracy in the production of single-unit crowns and prostheses is important in the reduction of micro-leakages, prevention of potential accumulation of bacteria, and protection of prepared tooth pulps, which may result in soft tissue inflammations around the implants and teeth [16, 29, 30, 31]. Greater marginal fit accuracy levels are also considered important for ensuring successful provisional restorations. Even though, at the occlusal surface, the structural durability is increasingly reliant on adaptation, maintenance is often influenced by the single unit crowns' axial fit [16, 31].

In their study, McLean and Fraunhofer established a 120 µm clinically satisfactory marginal gap, though subsequent research indicates variability in approval thresholds [32, 33]. Marginal gaps of approximately 455 µm being approved have been reported, even as marginal gaps of 117 µm and below have been disallowed [33]. Particularly, in vitro studies have experienced challenges in their bids to explore the correlations between marginal gaps and leakages, with gap variations of between 0 and 831 µm [34, 35]. Nonetheless, a sturdy correlation has been observed between gingivitis and marginal discrepancy (5-430 µm), highlighting the implication of accuracies in AMD measurement [36]. In this regard, Rosetti et al. have maintained that gaps of up to 120 µm do not affect the success and longevity of polycarboxylate cement-luted provisional crowns and restorations [34]. Further, gaps of more than 200 µm have been reported in CAD/CAM and heat-pressed all-ceramic crowns that are cemented using adhesive techniques [37]. Generally, CAD/CAM single-unit crowns and restorations have indicated greater clinical success, raising questions regarding the need to limit the cement film thickness to 120 µm [38, 39]. In instances of gold cast restorations, gaps of more than 150 µm have been found, despite such gaps indicating greater clinical success [40, 41]

CAD/CAM-manufactured ceramic restorations produced marginal gaps that ranged between 18 and 128 µm, which confirms the findings of this study [15, 42]. Despite the variance in the preparation designs, milling units, and assessment methods, the study conducted by Tsirogiannis, Reissmann, and Heydecke, has disclosed that there was no considerable influence of the preparation design on the size of the gaps [42]. Nevertheless, despite the observation of higher levels of heterogeneity, statistical analyses have indicated greater internal fit accuracy in AM printed crowns in comparison to CAD/CAM printed crowns, even as there was no statistically significant difference between the marginal fit accuracies of AM and CAD/CAM printed crowns [34, 37]. Such observations have been corroborated by the findings of studies conducted on zirconia crowns, which disclosed acceptable internal fit accuracies in different production methods [43, 44]. Moreover, AM methods have been found to have better internal fit accuracies than the conventional methods; however, there were no statistically significant differences in the methods [43, 44]. Advanced AM methods, including precision additive 3D gel deposition, have been acknowledged to enable the manufacture of self-glazed zirconia crowns with improved surface properties, thereby minimizing the interface fracture risks [45-47]. Consequently, the study has disclosed that the lowest level of marginal discrepancies was realized in 3D-printed crowns than in CAD/CAM and conventional methods, despite being within the 120 µm clinically acceptable limit [48-50]. Further, reviewed studies that compared AM and CAD/CAM methods indicated that there were no statistically significant differences in both the marginal fit and internal fit accuracies [26, 50]. Nonetheless, AM methods were also found to have a significant advantage over the conventional methods with regard to the marginal fit accuracy regardless of the higher levels of heterogeneity [32-36].

The marginal discrepancies variations might additionally emerge from the finish line designs, given that rounded shoulders have been found to have reduced discrepancies in comparison to knife-edge and chamfer designs [51]. Moreover, such differences in marginal discrepancies have been attributed to the chamfer finish lines' curved topography, which has been reported to increase the risk of stair-stepping errors in the course of incremental layer build-up during 3D printing [52]. Additionally, this systematic review assessed the single-unit crowns internal adaptations and disclosed the existence of minimal discrepancies in 3D-printed crows than in the CAD/CAM and conventional methods printed crowns [53-57]. Also, CAD/CAM-printed single-unit crowns were found to have similar internal discrepancies [58].

Nevertheless, various studies have also documented higher average occlusal discrepancies in comparison to the axio-gingival, inter-marginal, and axio-occlusal discrepancies [54, 56-59], which are attributable to the limited size and angle of the various cutting tools employed, which, in turn, affect the intaglio surface [60]. Still, conventional provisional resins have been found to have increased volumetric polymerization shrinkage, especially PMMA in comparison to acrylic composite resins [61, 62]. The crowns are further distorted by the manual trimming that takes place during setting, resulting in poorer marginal and internal adaptations in comparison to the CAD/CAM processes that employ pre-polymerized blocks in the prevention of shrinkage [63-66]. Remarkably, 3D-printed single-unit crowns and FDPs exhibited greater marginal adaptation than the CAD/CAM printed restorations, which was attributed to innovative layering processes that effectively compensate for polymerization contraction [58, 67, 68]. Nevertheless, the results of 3D printing have been observed to diverge as a result of the differences in aspects that include the type of printer and their settings, the thickness of the layers, and post-processing techniques [45, 60, 63, 68 69].

Furthermore, some of the studies reviewed have disclosed a higher rate of discrepancies within the three-unit FDPs in comparison to the single-unit crowns, and this has been attributed to increased deformations and increased volumetric shrinkage attributable to their geometries [63, 70]. Consequently, while some studies assessed the discrepancies following the cementation process [53, 71], other studies have been observed to have utilized either mixed or non-cementation methods [57, 59, 67]. Additionally, the increased variability in both the prosthesis placement and cementation processes was noted to have significantly influenced the results [55, 56, 57, 67, 72]. The results have also been significantly affected by the different measurement methods used in the determination of the marginal and internal fit accuracies, including cross-sectioning, silicone impressions, and micro-CT. In this regard, micro-CT has been reported to generate greater accuracy levels and reproducibility in comparison to the various conventional methods [73-75].

The present systematic review has also acknowledged significant heterogeneity across the included studies resulting from the differences in scanner types, methodologies, and study designs (in vivo and in vitro) [76-78]. In this regard, Elrashid et al. disclosed the least marginal gap through the use of a customized hold and pin, even though others applied less precise methods, including the silicone impression and finger pressure methods [79]. Micro-CT produced increasingly accurate and consistent results, despite it being less practicable for clinical in vitro trials as a result of factors that include saliva issues and patient compliance [79-81].

Moreover, some of the included studies evaluated the internal fit accuracy of AM and CAD/CAM printed provisional crowns, and the results indicated an increased preference of 3D measurements over 2D as a result of the ability to generate intricate tooth geometries [81]. Also, a study conducted by Kim et al. that made use of micro-CT disclosed the lowest internal fit inaccuracies [82]. Nonetheless, most in vivo studies have utilized less precise traditional techniques that have made direct comparisons increasingly difficult [83, 84].

The intricate preparation of onlays has also made the attainment of milling accuracy a challenge, as they require burs to ascertain accurate fabrication [82]. Although there are a limited number of clinical trials that have focused on onlays, their conventional designs have been aligned with marginally invasive dentistry tendencies [85]. On the other hand, CAD/CAM-manufactured restorations have been found to have smaller marginal gaps with bigger occlusal gaps, which have been attributed to the tool compensation requirements [71, 86]. The marginal fit accuracies have been significantly enhanced by the use of five-axis milling machines [87, 88], even as many studies have disclosed marginal discrepancies that are lower than the clinically approved 120 μm threshold [77].

Exploration of additive manufacturing in fixed prosthodontics

The use of AM in in the production of single-unit crowns and fixed prosthodontics is still a largely new and underexplored technique. The differences in techniques employed, hardware, software, and printing parameters, found in extant literature have continued to pose challenges concerning carrying out direct comparisons. However, this study is aligned with various studies that have focused on the evaluation of the fit of accuracy of single-unit crowns manufactured using AM and CAD/CAM methodologies. Studies have further indicated that AM-manufactured crowns' internal and marginal fits were considerably better

Harbi et al. and Dawood et al. demonstrated that marginal and internal fit accuracies in AM crowns were significantly better compared to the fits of accuracy of subtractive-manufactured crowns, despite the two methods generating outcomes that were within clinically approved ranges [52, 89]. Likewise, Peng et al. assessed the internal fit accuracy of AM and subtractive method-manufactured interim crowns and disclosed that there were no significant variations in the accuracy levels between the two methodologies [58]. Consequently, the study conducted by Mahmood et al. disclosed that despite CAD/CAM crowns' greater internal and marginal fit accuracies than the traditionally produced single-unit crowns, AM-manufactured crowns indicated increasingly accurate marginal fit accuracies compared to the subtractive techniques [90]. These findings indicate a trend in the direction of greater adaptation in AM-manufactured restorations than those manufactured using subtractive techniques. Conversely, factors including the lack of in vivo studies alongside the heterogeneity of methodologies, hardware, and software, across studies have made direct comparisons complex and almost impossible [91].

Study strengths and limitations

Among the notable strengths of this study include the use of a detailed systematic methodology and search strategy, which have aided in reducing the potential biases throughout the study selection process. Every study that focused on the fit accuracy and adaptation of different materials were subjected to rigorous selection criteria. The measurement units were also standardized to improve future reviews' informativeness, even as the use of consistent manufacturing protocols for crowns has been proposed. Further, this study has gained from the higher quality of methodologies utilized in included studies that have indicated lower publication bias and better MINORS score of ≥15. Further, the other key strength entails the observation that the inclusion of studies evaluating the accuracy of single unit crowns manufactured using different materials has underscored AM manufacturing potential with regard to dental crowns and other dental applications. Consequently, regarding the limitations of this study, it can be noted that significant data variability exists and can be attributed to different types of resins and production techniques used for the restorations.

Based on these strengths and limitations, it is recommended that prospective studies should utilize consistent protocols with regard to the preparation of specimens, milling machines, types of scanners, and methods of measurement, as this will enable the realization of comparable and practical outcomes. Despite this study mainly focusing on the accuracy of single-unit crowns, the outcomes are likely to diverge for bigger restorations, including multiple crowns and longer-span bridges. The variability in the research designs also limits the aptitude of clinicians to arrive at definitive decisions in choosing between conventional and digital methods. As such, it is recommended that prospective studies should make use of standardized methods to guide clinical decisions in different scenarios.

Conclusion

The present study has indicated that there are no significant differences between CAD/CAM methods and AM printing with regard to accuracy, internal and marginal discrepancies, and trueness. Nonetheless, AM printing has indicated increased accuracy and superior marginal fit in comparison to various traditional methods. As such, it can be deduced that, regarding superior fit and accuracy, CAD/CAM and digital manufacture provisional crowns have indicated improved internal and marginal fits in comparison to the traditional and manually fabricated crowns. Further, provisional crowns produced through the use of 3D printing resins have indicated superior marginal and internal fit adaptations in comparison to the traditional and CAD/CAM-produced provisional resins, which makes them increasingly reliable options. Also, regarding the clinically satisfactory accuracy levels, the findings indicate that the marginal and internal discrepancy values remained within clinically acceptable ranges. Lastly, regarding the influencing factors, it is noteworthy that the 3D-printed provisional crowns' accuracy levels are mostly influenced by different aspects, such as the 3D printing technologies utilized, the thickness of the layers, types of resins, and printing orientations. Therefore, it is recommended that biases should be reduced through strict adherence to blinding protocols to enhance prospective studies' quality. Technological advancement, including digital technologies, will still be considered viable options to the traditional techniques in the production of onlays and single crowns. Despite the high rates of success indicated by restorations (digital and conventional), there is still limited and inadequate evidence in support of digital methods as effective replacements for traditional methods. Challenges that include the existence of a wider array of scanners, milling machines, and 3D printing models, which have further complicated the arrival at definitive conclusions regarding the best methods. Additionally, high-quality in vitro and clinical studies are essential to the provision of pragmatic scenarios and the much-needed insights that go beyond the usual laboratory contexts. Lastly, increased clarity and standardization are essential for effective measurement methods for the internal and marginal gaps. The existing disparities in methodologies have made it increasingly challenging to successfully compare and utilize the findings across distinct clinical scenarios.

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