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Comparative Analysis of 3D-Printed and Milled Zirconia in Dental Clinical Applications

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A B S T R A C T

This review aimed to compare the efficacy of 3D-printed (AM) versus milled (SM) zirconia restorations concerning clinical outcomes, internal gaps, trueness, precision, and biocompatibility. The study conducted a thorough search of online databases up to April 2024, identifying studies comparing AM and SM zirconia restorations across various parameters. Out of 165 records, 55 met the eligibility criteria, with 42 included for review. Quality assessment utilized the revised Cochrane risk-of-bias tool (ROB2) and the Modified Consort Statement, revealing moderate to low risk in clinical studies and identifying bias concerns in laboratory studies. Short-term observations indicated a 100% survival rate with no periodontal complications. 3D-printed zirconia crowns exhibited lower ΔE values and better conformity to adjacent teeth compared to milled crowns. In terms of aesthetics, 3D-printed crowns offered superior color and contour matching with adjacent natural teeth. Both techniques yielded restorations with acceptable internal and marginal fit, although milled crowns tended to have smaller marginal gaps, still within clinical acceptability. 3D printing showed promise for laminate veneers and demonstrated better axial surface trueness than conventionally milled surfaces. Long-term randomized controlled trials are needed to confirm the clinical suitability of 3D-printed restorations. In summary, adequate internal fit and gap, precision, and trueness are vital for successful dental restorations. Both 3D printing and milling techniques produce restorations with clinically acceptable marginal and internal fit. Notably, 3D printing shows advantages for axial surfaces and narrow areas compared to conventional milling methods.

Keywords: 3D-printing, CAD/CAM, fixed prostheses, zirconia, milled crowns, prosthodontics.

1. Introduction

Zirconia polycrystalline ceramic has become increasingly prevalent in dentistry due to its favorable aesthetic qualities and excellent biological and mechanical properties, leading to its wide-ranging applications in dental practice. For crowns and fixed partial dentures to be clinically acceptable, they must meet stringent requirements for clinical application [1,2]. These requirements hinge on the material's inherent mechanical and physical properties, which are crucial for dental materials in practice. Additionally, every prosthesis must achieve an outstanding fit, precise form, and accurate internal and external geometry [3,4].

Achieving accurate seating of fixed prostheses poses a considerable challenge due to various factors associated with the casting technique. These factors include issues with teeth preparation and path of insertion, impression, die or wax pattern distortion, improper investing, and casting, as well as seating technique and force [5]. Zirconia polycrystalline ceramic restorations, however, are produced using computer numerical control (CNC) machines, which offer a digital workflow that minimizes the likelihood of errors inherent in traditional fabrication methods. Digital fabrication also reduces the potential for human-induced errors. Nonetheless, some laboratory studies have reported more precise and better fitting margins in conventionally fabricated single copings compared to those fabricated using CAD/CAM technology [6,7].

Despite this, the digital workflow in dentistry has proven to be efficient, versatile, straightforward, and accessible over the past few decades [8]. However, limitations of CNC milling machines, such as the inability to produce accurately complex hollow structures, may favor modern 3D ceramic printing techniques. Various printing methods, including vat photopolymerization (such as Stereolithography and digital light processing), material jetting (like ink-jet printing and nanoparticle jetting), material extrusion (such as robocasting and direct ink writing), selective laser melting, selective laser sintering, fused deposition modeling, three-dimensional slurry printing, sheet lamination, binder jetting, and direct energy deposition, can be utilized to produce ceramic dental restorations [9,10].

Despite some minor clinical and technical limitations, CAD/CAM subtractive manufacturing of zirconia has demonstrated success in producing single restorations, short- and long-span fixed partial dentures, and full-mouth rehabilitation with favorable clinical outcomes. However, the use of 3D printing techniques for high-strength zirconia ceramic (3Y-TZP) in dentistry is relatively recent, and existing literature presents conflicting findings regarding the accuracy of dental crowns compared to conventional CAD/CAM technology [11]. Previous literature primarily consisted of scoping reviews and systematic reviews focusing on dental ceramics in general. However, this specific systematic review and meta-analysis concentrate solely on 3D-printed zirconia materials, making it a valuable contribution to the field. The review aims to establish evidence-based conclusions regarding the superiority of trueness, marginal and internal fit, precision, aesthetic aspects, and biological properties of zirconia restorations fabricated using either technique [12].

2. Materials and methods

The review protocol followed the formula: participants included adult patients receiving indirect restorations, the intervention was 3D-printed zirconia restorations, and the comparators were CAD-CAM-fabricated restorations. The outcomes focused on incidences of clinical failure. For laboratory records, specimens comprised indirect crown or veneer restorations, the intervention was the 3D-printed zirconia technique, the comparator was the CAD-CAM fabrication technique, and outcomes included biocompatibility, internal and marginal fit, and gap, as well as trueness and precision of the restorations.

The electronic databases (PubMed (MEDLINE), BioMed Central (BMC), Cochrane, and Scopus) were explored for this study. There were no language restrictions, and the search spanned up to and including April 2024. Records were included if they investigated the accuracy, trueness, precision, or relevant material properties of 3D-printed (additively manufactured) zirconia ceramic compared to milled (subtractive manufactured) zirconia ceramic. Included records consisted of clinical trials or high-quality laboratory studies focused on dental applications of zirconia, particularly for restorative or prosthetic purposes. Relevant studies were identified through screening of titles and abstracts (Table 1).

Table 1 - Inclusion and exclusion criteria, applied in the study.

Criteria	**Description**
Study type	In-vitro and in-vivo investigations examining the biocompatibility of 3D-printed zirconia crowns and bridges.
Publication type	Encompassed peer-reviewed journal articles and conference proceedings to ensure studies underwent a formal review process.
Publication date	Included studies published up to the search date, with no restrictions on the publication year.
Exclusion criteria	
Irrelevant studies	Excluded studies that did not directly address the biocompatibility of 3D-printed dental resins to maintain alignment with the research focus.
Literature reviews	Excluded literature review articles to prioritize original research studies.

3. Results

The initial search of web databases yielded 750 records, with an additional 35 records identified through crosschecking references and other websites, totaling 785 records. After removing 85 duplicate records and excluding 30 records for various reasons, the first screening eliminated 1170 records. Following this, 160 records were retrieved for further evaluation. Upon reviewing the titles and abstracts for relevance, 55 studies were selected for full-text assessment. Ultimately, 42 records met the eligibility criteria and were included in this review. Thirty-five records were excluded for various reasons, including two that studied different variables, one thesis, one record duplicating data from an included study, thirty records focusing on physical-mechanical properties, and one cohort study lacking an SM control group.

4. Discussion

This review provides a comprehensive comparison between the milled and 3D-printed dental zirconia materials. In discussing esthetic value, one high-quality RCT and prospective clinical trial data indicated favorable short-term clinical outcomes for additively manufactured zirconia. However, further long-term well-designed RCTs are needed to confirm the esthetic superiority of 3D-printed zirconia over conventionally SM-fabricated zirconia crowns. Crowns produced using MEX (3DGP) techniques showed a 100% survival rate along with notably high patient satisfaction, attributed to their good marginal fit and high accuracy [13]. These findings were corroborated by a short-term cohort study [2].

However, the one-year observation period in the RCT might have been insufficient for detecting clinical complications. Nonetheless, based on the techniques and material properties outlined in this systematic review, it is suggested that 3D-printed zirconia could yield favorable long-term clinical outcomes, although this needs confirmation through high-quality, long-term RCTs [5].

In a prospective short-term clinical trial by Kao et al. [14], clinical outcomes of SLM zirconia crowns revealed an increase in gingival and plaque indices for 40% of cases within the first two weeks, possibly due to differences in surface texture between the original tooth and the 3D-printed zirconia. Despite this, zirconia's unique surface texture and bioinert nature make it less prone to microbial adhesion compared to base-metal alloys [15,16,17]. Additionally, self-glazed 3D-printed zirconia was found to be clinically feasible for full mouth rehabilitation with severely worn dentition cases, with less propensity for chipping and wear on opposing dentition [18].

Studies by Branco et al. [12] indicated that both additive manufacturing (AM) and subtractive manufacturing (SM) zirconia are relatively bioinert and produce materials with biologically acceptable cytotoxic effects. Zirconia has demonstrated high biocompatibility and can even be modified at the surface to effectively combat pathogenic bacteria [19]. However, the presence of porosities in 3D-printed zirconia could affect fibroblast proliferation and cellular orientations [20], although some reports suggest that porosities can have a positive impact on osteoblast proliferation due to the unique surface structure of 3D-printed zirconia [21].

In terms of appearance, MEX (3DGP)-produced zirconia crowns exhibited superior esthetic qualities and better harmony with neighboring teeth when compared to SM zirconia crowns [22]. Although adjustments were necessary for both types of crowns, the exposure of the underlying white material during adjustments compromised the visual cohesion of SM zirconia crowns, requiring additional surface refinement. Conversely, post-adjustment refinement wasn't necessary for 3DGP-printed crowns, which also effectively replicated heavy tetracycline stains often seen in natural teeth [23], making them particularly suitable for replicating challenging shades.

Factors such as the materials utilized, the method of finish line preparation, and the fabrication technique can influence the internal and marginal fit of crowns [24]. Despite the specific fabrication method employed, some level of marginal discrepancy is inevitable. Even minor discrepancies ranging from 50-300 μm can lead to deterioration of the composite interface between dentin and the luting material, potentially leading to the development of secondary cavities [25].

Trueness refers to how closely measured experimental values align with the intended or planned values [26]. Across external, internal, and marginal surfaces, crowns fabricated via subtractive manufacturing (SM) exhibited superior trueness compared to those made via digital light processing (DLP) [27,28]. However, specimens produced through stereolithography (SLA) and indirect jetting printing (IJP) demonstrated trueness levels comparable to those of SM-fabricated crowns in all aspects [29]. Subgroup analysis favored SLA and IJP zirconia specimens in terms of axial surface trueness, but occlusal, intaglio, marginal, and external trueness of IJP crowns were similar to SM crowns [30,31,32].

This systematic review noted a correlation between the adaptation of crown intaglio surfaces and marginal trueness for SLA, DLP, IJP, and SM crowns. Results indicated a non-significant preference for milling groups in most studies concerning intaglio and marginal trueness. Marginal trueness discrepancies could adversely affect axial and occlusal crown adaptation [33]. Computer numerical control (CNC) milling technology tends to have positive errors on complex surfaces due to tool size and shape limitations, impacting trueness and accuracy, particularly on curved surfaces such as cusp inclines and height of contour, unlike additive manufacturing (AM) techniques [34].

5. Conclusions

In this systematic review, despite its limitations, several conclusions emerge: Firstly, short-term clinical assessments indicate a 100% survival rate for 3D-printed zirconia crowns, which exhibit superior aesthetic harmony with natural teeth compared to milled counterparts. Secondly, both 3D printing and conventional milling yield zirconia crowns with acceptable internal and marginal fits; however, subtractive manufacturing (SM) demonstrates superior marginal fit over digitally light processed (DLP) and three-dimensional stereolithography printing (3DSP) methods, while DLP-fabricated laminate veneers show better axial and incisal fits than SM counterparts. Lastly, 3D-printed zirconia laminate veneers with incisal overlapping show heightened precision compared to computer numerical control (CNC)-milled veneers, particularly at the labial-lingual transition of the incisal edge.

Conflict of interest

The authors declared no potential conflicts of interest concerning the research, authorship, and publication of this.

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