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Review article

3D-printed versus conventionally milled zirconia for dental clinical applications: Trueness, precision, accuracy, biological and esthetic aspects

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ABSTRACT

Objectives: This systematic review aimed to compare the clinical outcome, internal gap, trueness, precision, and biocompatibility of 3D-printed (AM) compared to milled (SM) zirconia restorations.
Data Source: A thorough search of Internet databases was conducted up to September 2023. The search retrieved studies compared AM zirconia to SM zirconia restorations regarding clinical outcome, fit, trueness, precision, and biocompatibility.
Study Selection: Of 1736 records, only 59 were screened for eligibility, and 22 records were included in this review. The quality of studies was assessed using the revised Cochrane risk-of-bias tool (ROB2), and the Modified Consort Statement. One clinical study showed a moderate risk of bias and one has a low risk of bias. All laboratory studies revealed some bias concerns. Short-term observation showed 100 % survival with no signs of periodontal complications. 3D-printed zirconia crowns showed statistically significant lower ΔE and a better match to adjacent teeth ($p \leq 0.5$). The fit, trueness, and precision vary with the printing technique and the tooth surface.
Conclusions: 3D-printed zirconia crowns provide better aesthetic color and contour match to adjacent natural teeth than milled crowns. Both 3D printing and milling result in crowns within the clinically acceptable internal and marginal fit. Except for nanoparticle jetting, the marginal gap of SM crowns was smaller than AM crowns, however, both were clinically acceptable. Laminate veneers might be more accurately produced by 3D printing. 3D-printed axial surface trueness was better than milled axial surfaces. Long-term RCTs are recommended to confirm the clinical applicability of 3D-printed restorations.
Clinical significance: Internal fit and gap, precision, and trueness are fundamental requirements for successful dental restorations. Both techniques produce restorations with clinically acceptable marginal and internal fit. Axial surfaces and narrow or constricted areas favored 3D-printed than conventionally milled zirconia.

1. Introduction

Zirconia polycrystalline ceramic is widely used nowadays in dentistry. The relative esthetic nature and the inherited good biological and mechanical properties promote the material's several applications in dental practice. The clinically acceptable crowns and fixed partial dentures must meet the clinical application requirements. Adequate inherited mechanical and physical properties are the fundamentals of applied dental materials. Moreover, every fabricated prosthesis must achieve a basic excellent fit, precise form, and true internal and external geometry [1,2].

Trueness, precision, and accuracy are frequently used as synonyms in everyday language, apart from the measurements in the scientific and technical contexts; according to the International Standardized Organization (ISO), the term "precision" refers to the closeness of agreement between different tests results; that is, the closeness of two or more measurements to each other. While "trueness" refers to the closeness of agreement between the arithmetic mean of many test results and the true or accepted reference value, in other words, trueness refers to how close a measured value is to a known value or standard. "Accuracy" refers to the combination of trueness and precision [3,4].

The numerous fabrication steps of conventional dental prostheses

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render their accuracy quite challenging. The causes of improper seating of fixed prostheses fabricated using the casting technique are variants; faulty teeth preparation and path of insertion, impression, die or wax pattern distortion, improper investing and casting, or improper seating technique and force. Restorations made of zirconia polycrystalline ceramic are fabricated using a computer numerical control machine (CNC). The computer and digital workflow were considered beneficial as they overcame the probability of multistep classic fabrication errors. Moreover, digital fabrication might bypass human-induced errors. However, some laboratory studies reported more accurate and highly fit margins of conventionally fabricated than CAD/CAM-fabricated single copings [5,6]. Nevertheless, the digital workflow in dentistry has proven in the past decades to be a time-efficient, multifunctional, effortless, and accessible approach. The inherited shortages of CNC milling machines represented by the incapability to produce accurate complex hollow structures [7,8], may give preference to modern 3D ceramic printing [2]. Many printing techniques can be used to produce ceramic dental restorations including; vat photopolymerization (Stereolithography (SLA), digital light processing (DLP)) [9–12], material jetting; MJT (ink-jet printing (IJP), nanoparticle jetting (NPJ)) [13,14], material extrusion; MEX (robocasting, direct ink writing (DIW), 3D gel deposition/printing (3DGP)) [15–17], selective laser melting (SLM) [18] and selective laser sintering (SLS), fused deposition modeling (FDM) [19], three-dimensional slurry printing (3DSP) [20], sheet lamination; SHL [21], binder jetting; BJT [21], and direct energy deposition; DED [21].

Despite minor clinical and technical limitations, zirconia CAD/CAM subtractive manufacturing has been proven to produce single restorations, short- and long-span fixed partial dentures, and, full-mouth rehabilitation with good clinical prognosis [22–24]. However, 3D printing techniques for high-strength zirconia ceramic (3Y-TZP) have only recently been introduced in dentistry, and literature reports have shown controversial agreements on the accuracy of dental crowns compared to the conventional CAD-CAM technology. The existing literature primarily consists of two scoping reviews [25,26] and another systematic review focusing on dental ceramics as a whole [27]. However, this particular systematic review and meta-analysis specifically concentrates on 3D-printed zirconia materials, making it a genuine contribution to the field. The review aims to establish evidence-based conclusions on the superiority of trueness, marginal and internal fit, precision, esthetic aspect, and biological properties of zirconia restorations fabricated by either technique.

2. Review method

The review protocol was registered in the international database of prospectively registered systematic reviews in health and social care (PROSPERO: CRD42023414317). The following PICO formula was assigned for this review; the participants are adult patients receiving indirect restorations, the intervention is 3D-printed zirconia restorations, and the comparators are CAD-CAM-fabricated restorations. The outcomes are clinical failure incidences. For laboratory records; the specimens are indirect crown or veneer restorations, the intervention is the 3D-printed zirconia technique, the comparator is the CAD-CAM fabrication technique, and the outcomes are biocompatibility, internal and marginal fit and gap, trueness and precision of the restorations.

The electronic databases (PubMed (MEDLINE), BioMed Central (BMC), Cochrane, and Scopus) were independently screened by two reviewers (M.A.A and A.Y.A). There were no language restrictions, and the search was up to and including September 2023. The records were included if they investigated the accuracy, trueness, precision, or relevant material properties of 3D printed (additively manufactured) zirconia ceramic in comparison to milled (subtractive manufactured) zirconia ceramic. The records were clinical trials or high-quality laboratory studies interested in dental applications of zirconia, particularly for restorative or prosthetic purposes. The titles and abstracts of the records were screened for relevant studies. The retrieved studies' full texts were screened for eligibility. Furthermore, the reference lists of relevant studies and others within the web science sites were manually screened to broaden the search.

The revised Cochrane risk-of-bias tool (ROB2) was used to evaluate the randomized controlled trials [28,29]. The modified consort statement was used to judge the included studies, where thirteen items were included for the risk of bias judgment. The item that was fulfilled in the record was marked "yes", and "No" if the record failed to fulfill the item requirement. The number of votes differentiated the record's risk of bias into high, moderate, or low [30,31] (Tables 2a and 2b).

2.1. Effect measures and syntheses methods

The main effect measures are the internal and marginal fit and gap, trueness, and precision of 3D-printed zirconia compared to milled zirconia restorations. The secondary effect measures were esthetic aspects and biological outcomes and complications.

The review manager software version 5.4 of the Cochrane collaboration accomplished the meta-analysis. The analytical methods were set for inverse variance, and the result was presented as standardized mean difference or mean difference utilizing 95 % confidence intervals (CI). The I^2 statistic assessed the heterogeneity; a random-effects model was used if there was substantial heterogeneity (I^2>40 %); otherwise, a fixed-effects model was applied.

Five major outcomes were assigned for this analysis: clinical esthetic value, internal and marginal fit, trueness, precision, and crown accuracy of different marginal preparations. The major outcomes were further divided into occlusal, axial, marginal, intaglio, external, and overall outcomes. The subgroup analysis was assigned based on the printing techniques used. The statistical difference was significant if the p-value was $\leq$0.05.

3. Results

3.1. Literature results

The search of the web Databases resulted in 1701 records; 35 records were added later from the crosscheck of the reference list of the included studies and the other websites (n = 1736 total). Eighty-six duplicated records were removed, and 32 were removed for other reasons. The first screening excluded 1484 records. Hundred and forty-three records were sought for retrieval, after the titles and abstracts of the records were checked for relevance, 59 studies were retrieved and assessed for illegibility. Twenty records (one clinical and nineteen laboratory records) [2, 7-9,11-13,16,32-43] were included in this review and thirty-eight records were excluded for reasons [10,14,15,17,18,32,33,44-70] (two studied different variables, one thesis, and one record had the same data of an included study, thirty-four records studied the physical-mechanical properties, and one cohort study without SM control group) Fig. 1.

3.2. Characteristics of the included studies

One randomized control trial was included on 27 patients receiving identical MEX (3DGP) and SM zirconia crowns. The study compared the survival rate and esthetic values of MEX (3DGP) zirconia to milled zirconia crowns with three different post and core materials; fiber post, cast gold post and core, and no post and core group. The observation period was 12.2 ± 3.5 months [32].

Eight laboratory records studied SLA zirconia crowns [2,8,9,11,35, 36,40,41], and seven records compared the DLP fabrication technique to SM-fabricated zirconia crowns and veneers [7,11,34,37-40]. Three studies compared MJT (IJP, NPJ) zirconia crowns to SM additive-manufactured zirconia crowns [11,13,43], one study compared MEX (3DGP) to SM zirconia crown clinically [32] and one record studied 3DSP [20]. Ten records reported the internal fit and gap of the

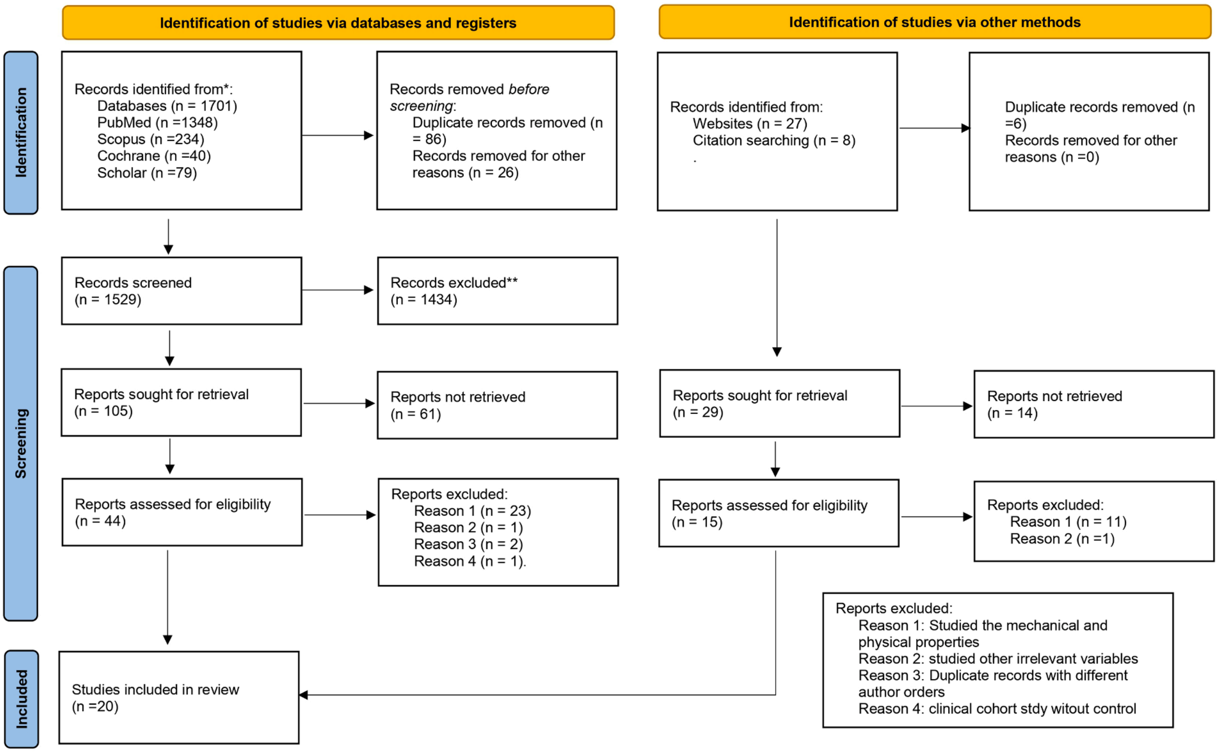

Fig. 1. PRISMA 2020 flow diagram shows the steps of the search strategy and study selection.

restorations [2,20,34-40,43]. Eight records reported the restoration trueness [2,7,11,13,34,36,41,43], two records reported the precision of 3D-printed zirconia to milled zirconia crowns [2,7], two records reported the dimensional accuracy of specimens [40,70], and two records compared the fabrication accuracy of three different marginal preparations for 3D-printed and milled zirconia crown [9,43]. One study evaluated the biocompatibility of 3D-printed zirconia [16], and one record compared the gingival fibroblast growth on 3D-printed zirconia to milled zirconia specimens [42]. Eleven records evaluated crown fit and accuracy by triple scan method (TSM) [2,7,9,11,12,20,34,36,37,41,43], two records used silicon rubber and micro-computed tomography (MCT) [12,13], two records used the silicon replica technique (SRT) [38,40] and one record used the cross-sectional method (CSM) [39], detailed characteristics of the included studies are enlisted in Table 1a and b.

3.3. Quality assessment

The RCT was at low risk of bias according to ROB2 [32] (Table 2b). According to the modified consort statement for clinical and laboratory studies on dental materials [30,31], five laboratory studies [7,16,34,39,42] were at low risk of bias and ten were at moderate risk of bias [2,8,9,11-13,20,36,37,41] (Table 2a).

3.4. Clinical evaluation

In the included RCT the operators used an extended visual rating scale for appearance match (EVRSAM) and by participants using a visual analog scale (VAS), the anatomical contour of MEX (3DGP) 3D-printed zirconia crowns showed a better match to adjacent natural teeth and had higher esthetic value than the milled zirconia crowns, the detailed statistical evaluation is presented in the meta-analysis section. In terms of survival rate, all crowns showed 100 % survival with excellent marginal adaptation. The anatomical form was excellent for both techniques except for one crown made by MEX (3DGP) 3D-printing, where the crown was slightly over-contoured and was adjusted. The result was as satisfying as the rest of the restoration [32].

3.5. Biological complications and biocompatibility

The included RCT reported no biological complications of the oral and periodontal tissues after one year of observation [32]. Branco et al. [16] showed no statistically significant difference in the biocompatibility of IJP-fabricated zirconia compared to SM zirconia specimens, the fibroblast viability reduced by 28.1 % for IJP zirconia and 19.4 % for SM specimens after 7 days of exposure to the extract solutions, according to guideline cytotoxic threshold of the international standardization organization (ISO 10,993–5) both SM and IJP zirconia specimens had no cytotoxicity for fibroblast cells. The cell attachment to unglazed SM and IJP specimens were comparable, after three days the IJP zirconia showed slightly higher cellular attachments than SM specimens. Both glazed and unglazed specimens showed the same irregular and elongated shape of cells with long filopodia. It was reported that the glazed surfaces are less susceptible to cellular adhesion, hence there were no cells in several regions of the glazed surfaces.

Zandinjad et al. [42] compared the fibroblast proliferation on SM specimens to SLA 3D-printed zirconia specimens with 0 %. 20 % and 40 % porosities at 48 h, the results showed comparable fibroblast proliferation between SM and 0 % porosities SLA zirconia specimens. However, there was statistically significantly reduced fibroblast cell proliferation on SLA zirconia specimens with 20 % and 40 % porosity. The fibroblast count reduced drastically for the 20 % porosity specimens, and for the 40 % porosity zirconia, the fibroblasts appeared in clumps and lost their normal orientations.

3.6. Meta-analysis

3.6.1. Clinical esthetic value

The ΔE - (Delta E, dE) was significantly lower for IJP zirconia than SM zirconia crowns, and thus IJP zirconia crowns had a statistically significantly better match to the adjacent natural teeth than the SM zirconia crowns, for prepared teeth with fiber post and composite core ($P = 0.002$; MD: −1.61; 95 % CI: −2.61 to −0.61), gold cast post-and-core ($P = 0.01$; MD: −2.14; 95 % CI: −3.78 to −0.50), and no post and core

Table 1a
Characteristics of the included laboratory studies .

No.	Author	Study type	Specimens/ restorations used	Dimensions	Marginal preparation	Duplication	Model	Designing	Cement space	group	Materials	Yttrium % & compos.	Manufacturer	Fabrication technology	Sintering temp.	Test used	Primary outcome	Secondary outcome
1	Abualsaud et al. 2nd [2]	Vitro	Crown Molar	Occ. 1.5–2.0 mm Axial 0.8–1.2 mm	0.8 mm shoulder	3Shape desktop scanner	Analogue Printed resin from STL	3Shape CAD software	60 µm	SM	IPS e.max ZirCAD LT	3mol% Y-TZP	Ivoclar Vivadent	Dry milling 5-axis milling machine (PM7)	1500 °C for 9 h	Triple scan method (TSM)	Fit & Precision	Trueness
										AM	3DMix ZrO2	3mol% Y-TZP	3D Ceram	SLA (CERAMAKER C900)	1450 °C for ~ 2 h			
2	Branco et al. 2020 [15]	Vitro	Blocks	15 × 15 × 4 mm^3	——	——	——	——		SM	Prettau, zirconia	3Y-TZP	Zirconzahn	5-axis milling, M5 Zirconzahn	1600 °C	VHN; bending test, SEM, Archimedes method & cell culture,	Physical-mechanical properties	Biological properties And biocompatibility
										AM	LithaCon 3Y320 Ceramic	3Y-TZP	Lithoz	Robocasting Delta WASP 2040	1450 °C			
3	Camargo et al. 2022 [13]	Vitro	Crown Human extracted Maxillary molar	2 mm occlusal	Chamfer finish line	CEREC Omnicam camera	Virtual 'master' CAD model	Cerec 'Biogeneric individual' software	80 µm	SM	Cerec Zirconia Mono L	3 mol% Y-TZP	GC, Tokyo, Japan	5-axis Matsuura Machinery	1450 °C for 6 h and 30 min	Micro-computed tomography (MCT) & SEM	Trueness	Crown adaptation and cement space
										SM	Ini_HT Zirconia HT	3 mol% Y-TZP	Dentsply Sirona	Cerec MCXL L	CEREC SpeedFire			
										AM	C800 zirconia	3 mol% Y-TZP	XJET	Inkjet Carmel 1400 (Xjet)	1450 °C for 2 h			
4	Hsu et al. 2019 [20]	Vitro	Crown on Nissi Dentoform	2 mm occlusal and 6 °convergence	0.8 mm chamfer	3 Shape desktop scanner	Virtual 'master' CAD And an analog stone model	3Shape software	NR	SM	Copran Zr-i Monolith A3	3 mol% Y-TZP	Zirkonblank, Dental solution	four-axes system (CORiTEC 245i)	1550 °C	Vicker hardness, bending test, and TSM	Fitness and accuracy	Mechanical properties
										AM	slurry YTZP	NR	NR	3DSP System	1450 °C & 1550 °C			
5	Ioannidis et al. 2022 [32]	Vitro	Occlusal veneer on 60 Human premolars	0.5 mm thickness	No finish line only a bevel	Identica 3D Desktop Scanner	Virtual 'master' CAD model	3Shape software	50 µm	SM	Ceramill Zolid FX	5,4–5,8 wt% yttrium oxide	Amann Girrbach	5-axis milling (Ceramill)	Ceramill Zolid FX sintering protocol	TSM And STL files fitness comparison	Internal and marginal adaptation	Trueness and precision
										AM	ceramic powder	3mol% YSZ	NR	LCM (CeraFab 7500-system)	NR			
6	Lerner et al. 2021 [7]	Vitro	Crown, maxillary premolar model	NR	90∘ shoulder preparation	industrial scanner (ATOSQ, Gom)	3D-printed resin dies	Exocad	NR	SM	NR	3 mol% Y-TZP	NR	DWX-52D, DGShape	NR	TSM, Inspection under Zeiss 4.5x	Trueness and precision	
										AM	LithaCon 3Y 210	3 mol% Y-TZP	Lithoz	LCM CerafabS65, Lithoz	1450 °C for 2 h			
7	Li et al. 2019 [33]	In vitro	Crowns	NR	NR	Intraoral scanner (CEREC; Omnicam, Dentsply)	Virtual 'master' CAD model	NR	NR	AM	45 vol% Zr. suspension	3 mol% Y-TZP	NR	SLA printer (CSL; 150; Porimy)	1500 °C for 2 h	3D subtractive analysis	Internal gap	Mechanical properties
8	Li et al. 2021 [9]	Vitro	Crown Typodont maxillary molar	1.0–1.5 mm occlusal 6–10∘ taper	knife edge, chamfers, or shoulder	Desktop scanner DS-EX Pro, Shining3D	3D-printed resin dies	Exocad, software	NR	SM	SHT	3 mol% Y-TZP	Aidite, China	AK-D4, Aidite, China	1450 °C for 2 h	TSM Observation at 200 × magnification	Crown accuracy analysis	
										AM	47 vol% Zr. suspension	3 mol% Y-TZP	NR	SLA (CSL 100, Porimy)	1450 °C for 2 h			
9	Li et al. 2022 [34]	Vitro	Crown	1.0–1.5 mm occlusal	0.5 wide chamfer,	intraoral scanner (TRIOS 3, 3shape)	Virtual 'master' CAD model	3Shape designed software	80 µm internal and 30 µm axial	SM	Katana ML	3 mol% Y-TZP	Kuraray	250i; imes-icore)	1500 °C for 2 h	TSM Accuracy comp. via 3D scanner	Accuracy and trueness	Cement gap
										AM	47vol% Zr. Susp.	NR	NR	SLA; CSL 100; Porimy	Two-stage sintering			
10	Lüchtenborg et al. 2022 [11]	Vitro	4 unite FPD 3D model of an FDP	NR	NR	NR	Virtual 'master' CAD model	NR	NR	SM	Priti Zr.	3 mol% Y-TZP	Pritidenta	Milling	1450 °C for 2 h	TSM Profilometer, Laser scanning, Dynamic depth scanning technology	Accuracy	
										SLA	3DMix Zr-P03 paste	3 mol% Y-TZP	3DCeram	SLA Ceramaker900, 3DCeram	1450 °C for 2 h			
										IJP	C800 7250001ink	3 mol% Y-TZP	XJET	IJP	1450 °C for 2 h			

(*continued on next page*)

Table 1a (*continued*)

No.	Author	Study type	Specimens/ restorations used	Dimensions	Marginal preparation	Duplication	Model	Designing	Cement space	group	Materials	Yttrium % & compos.	Manufacturer	Fabrication technology	Sintering temp.	Test used	Primary outcome	Secondary outcome
										DLP	LithaCon slurry	3 mol% Y-TZP	Lithoz	DLP	1450 °C for 2 h			
11	Meng et al. 2022 [12]	Vitro	Crown Typodont maxillary molar	NR	NR	model scanner (Identica Blue)	Virtual 'master' CAD model	3Shape design	NR	SM	NR	NR	NR	NR	milling technique	MCT TSM	Crown fit	Dimensional accuracy
										AM	JA-TZP-3Y	3 mol% Y-TZP	Jin'ao, Shandong	DLP	1500 °C for 1 h	3D model evaluation (Map 600)		
12	Moon et al. 2022 [35]	Vitro	Crown typodont molar	NR	NR	model scanner (Identica Blue)	Virtual 'master' CAD model	3Shape designer sofware	NR	SM	Lauxen Zirconia 1200	3 mol% Y-TZP	Dental Max Co,	5X-500 L Arum, Daejeon. Korea	1530 °C	TSM evaluation using model and crowns 3D scanner	Crown accuracy	Bond strength of porcelain to zirconia
			Bars	25×4 × 10 mm						AM	INNI-Cera	NR	AON, Korea	DLP-type 3D printer	as recommended by the manufacturer			
13	Revilla-León et al. 2020 [8]	Vitro	Crown for Maxillary implant	0.5 to 1.0 mm thickness	Shoulder	laboratory scanner (DWOS 7 Series scanner	Zr. abutment	CAD software (CARES)	NR	SM	CARES Zr.	NR	Straumann	Milling 5-axis	NR	Silicone Replica Technique (SRT)	Cement space	Mechanical properties
										AM	3DMix ZrO2	3 mol% Y-TZP	3DCeram	SLA CERAMAKER 900	1450 °C for 2 h			
14	Rues et al. 2023 [37]	Vitro	Laminate Veneer Typodont maxillary central	0.5 mm thickness	Chamfer	laboratory scanner (D2000, 3Shape)	Acrylic resin (3D printed)	3Shape designer sofware	60 µm internally and 20 µm at the margins	SM	Cercon ht,	3 mol% Y-TZP	Dentsply Sirona	Cercon brain expert, Degudent	1500 °C Cercon heat	Cross-Sectional Method (CSM) ×130 Smartzoom 5, Zeiss	Accuracy and restorations fit	
										AM	LithaCon 3Y 210,	3 mol% Y-TZP	Lithoz	DLP CeraFab 7500; Lithoz, Vienna, Austria	1450 °C			
15	Wang et al. 2019 [39]	Vitro	Crown Typodont maxillary 2nd molar	Ceramic crown dimensions	NR	laboratory scanner (D810; 3shape)	Virtual 'master' CAD model	3Shape designer sofware	NR	SM	Zenostar;	3 mol% Y-TZP	Wieland Dental	5-axis milling (DWX-50; Roland)	NR	TSM	Trueness	
										AM	3DMIXZrO2L	3 mol% Y-TZP	3DCeram	SLA CERAMAKER 900	NR			
16	Zandinjad et al. 2023 [41]	Vitro	Blocks	8 × 4 × 3 mm^3	——	——	——	——	——	SM	ArgenZ ST	8.5–10 mol% Y-TZP	Argen.co (San Diego, CA)	ProgramMill P7; Ivoclar vivadent, Shaan, Liechtenstein	1500 °C	Fibroblast proliferation via MTT assays (Biotium, Fremont, CA, USA)	Fibroblasts proliferation over 0 %, 20 %, and 40 % porosities specimens	
										AM	3DMix ZrO2 paste	3 mol% Y-TZP	3D Ceram	SLA 3D printer (CeraMaker900)	1250–1500 °C depends on the porosities			
17	Rafaie et al. 2023 [36]	In-vitro	Crown	1 mm chamfer, 1.5 mm occlusal, and 6° convergence	Round Chamfer	Addition silicone impression material	epoxy die (KEMAPOXY) and scanner (Medit T500)	Exocad version 3.0, exocad Gmbh	70 µm	SM	IPS e.max ZirCAD LT	3Y-TZP	(Ivoclar Vivadent	DGSHAPE DWX-520, Roland company	1530 °C	SRT, using low-viscosity silicone impression material (Honigum light,DMG)	Internal fit and marginal gap	
										AM	Lithoz 210 3Y	3Y-TZP	Lithoz GmbH	DLP: CeraFab7500 printer (Lithoz GmbH)	120 °C/ 134 h, 1000 °C/ 103 h & sintered 1450 °C/ 17 h			
18	Wang et al. 2021 [38]	In-vitro	Crown	NR	NR	extraoral scanner (D700 Scanner; 3Shape)	Virtual 'master' CAD model	CAD software (3Shape)	30 mm	SM	Zirconia	3Y-TZP	XTCERA	X-MILL500 [XM]; XTCERA	1550 °C for 3 h	SRT	Dimensional accuracy	
										SLA	Zirconia, HDDA, PET4A	3Y-TZP	PORIMY	CSL150	Up to 1550 °C			
19	Zhu et al. 2023 [42]	In-vitro	Crown	1.0 to 1.5 mm and 6–10° taper	0.5-mm-chamfer	intraoral scanner (TRIOS 4;	Virtual 'master' CAD model	CAD software program	60-µm	SM	VITA YZ HT and UPCERA MT	3Y-TZP	VITA Zahnfabrik	3D printer (AccuFab-L4K; SHINING 3D)	1450 °C for 2 h	TSM: trueness was measured by Mean	Marginal and internal fit,	Crown fracture load

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Table 1a (*continued*)

No.	Author	Study type	Specimens/ restorations used	Dimensions	Marginal preparation	Duplication	Model	Designing	Cement space	group	Materials	Yttrium % & compos.	Manufacturer	Fabrication technology	Sintering temp.	Test used	Primary outcome	Secondary outcome
						3Shape A/ S)		(Dental System;					and UPCERA MT			positive-, negative-, and root-deviation (MPDs), (MNDs), (RMS)	and accuracy.	
								3Shape A/ S)		AM	Printable ink containing Zirconia	NR	NR	NPJ: 3D printer (Carmel 1400; XJET)	NR			

Table 1b
Characteristics of the included clinical study.

No.	Author	Study type	Patients/ crowns	Dimensions mm	Marginal preparation	Duplication	Model	Designing	group	Materials	Yttrium % & compos.	Manufacturer	Fabrication technology	Provisional	Permanent cementation	Test used	Primary outcome	Secondary outcome
20	Cui et al. 2020 [30]	clinical	27 participants/ 54 Crowns	1 axial and 1–1.5 occlusal 2–5° taper	0.6–0.8 chamfer located 0.5 mm subgingival	laboratory scanner (D2000, 3Shape)	Type IV gypsum (GC Fujirock EP; GC)	3Shape designer sofware	SM	Zenostar	3 mol% Y-TZP	Zenotec Select Hybrid Wieland Dental	dry milling 5-axis milling machine	NR	RelyX U200 Self-adhesive luting resin	VAS and EVRSAM scores (chromatic values evaluation (CIE1976-L* a* b*) (ΔE))	Esthetic appearance	Satisfaction
									AM	Self-Glazed Zirconia	3 mol% Y-TZP	Erran Tech	3DGP additive wet deposition process					

Table 2a
The Modified Consort Statement evaluation of the included records.

No.	Author and year	abstract	Introduction		Method								Results	Discussion	Funding	Risk of bias
	Item	1	2a	2b	3	4	5	6	7	8	9	10	11	12	13	
1	Abualsaud et al. 2nd [2]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	Yes	9
2	Branco et al. 2020 [15]	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	10
3	Camargo et al. 2022 [13]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	Yes	9
4	Hsu et al. 2019 [20]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	Yes	9
5	Ioannidis et al. 2022 [32]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	11
6	Lerner et al. 2021 [7]	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	11
7	Lie et al. 2019 [33]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	No	Yes	8
8	Li et al. 2021 [9]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	Yes	9
9	Li et al. 2022 [34]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	Yes	9
10	Lüchtenborg et al. 2022 [11]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	Yes	9
11	Meng et al. 2022 [12]	No	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	Yes	8
12	Moon et al. 2022 [35]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	Yes	9
13	Revilla-León et al. 2020 [8]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	Yes	9
14	Rues et al. 2023 [37]	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	10
15	Wang et al. 2019 [39]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	Yes	9
16	Zandinjad et al. 2023 [41]	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	10
17	Rafaie et al. 2023 [36]	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	10
18	Wang et al. 2023 [39]	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	10
19	Zhu et al. 2023 [42]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	Yes	9

Table 2b
ROB2, evaluation of the risk of bias for randomized control trial.

Author	Randomization	intended interventions	Missing outcome data	measurement of the outcome	selection of the reported result	Overall risk
Cui et al. [30]	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk

crowns ($P = 0.0003$; MD: −2.39; 95 % CI: −3.68 to −1.10) [32].

The number of SM-fabricated crowns that mismatched the adjacent teeth was statistically significantly higher than the IJP zirconia crowns ($P = 0.0002$; MD: −0.41; 95 % CI: −0.62 to −0.19) [32].

3.6.2. *Internal fit and gap*

3.6.2.1. Occlusal. The internal gap was statistically significantly lower for the SM zirconia crowns than 3D-printed crowns at the occlusal surface for the SLA printing technique ($p = 0.04$; SMD: 1.61; 95 % CI: 0.11 to 3.11; heterogeneity: $p = 0.005$, I^2=81) [2,36,40]. The DLP-fabricated occlusal veneer and full crowns showed statistically significant higher occlusal discrepancy than SM occlusal veneers ($p = 0.04$; SMD: 1.31; 95 % CI: 0.62 to 2.00) [34], and ($p \leq 0.0001$; SMD: 7.61; 95 % CI: 4.84 to 10.39) [40]. However, the internal incisal gap of anterior laminate veneers was statistically significantly lower for DLP-fabricated than SM-fabricated laminate veneers ($p \leq 0.001$; SMD: −13.27; 95 % CI: −17.46 to −9.09) [39]. Nonetheless, the occlusal gap was not statistically significantly different between IJP crowns and SM crowns ($p = 0.06$; SMD: −0.47; 95 % CI: −0.97 to 0.02; heterogeneity: $p = 0.78$, I^2=0), with 3D- printed zirconia favorability [43] (Table 3).

3.6.2.2. Axial. The axial internal gap was statistically significantly lower for DLP-fabricated than SM-fabricated laminate veneers ($p = 0.02$; SMD: −0.98; 95 % CI: −1.84 to −0.13) [39]. While, SM-fabricated crowns revealed no statistically significantly different internal axial gap than SLA-fabricated restorations ($p = 0.21$; SMD: −1.51; 95 % CI: −3.85 to 0.84; heterogeneity: $p \leq 0.001$, I^2=91 %) [2,36,40], DLP-fabricated zirconia restorations ($p = 0.37$; SMD: −4.66; 95 % CI: −14.82 to 5.50; heterogeneity: $p \leq 0.001$, I^2=97 %) [37,40], and IJP crowns ($p = 0.37$; SMD: 0.24; 95 % CI: −0.28 to 0.77; heterogeneity: $p = 0.29$, I^2=11 %) [43] (Table 3).

3.6.2.3. Marginal. The marginal fit of SLA-fabricated zirconia crowns revealed no statistically significant differences to SM-fabricated zirconia crowns ($p = 0.16$; MD: 14.82; 95 % CI: −5.71 to 35.34; heterogeneity: $p \leq 0.001$, I^2=91 %) [2,36,40]. The SM crowns showed statistically significantly better marginal fit than DLP-fabricated crowns and veneers ($p = 0.0002$; MD: 22.92; 95 % CI: 10.82 to 35.03) [34,37,39,40], and 3DSP fabricated zirconia crowns ($p \leq 0.0001$; MD: 40.63; 95 % CI: 30.33 to 50.93; heterogeneity: $p < 0.001$, I^2=99 %) [20]. However, the marginal fit was statistically significantly better for IJP-fabricated crowns than SM-fabricated crowns ($p = 0.04$; MD: −9.06; 95 % CI: −17.74 to −0.38; heterogeneity: $p = 0.72$, I^2=0 %) (Table 3).

3.6.2.4. Overall. The overall internal fit of SLA-printed crowns was comparable to SM-fabricated crowns ($p = 0.29$; MD: 17.77; 95 % CI: −15.47 to 51.02; heterogeneity: $p = 0.0004$, I^2=92 %) [2,40] (Table 3).

3.6.3. *Trueness*

3.6.3.1. Occlusal. The occlusal trueness of SM-fabricated crowns revealed no statistically significant differences from SLA-fabricated crowns ($p = 0.11$; SMD: −2.05; 95 % CI: −4.55 to 0.45; heterogeneity: $p = 0.004$, I^2=88 %) [2,40], and IJP-fabricated crowns ($p = 0.24$; SMD: −0.57; 95 % CI: −1.51 to 0.37) [13,16,43]. However, DLP-fabricated crowns had statistically significantly better trueness than SM-fabricated crowns ($p \leq 0.0001$; SMD: 5.17; 95 % CI: 3.18 to 7.16) [7] (Table 4).

3.6.3.2. Axial. The axial trueness of SLA crowns was statistically significantly better than SM crowns ($p = 0.0002$; SMD: −1.56; 95 % CI: −2.40 to −0.73) [2]. Likewise, the axial trueness of IJP-fabricated zirconia crowns was statistically significantly better than SM-fabricated crowns ($p = 0.05$; SMD: −3.64; 95 % CI: −7.34 to 0.06; heterogeneity: $p \leq 0.001$, I^2=96 %) [13,16,43] (Table 4).

3.6.3.3. Marginal. The marginal trueness of SM-fabricated crowns was not statistically significantly different than SLA-fabricated crowns ($p = 0.37$; SMD: 0.21; 95 % CI: −0.25 to 0.66; heterogeneity: $p \leq 0.001$; I^2= 0 %) [2,11,41], DLP-fabricated zirconia crown ($p = 0.17$; SMD: 2.75; 95 % CI: −1.20 to 6.71; heterogeneity: $p \leq 0.001$; I^2= 92 %) [7,11], and IJP-fabricated crowns ($p = 0.50$; SMD: 0.33; 95 % CI: −0.62 to 1.28;

Table 3
Extracted nominal data of Internal fit gap of 3D printed in comparison to milled zirconia restorations; represented by the mean values and SD (μm).

Author	Abualsaud et al. 2nd [2]		Rues et al. 2023 [37]		Hsu et al. 2019 [20]			Moon et al. 2022 [35]				Ioannidis et al. 2022 [32]		Li et al. 2022 [34]		Zhu et al. 2023 [42]			Refaie et al. 2023 [36]		Li et al. 2019 [33]	Wang and Sun 2021 [38]		
Restoration	Crown on molar		Veneer on incisor		Crown			Crown				Veneer				Crown			Crown		Crown	Crown		
No. of specimens	10	10	12	12	5	5	5	10	10	10	10	20	20	6	6	16	16	16	20	20	5	10	10	10
Fabrication	SM	SLA	SM	DLP	SM 1550 °C	3DSP 1550 °C	3DSP 1450 °C	SM AR	SM K5	SMAO	DLP	SM	DLP	SM	SLA	Upcera	Vita	NPJ	SM	DLP	SLA	SM	DLP	SLA
Occlusal	40.20 _ 7.96	45.67 _ 4.57	391 ± 26	78 ± 19								229 ± 129.5	404.5 ± 133.5	97 ± 11	111 ± 21	117.7 ± 16.7	116 ± 27.6	100.4 ± 30.4			63.40 ± 6.54	28 ± 5	210 ± 32	149 ± 46
Axial	49.23 _ 5.25	47.75 _ 3.16	85 ± 19	68 ± 14				21.06 ± 11.71	25.20 ± 9.38	48.75 ± 4.39	48.93 ± 4.90			83 ± 19	90 ± 14	67.3 ± 4.7	72.2 ± 6.2	72.0 ± 11.7			135.08 ± 10.55	131 ± 5	55 ± 9	71 ± 15
Marginal	36.68 _ 6.04	38.26 _ 4.87	44 ± 11	55 ± 9	57.93 ± 1.075	93.32 ± 0.825	103.38 ± 1.4	15.89 ± 5.81	26.17 ± 4.49	40.41 ± 1.25	46.35 ± 4.33	76 (36)	96 (30)	64 ± 8	66 ± 12	100.3 ± 10.4	97.1 ± 12.4	89.7 ± 22.3	60 ± 20	80 ± 30	169.58 ± 18.13	62 ± 9	93 ± 32	109 ± 27
Overall	44.63 _ 6.24	46.67 _ 2.80														95.1 ± 10.6	95.1 ± 15.4	87.36± 21.46				73.66 ± 6.33	119.33 ± 23.33	109.66 ± 29.33

heterogeneity: $p \leq 0.001$; I^2= 83 %) [11,13,43] (Table 4, Fig. 2).

3.6.3.4. Intaglio surface. The intaglio surface trueness showed no statistically significant difference to SLA-fabricated zirconia crowns (p = 0.12; SMD: 1.18; 95 % CI: −0.31 to 2.67; heterogeneity: $p \leq 0.001$; I^2= 88 %) [2,11,36,41], and IJP zirconia crowns (p = 0.53; SMD: 0.27; 95 % CI: −0.58 to 1.13; heterogeneity: p = 0.002; I^2= 80 %) [11,13,43]. However, the SM-fabricated restorations showed statistically significantly lower intaglio surface trueness than DLP-fabricated restorations ($p \leq 0.0001$; SMD: 4.58; 95 % CI: 2.77 to 6.40) [7] (Table 4, Fig. 3).

3.6.3.5. External. There was no statistically significant difference in the SM crowns' external trueness compared to SLA zirconia crowns (p = 0.14; SMD: 1.08; 95 % CI: −0.37 to 2.54; heterogeneity: p = 0.003; I2= 83 %) [11,36,41], and IJP-fabricated crowns (p = 0.60; SMD: −0.22; 95 % CI: −1.03 to 0.60; heterogeneity: p = 0.15; I^2= 52 %) [11,13]. While the external trueness of the DLP-fabricated zirconia was statistically significantly better than the SM-fabricated zirconia crown ($p \leq 0.0001$; SMD: 6.93; 95 % CI: 4.29 to 9.56) [11] (Table 4).

3.6.3.6. Overall. The overall trueness of SLA-fabricated zirconia crowns was not statistically significantly different than SM-fabricated zirconia crowns (p = 0.07; SMD: −0.68; 95 % CI: −1.42 to 0.05) [2]. Likewise, the overall trueness was comparable for SM- and IJP-fabricated crowns (p = 0.43; SMD: −0.67; 95 % CI: −2.34 to 0.99; heterogeneity: $p \leq$ 0.001; I^2= 91 %) [13,43] (Table 4).

3.6.4. Precision

The precision was compared in one record that used the SLA printing technique for crown fabrication [2] and one record used the DLP technique compared the marginal precision [2]. The comparison revealed statistically significantly better precision of SLA printed than SM-fabricated crowns at all surfaces as follows: occlusal ($p \leq 0.0001$; MD: −5.48; 95 % CI: −7.14 to −3.82), axial ($p \leq 0.0001$; MD: −11.16; 95 % CI: −14.15 to −8.17), marginal ($p \leq 0.0001$; MD: −7.11; 95 % CI: −9.16 to −5.06), intaglio ($p \leq 0.0001$; MD: −5.04; 95 % CI: −6.66 to −3.42), and the overall precision ($p \leq 0.0001$; MD: −7.72; 95 % CI: −9.48 to −5.96). On the other hand, the marginal precision of premolar crowns revealed no statistically significant difference between SM and DLP-fabricated crowns (p = 0.27; SMD: −0.34; 95 % CI: −0.95 to 0.27) [2] (Table 5).

3.6.5. Fabrication accuracy of different margins

The accuracy of different margins for SM and 3D-printed crowns was comparable. The fabrication accuracy of IJP crown margins was not statistically significantly different compared to SM-fabricated crown margins for the following marginal preparation forms: Chamfer (p = 0.49; MD: 1.92; 95 % CI: −3.54 to 7.38), rounded shoulder (p = 0.06; MD: −3.34; 95 % CI: −6.81 to 0.13), and knife edge preparation (p = 0.99; MD: −0.06; 95 % CI: −7.15 to −7.03) [9] (Table 6).

4. Discussion

For esthetic value comparison, the evidence withdrawn from one good quality RCT, which encountered level II evidence, the clinical outcome pooled from the USPHS criteria of the prospective clinical trial represented level III evidence [71]. Accordingly, long-term well-designed RCTs are strongly recommended to confirm the short-term clinical outcomes and the esthetic value superiority of 3D-printed zirconia over SM-fabricated zirconia crowns.

4.1. Clinical, biological, and esthetic outcomes

Additively manufactured zirconia performed well clinically after short-term observation. There were no signs of biological complications,

Table 4
Trueness comparison of 3D-printed zirconia to milled zirconia, mean and SD (μm).

Author		Abualsaud et al. 2nd [2]		Wang et al. 2019 [39]		Lerner et al. 2021 [7]		Li et al. 2022 [34]		Lüchtenborg et al. 2022 [11]				Ioannidis et al. 2022 [32]		Camargo et al. 2022 [13]			Zhu et al. 2023 [42]		
Restoration		Crown on molar		Crown		Crown		Crown		4 unite FPDs				Veneer		crown			Crown		
No. of specimens		10	10	10	10	10	10	6	6	16	11	16	4	20	20	10	10	10	16	16	16
Fabrication		SM	SLA	SM	SLA	SM	LCM	SM	SLA	SM	SLA	IJP	DLP	SM	DLP	Cerec	SM	IJP	Upcera	Vita	NPJ
Trueness	Occlusal	14.78 _ 2.23	8.77 _ 0.89	41 ± 15	27 ± 17	21.9 (5.8)	50.4 (4.7)									121 ± 38	123 ± 54	127 ± 54	32.4 ± 5.6	25.5 ± 3.8	27.1 ± 5.2
	Axial	20.37 _ 4.49	14.77 _ 2.03													39 ± 16	37 ± 13a	33 ± 7a	49.5 ± 5.8	45.8 ± 5.2	21.0 ± 4.1
	Marginal	16.24 _ 4.62	16.35 _ 0.84	35 ± 7	34 ± 5	12.4 (0.8)	25.6 (3.6)			49 ± 15	70 ± 46	125 ± 109	67 ± 40			100 ± 17	75 ± 19	97 ± 20	32.6 ± 4.9	26.2 ± 4.6	27.9 ± 3.8
	Intaglio	20.29 _ 3.82	23.90 _ 1.60	43 ± 12	38 ± 12	21.2 (4.7)	37.8 (1.4)	13.1 ± 1.5	16.4 ± 2.3	40 ± 8	68 ± 8	53 ± 19	141 ± 7	132 ±73	201 ±79				21.2 ± 4.9	15.6 ± 3.9	17.2 ± 3.9
	External			52 ± 18	53 ± 9			15.6 ± 1.7	17.8 ± 3.3	44 ± 7	73 ± 16	46 ± 17	108 ± 15			81 ± 28	75 ± 18	64 ± 12			
	Overall	18.58 _ 3.03	17.00 _ 0.95											14 ± 4	27 ± 7	100 ± 17a	75 ± 19	97 ± 20	33.93 ± 5.3	28.28 ± 4.38	23.3 ± 4.95

particularly pulpal inflammatory changes or periodontal complications. The crowns fabricated by MEX (3DGP) techniques reported 100 % survival with very high patient satisfaction, the good marginal adaptation and high accuracy play an essential role in the high survival rate and excellent patient satisfaction [32]. These findings were supported by a short-term cohort study [18]. The observation period was one year in the RCT, this very short observation time might not be enough for the clinical complications to occur. Based on the technique and the material properties concluded in this systematic review, 3D-printed zirconia might also have a favorable long-term clinical outcome. Although, high quality, long-term RCTs must confirm this.

A prospective short-term clinical trial by Kao et al. [18] studied the clinical outcomes of SLM zirconia crowns and reported an increase in gingival and plaque indices from 0 to 1 in the first two weeks for 40 % of the cases; this was referred to the differences between the original tooth and the 3D-printed zirconia surface texture, as the rough prosthetic surface is more prone to biofilm formation and bacterial colonization. Moreover, the patients' unstable PL scores might be due to improper oral hygiene measures. Despite the very limited increase in plaque index, zirconia with its unique surface texture and bioinert nature possesses less microbial adhesion potential than base-metal alloys [72]. Huang et al. [73] reported that self-glazed 3D-printed zirconia provides a clinically feasible approach for full mouth rehabilitation with severely worn dentition cases. The prostheses were presumed to be less prone to chipping and to exert less wear on the opposing dentition.

Branco et al. [16] found that both AM and SM zirconia are relatively bioinert, and both techniques of fabrication produced materials with biologically acceptable cytotoxic effects. Zirconia has been used to replace joints and as surgical scaffolds, and has proven not only to be the most biocompatible ceramic [74,75] but the Nano-crystalline material can be modified on the surface to effectively kill pathogenic bacteria [76]. Zandinjad et al. [42] promoted 3D-printed zirconia with 0 % porosities to be as biocompatible as SM zirconia with the same size and orientation of fibroblast cellular attachments, increasing the porosities though it would harm the fibroblasts proliferation and cellular orientations. Variously, Zhang et al. [77] reported a positive impact of porosities on the 3D-printed dental implants, owing to the unique surface structure of 3D-printed zirconia, which facilitates osteoblast proliferation and induces an elongated osteoblast morphology with uniform cell orientation.

Zirconia crowns made via MEX (3DGP) showed a highly esthetic value and a better match to the adjacent teeth than SM zirconia crowns [32] (Table 6). The match of 3D-printed zirconia could be related to the capability of the printing technology to reproduce complex structures with multiple angulated geometry. However, two crowns of both groups needed to be adjusted, and the adjustment of SM zirconia led to the exposure of the white base material that further compromised the esthetic mismatch, necessitating re-characterization of the surface. Unlike additive wet deposited zirconia crowns, which were not stained except for the pits and fissures, post-adjustment characterization was not required. Moreover, the tetracycline heavy stain of natural dentition was perfectly mimicked by the MEX (3DGP) crown [32], the authors considered 3DGP printed zirconia suitable for challenging shade duplication.

4.2. *Internal and marginal fit*

The internal and marginal fit of crowns might be influenced by several factors, overall: the materials used, the type of prepared finish line, and the fabrication technique [78]. The available evidence concluded that no matter what the fabrication technique used, a variable dimension of the marginal gap will always exist. The dentin-luting composite interface is more prone to degradation when a marginal gap of 50–300 μm exists [79]. Moreover, secondary caries might develop even with 30-micron luting gaps, independent of caries risk level [80]. The complexity, length, curvature, and configuration of CAD-CAM

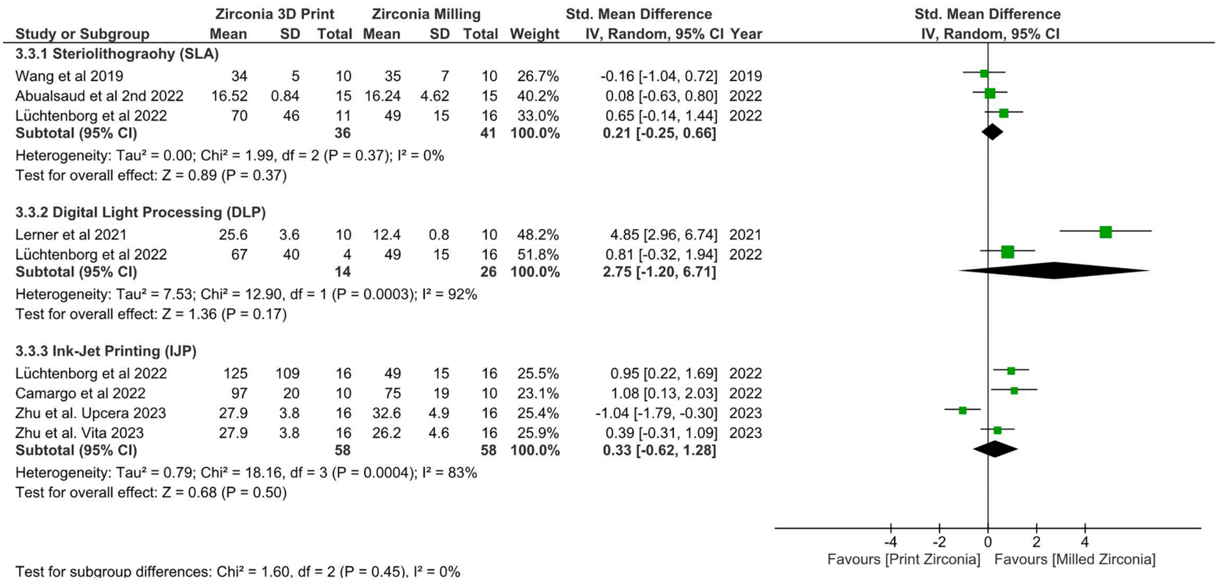

Fig. 2. Forest plot showing the marginal trueness of 3D-printed zirconia crowns compared to milled zirconia crowns.

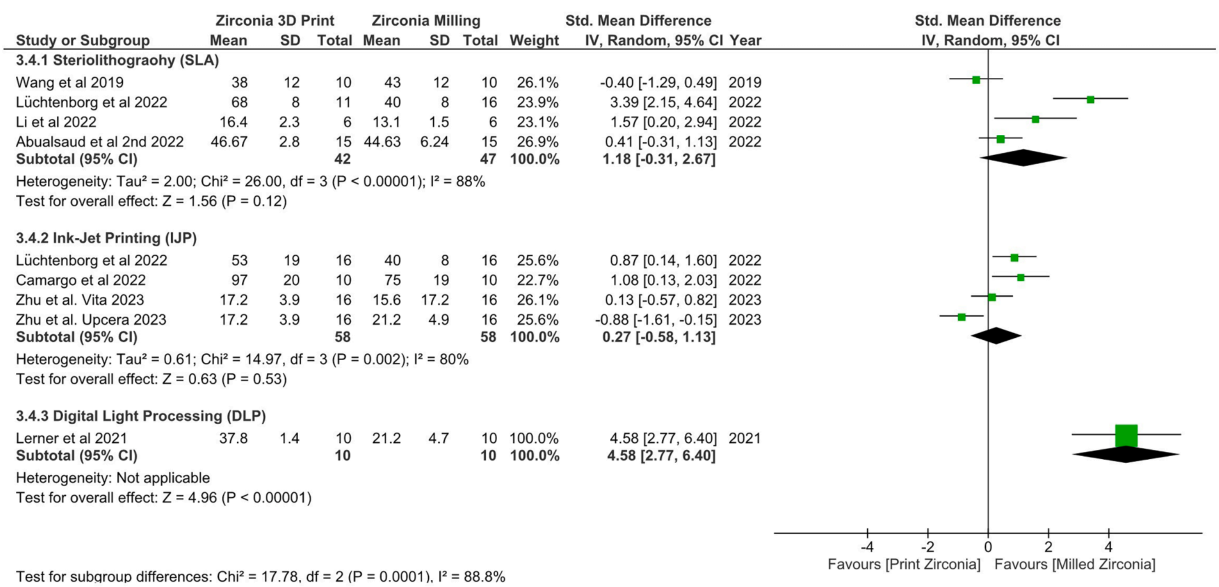

Fig. 3. Forest plot showing the Intaglio trueness of 3D-printed zirconia crowns compared to milled zirconia crowns.

Table 5
Precision of 3D-printed zirconia in comparison to milled zirconia, mean and SD (μm).

Author		Abualsaud et al. [2]		Lerner et al. 2021 [7]	
Restoration		Crown on molar		Crown on premolar	
No. of specimens		10	10	10	10
Fabrication		SM	SLA	SM	DLP
Precision	Occlusal	13.30 ± 2.46	7.82 ± 1.06		
	Axial	20.76 ± 5.62	9.60 ± 1.84		
	Marginal	16.84 ± 3.94	9.73 ± 0.92	4.74 (±0.44)	4.40 (±0.88)
	Intaglio	15.72 ± 2.96	10.68 ± 1.22		
	Overall	17.31 ± 3.39	9.59 ± 0.75		

milled fixed prostheses play a role in the marginal gap and fit [81]. For complex prosthetic structures and constricted restoration angles, the 3D-printed techniques are anticipated to provide better adaptation than zirconia block machining. The evidence in the presented review indicates a smaller occlusal gap of SM than SLA and DLP zirconia crowns, while the incisal overlap and axial gap of laminate veneer were statistically significantly better for DLP fabrication than SM zirconia, this is referred to as the constricted area between labial and lingual sides of the veneer, that bypassed by the CNC machine as an undercut [39]. The axial surfaces showed comparable internal gaps and fit between SLA, DLP crowns, and SM crowns [2,36]. The marginal gap was more remarkable for 3D-printed (DLP and 3DSP) compared to SM zirconia veneers and crowns. While the SLA printing technique revealed a comparable marginal fit to SM crowns [2,36]. All included records evaluating marginal and internal gaps were within the clinically acceptable limits (50–120 μm) [82,83]. In some records, the axial and marginal gap of the crowns was even less than 50 μm [2,37].

Nonetheless, the occlusal veneers studied by Ioannidis et al. [34]

Table 6
Miscellaneous outcomes of some included records.

			Fabrication accuracy, mean and SD (µm)				
			Chamfer		Rounded shoulder	Knife edge	
Li et al. 2021 [9]	Vitro	SM	20.76 ± 2.65		20.38 ± 1.54	22.64 ± 1.81	
		SLA	22.68 ± 4.03		17.04 ± 2.65	22.48 ± 6.00	
			The aesthetic value of zirconia crown with different cores ΔE				
			Fiber-post		Gold cast post-core	No post and core	
Cui et al. 2020 [30]	Clinical	SM	3.39 ± 0.56		5.31 ± 1.52	4.59 ± 1.63	
		IJP	1.78 ± 1.34		3.17 ± 1.99	2.20 ± 1.12	
			Margin quality of three different zirconia crowns				
			Smooth edge/ no defects	Smooth edge with few small separate defects	Several small defects	Rough edge continuous defects	Large defects
Zhu et al. 2023 [42]	In vitro	Vita	5	8	2	0	1
		Upcera	6	8	2	0	0
		NPJ	8	5	0	2	0
			Dimensional Accuracy (µm)				
Wang and Sun 2021 [38]	In-vitro	SM	72 ± 13				
		DLP	41 ± 11				
		SLA	65 ± 6				

reported a vast occlusal gap relative to the other records for both AM and SM zirconia (219 µm and 229 µm respectively); the gap of lost-wax, heat-pressed ceramic was even higher than AM and SM zirconia veneers (405 µm), these values were taken at the central fossa location, the manual block-out and digital bypass of the fossa-undercuts could explain such great gap values. Other records disagree with Ioannidis et al. [34] outcomes, where occlusal veneers reported less than 100 µm internal gap [84,85]. The preparation design of occlusal veneers does affect the marginal adaptation and consequently fracture strength of the restoration [86]. The shoulder marginal preparation, the addition of a central groove, or using a complex veneer design seemed to increase the occlusal discrepancy [87].

There are several ways to evaluate internal gap and marginal fit of crowns and restorations; the most known to the researchers are the cross-sectional method (CSM), silicone replica technique (SRT), triple scan method (TSM), micro-computed tomography (MCT), and optical coherence tomography (OCT). The included records used TSM [2,7,9,11,12,20,34,36,37,41,43], MCT [12,13], SRT [38,40] and CSM methods [39]. Most of the studies used the TSM method, although TSM reliability as an internal and marginal gap measuring method comes second after MCT, CSM, and SRT in the literature. The pooled nominal data in this review showed some variability in the gap ranges from one study to another, this could be related to the fact that different evaluation methods might have different measurements, the different predefined cement space values, in addition to the inevitable other methodological heterogeneities, and overall the operator factor [1].

4.3. Trueness

Trueness is the deviation or approximation of the measured experimental values from the intended or planned values [2,88]. The trueness of SM-fabricated crowns was better in all external, internal, and marginal surfaces than DLP-fabricated crowns [7,11,34]. However, SLA and IJP fabricated specimens showed comparable trueness to SM fabricated specimens in all aspects [40]. The subgroup analysis favored axial surface trueness of SLA and IJP zirconia specimens than SM. However, the occlusal, intaglio, marginal, and external IJP crown trueness were comparable to SM crowns [2,11,36,41].

This systematic review found a correlation between intaglio surface crown adaptation and the marginal trueness for SLA, DLP, IJP, and SM crowns. The trueness results of the margins match those of the intaglio surfaces. There was a non-significant favorability of milling groups in most of the included studies regarding the intaglio and marginal trueness. A mismatch in marginal trueness could lead to a cascade of effects that would impact the axial and occlusal adaptation of the crowns [13].

The CNC milling technology has positive errors at complex surfaces due to limitations imposed by the size and shape of milling tools, as well as the constrained milling angulations, resulting in reduced trueness and accuracy at the pits and fissures of the SM-fabricated restoration, unlike AM technique, the positive errors affect the accuracy of the curved surfaces, such as cusp inclines and height of contour [36].

The data of the Revilla-Leon et al. [8] study was presented as median values; subsequently, they were not included in the meta-analysis. The data in that study revealed higher marginal and internal discrepancies than the SM zirconia, which was beyond the clinically acceptable limit. The outcome of this record does not coincide with all other records included in this review, all other studies reported very comparable discrepancies between AM and SM groups, and in many comparisons, the AM zirconia crowns had even relatively better marginal and internal adaptation than SM zirconia restorations [2,7,11,13,20,34,37,39].

4.4. Precision

The SLA-fabricated zirconia crowns showed higher occlusal, axial, marginal, intaglio, and overall precision than SM-fabricated crowns. However, that was the conclusion of only one record [2]. DLP-fabricated occlusal veneers showed slightly higher marginal precision than SM zirconia but were not statistically significant [34].

To describe fit, precise and true dental crowns or fixed prostheses is always considered accurate; the accuracy in daily language could be defined as the closeness of measured value to a known standard. The ISO, as do the researchers, used the definition mentioned above to describe trueness, and the term "accuracy" is described by the combination of precision and trueness [3,89].

The internal and marginal fit of dental restorations and prostheses is an essential prerequisite for clinical success and survival. An inaccurate dental crown or prosthesis is a misfortune for the operator, as it consumes a lot of time for seating and adjustment and might eventually require remaking. The evidence-based conclusions revealed that the fit of zirconia single crowns and multi-unit FDPs could be considered clinically acceptable in the literature, with internal, marginal, and overall accuracy not exceeding 60 µm. Smaller gap values are associated with the digital workflow [90].

The misfit of zirconia crowns and the marginal discrepancies result in a gap at the crown tooth interface. Regardless that all discrepancies should be filled with luting resin, the large area of luting material exposed to oral and crevicular fluids will be more prone to dissolution leading to microleakage, periodontal complications, secondary caries, hypersensitivity, and pulpal inflammation [82]. Several factors influence the internal and marginal fit of crowns and FPDs such as predefined cement space value, ceramic veneering process, cement material and application professionalism, finish line configuration [91], degree of finish, and accuracy of marginal preparation [92] type of tooth [93], and inadequate or inappropriate teeth preparation [93,94].

The accuracy of 3D-printed zirconia crowns seemed to be affected by the correct build-up angle selection; horizontal printing with the occlusal surface facing the platform was found to produce the most accurate dental restorations [95–98], printing technology used [99], printing devices and materials [11,39], printing layer thickness [11,41,100], manufacturing and physical handling (particularly at green state) [9], debinding process and sintering shrinkage [8,13,41], the density of green body [11], degree of curvature (AM is more error-prone at curved than straight surfaces due to step effect leading to staircase surfaces) [9,13,41], methods used to evaluate the accuracy [1], deviation from the original CAD files, particularly for deep and narrow grooves and pits [7] and overall the delicacy of additive workflow, and the possible lack of technical background [39]. Moreover, the accuracy of 3D-printed restorations might be affected by the handling and removal of supporting structures; to avoid adding supports to the intaglio surface, the occlusal surface should be oriented toward the printing platform [36]. Furthermore, insufficient support of the support pillar during printing might affect the accuracy of the restorations (the supporting bases provide better support but they completely circumvent the occlusal surface) [36]. Manual removal of pillar support can lead to sporadic dot-like positive or negative error [9].

The CNC milling and 3D-printing of zirconia restorations differ not only in the production technology, but in the material composition, and the green body processing. The milling technology utilizes prefabricated dense packed blocks or discs, composed of more than 99 % ZrO_2+Y_2O_3 (+HfO_2); and traces of Al_2O_3; SiO_2; Fe_2O_3; Na_2O [101]. However, the composition of the printable zirconia ceramic is dependent on the printing technology and the manufacturer's preference. For instance, MEX (particularly, robocasting) uses zirconia powder with organic plasticizers and stabilizers, besides Dolapix as a dispersant [16], inkjet writing, which is under the MEX umbrella, utilizes primary ink contains zirconia powder, and sodium carbonate supportive ink, both inks supplied in a mixture of glycol ether and dispersing agent [13], while vat photopolymerization technology utilizes mainly photosensitive resin and zirconia powder [102]. Moreover, SLS uses a zirconia powder with a secondary low-melting binder, however, SLM technology adopts a high-energy deposition and could produce zirconia material from zirconia powder without the need for the secondary binder [103]. As a result, post-fabrication processing varies differently, whereas sintering of the green material is required for milling technology, and debinding and sintering processes are essential for all printing technologies except for SLM, which might require only sintering.

Accordingly, post-sintering volumetric shrinkage of milled zirconia materials is quite predictable, falling within the range of about 23 % [104]. The percentage volumetric shrinkage of 3D-printed specimens cannot be determined with certainty as it depends on several factors, such as the solid loading vol%, the printed design and form, the printing technology utilized, and the quality of the material itself [45,105]. The poor quality commercially available materials are not only expected to result in unpredictable volumetric shrinkage along the X, Y, and Z axes but also might show a catastrophic distortion after sintering [106,107]. Nevertheless, zirconia 3D printing in dentistry has made great progress in the last three years compared to other dental materials. The high-quality zirconia printable materials facilitate their use in multiple clinical studies [18,32,108,109], in contrast to glass-ceramic and resin materials, which have not been approved yet for permanent dental clinical applications [110–112].

The current systematic review found that the internal and marginal fit of 3D-printed (additively manufactured) zirconia depends primarily on the printing technique and restoration type. The crowns fabricated by all techniques (SLA, DLP, IJP, robocasting, NPJ) showed clinically acceptable marginal and internal fit, the differences found among comparisons might be referred to the different predefined cement space values, different printing techniques, and materials in addition to the operator factor. For occlusal and laminate veneers, the huge discrepancies were related to the incisal and occlusal surfaces, mainly at the central fossa and cusp tips. Laminate veneers with incisal overlapping might prefer the 3D-printed technology to avoid bypassing anatomical details of the incisal edge by the CNC milling machine, while occlusal veneers reported comparable occlusal discrepancies for both AM and SM fabrication techniques.

This systematic review retrieved the data that compared SM to AM zirconia materials. The comparison of different printing technologies and printing parameters, the development of high-quality printable ceramics, and the improvement of printing equipment in modern industry should be addressed in future studies. Printing of dental ceramic in general and zirconia ceramic, in particular, has made inroads into dentistry in recent years. Printing technologies continue to develop and soon there might be standard dental materials and standard parameters for the production of high-quality, reliable, and durable dental restorations. Moreover, the presented review was based mainly on laboratory findings, due to shortages in clinical trials as the 3D printing of zirconia was recently introduced to the field of dentistry; the pooled data, however, helped understand the biological and esthetic properties and the accuracy of additively manufactured restorations and prostheses concerning well established subtractive manufactured restorations and prostheses. The available clinical data showed promising short-term clinical outcomes and authentic aesthetic match to natural teeth, promoting the clinical application of 3D-printed zirconia. Long-term RCTs might confirm the clinical and laboratory evidence-based conclusions of this systematic review.

5. Conclusions

Within the limitations of this systematic review, the following could be concluded:

The clinical short-term evaluation revealed a 100 % survival of 3D-printed zirconia crowns. The aesthetic color and contour match of 3D-printed zirconia crowns to adjacent natural teeth was significantly better than milled zirconia crowns.

Both 3D-printing and conventional milling technologies result in full zirconia crowns within the clinically acceptable internal and marginal fit. SM zirconia restorations showed better marginal fit than DLP-fabricated crowns and veneers and 3DSP-fabricated crowns. However, DLP-fabricated laminate veneers showed better axial and incisal fit than SM-fabricated laminate veneers, 3D-printed zirconia laminate veneers with incisal overlapping seemed to be more accurate than CNC-milled veneers, due to the very constricted area at the labial-lingual transition of the incisal edge.

Zirconia 3D printing is a recently introduced technology, the investigated printing materials and techniques and those not included in the current study are still under development. Long-term RCTs for the available materials and techniques are recommended to confirm the clinical applicability of 3D-printed restorations and to gain further evidence on 3D-printed FPDs.

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CRediT authorship contribution statement

Mohammed Alghauli: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Writing – original draft, Writing – review & editing. **Ahmed Yaseen Alqutaibi:** Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing. **Sebastian Wille:** Validation, Writing – review & editing. **Matthias Kern:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that there is no conflict of interest.

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