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NÉMETH ANNA

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című program

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3D PRINTING IN DENTISTRY

Ph.D. Thesis

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Translational Medicine Program

Dental Research Division

SEMMELWEIS UNIVERSITY

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"Just remember, you can't climb the ladder of success with your hands in your pockets."

Arnold Schwarzenegger

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1 LIST OF ABBREVIATIONS

3D	three-dimensional
3DGP	three-dimensional gel deposition/printing
3DSP	three-dimensional slurry printing
ADA	American Dental Association
AI	artificial intelligence
AM	additive manufacturing
AMD	absolute marginal discrepancy
ASTM	American Society for Testing and Materials
bis-GMA	bisphenol A-glycidyl methacrylate
CAD/CAM	computer-aided design/computer-aided manufacturing
CEREC	Chair-side Economical Restoration of Esthetic Ceramic
CI	confidence interval
CLIP	continuous liquid interface production
Co-Cr	cobalt-chrome
DLP	digital light processing
DLS	digital light synthesis
DMLM	direct metal laser melting
DMLS	direct metal laser sintering
FDM	fused deposition modeling
FFF	fused filament fabrication
FPD	fixed partial denture
GRADE	Grades of Recommendation, Assessment, Development, and Evaluation
ID	identifier
IPA	isopropyl alcohol
ISO	International Organization and Standardization
LCD	liquid crystal display
LCM	lithography-based ceramic manufacturing
MD	mean difference

micro-CT	micro-computed tomography
MJ	MultiJet
NMA	network meta-analysis
NPJ	nanoparticle jetting
OCT	optical coherence tomography
PICO	population-intervention-control-outcome
PMMA	polymethyl methacrylate
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
QUADAS	Quality Assessment of Diagnostic Accuracy
QUIN	Quality Assessment For In Vitro Studies
RCT	randomized controlled trial
RMS	root mean square
RPD	removable partial denture
SD	standard deviation
SEM	scanning electron microscope
SLA	stereolithography
SLM	selective laser melting
SLS	selective laser sintering
SM	subtractive manufacturing
STL	standard tessellation language
SUCRA	Surface Under the Cumulative Ranking
UV	ultraviolet

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2 STUDENT PROFILE

2.1 Vision and mission statement, specific goals

My vision is to enhance patient care by integrating high-quality digital prosthodontic treatments supported by 3D printing technology as a daily routine. To achieve this, my mission is to facilitate the adoption of 3D printing into clinical practice and to bridge the gap between advanced technology and everyday dental care. My specific goal is to evaluate the accuracy of 3D printing technology by investigating the dimensional accuracy of dental models and the fit of fixed dental restorations.

2.2 Scientometrics

Number of all publications:	5
Cumulative IF:	21.00
Av IF/publication:	4.20
Ranking (SCImago):	D1, Q1
Number of publications related to the subject of the thesis:	2
Cumulative IF:	9.60
Av IF/publication:	4.80
Ranking (Sci Mago):	D1
Number of citations on Google Scholar:	5
Number of citations on MTMT (independent):	6
H-index:	3

The detailed bibliography of the student can be found on pages 87-88.

2.3 Future plans

My future plan is to apply the expertise I have gained from literature research, meta-analysis writing, and in vitro studies on 3D printing, combined with the skills I have acquired in patient treatment during my prosthodontics specialization by conducting in vivo studies and clinical trials focused on 3D printed dental appliances, especially fixed restorations. This will involve evaluating the clinical performance, accuracy, and long-term outcomes of 3D printed devices in a patient-centered context. With the digital transformation of prosthodontics, not only the technology and the machines but also the materials are entirely new, and more and more of them are available. Therefore, I intend to investigate printable materials to provide valuable insights into optimizing material selection for specific prosthodontic applications and open-system 3D printers to expand the potential of 3D printing in dental practice. My goal is to contribute to integrating 3D printing technology into clinical practice to increase the accuracy and efficiency of prosthodontic treatments.

3 SUMMARY OF THE THESIS

The rapid advancement of additive manufacturing has broadened the availability of several procedures across various materials. However, the accuracy of different printing technologies and materials used are conflicting in the literature. We conducted two meta-analyses to evaluate printing accuracy.

Our first study aimed to determine the accuracy of 3D printed dental models compared to digital reference models, and it was a network meta-analysis. The second study evaluated the fit and trueness of fixed restorations made by additive manufacturing (AM) compared to subtractive manufacturing (SM).

An electronic search was performed across four databases in November 2021 for Study I. After the systematic search, 11 in vitro studies were included. The outcomes were defined in terms of trueness and precision, measured using root mean square (RMS) and absolute mean deviation values (µm) across six subgroups. Additionally, seven different printing technologies were evaluated in the analysis. The QUADAS-2 was used for risk of bias assessment, and the GRADEpro tool for certainty check. Study I found that stereolithography (SLA), digital light processing (DLP), and PolyJet technologies were the most accurate in producing full-arch dental models.

For Study II, the systematic search was made in September 2023, and 57 eligible articles were found. The analysis was subgrouped by material type (metals, ceramics, acrylic resins, and composites). The outcomes were defined as internal fit, marginal fit, and trueness (µm). Additional subgrouping was performed based on the measurement area, including axial, occlusal, and marginal regions. QUIN and GRADEpro tools were used to evaluate the risk of bias and certainty of evidence. The results of Study II supported the use of AM for fabricating fixed dental restorations, as the adaptation showed no statistically significant difference between additively manufactured (AM) and subtractively manufactured (SM) metal and ceramic restorations. In addition, AM acrylic resin restorations showed a better occlusal fit than SM restorations.

We concluded that SLA, DLP, and PolyJet are the most accurate technologies for dental model fabrication and that fixed dental restorations fabricated with AM are valid alternatives in the digital workflow regarding marginal fit, internal fit, and trueness compared to SM.

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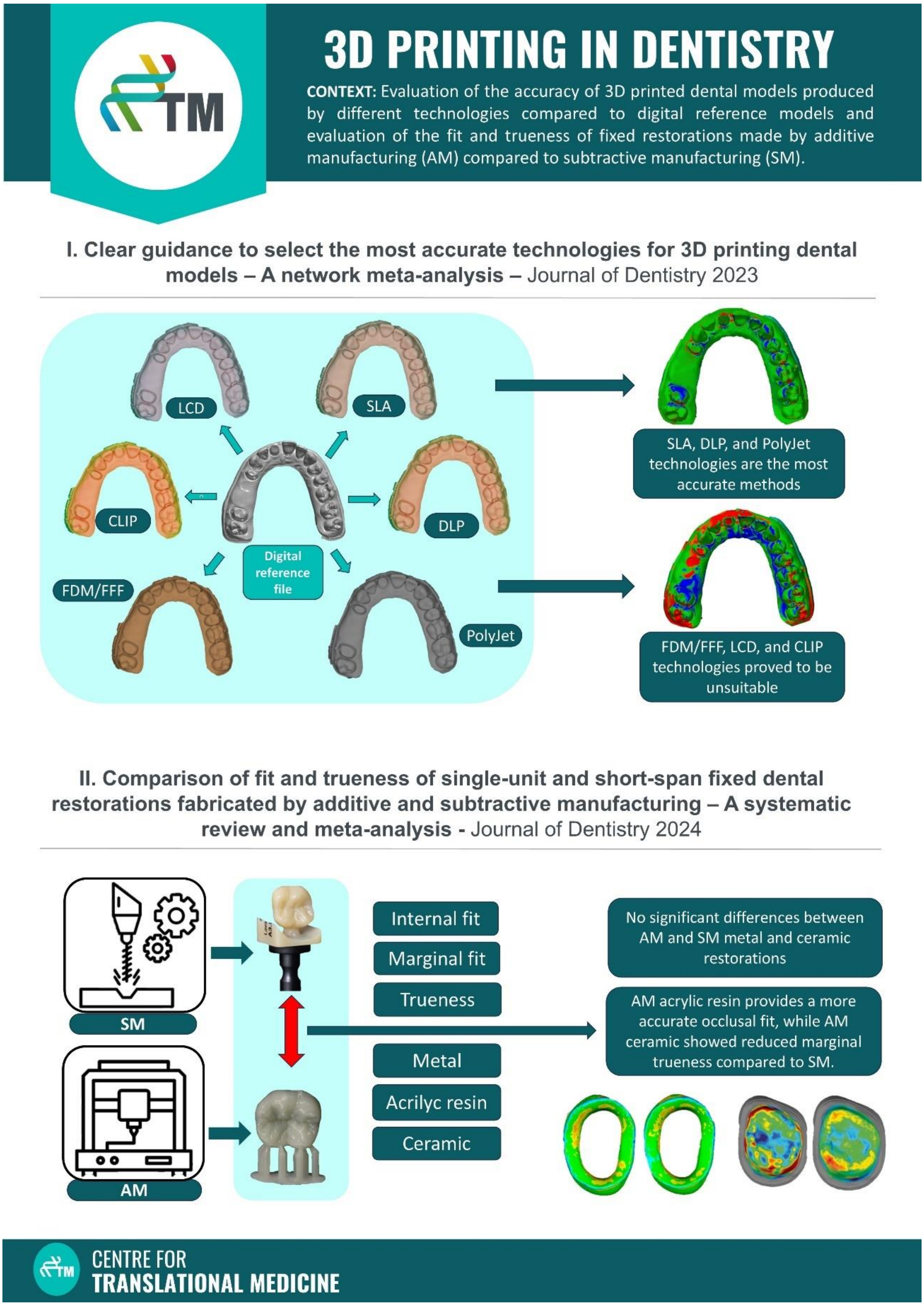
4 GRAPHICAL ABSTRACT



5 INTRODUCTION

5.1 Overview of the topic

5.1.1 What is the topic?

We evaluate the accuracy of 3D printing in producing dental models or fixed dental restorations.

5.1.2 What is the problem to solve?

Digital technologies in dentistry, especially 3D printing, are rapidly developing and offer numerous printing methods and materials. However, the literature presents conflicting findings regarding accuracy. Therefore, we aim to comprehensively evaluate printing accuracy by considering printing technologies and materials.

5.1.3 What is the importance of the topic?

The most significant breakthrough in modern dentistry was the advent of computer-aided design/computer-aided manufacturing (CAD/CAM) technology, which provides accurate restorations and time-saving manufacturing. CAD/CAM includes additive manufacturing, also known as 3D printing or rapid prototyping, a subject of considerable interest in digital dentistry. The increasing number of publications on this subject underscores its growing importance. Various types of 3D printers are available, each differing in mechanism and cost. However, discrepancies persist in the literature regarding the trueness and precision of 3D printing technology. Ensuring high accuracy is especially critical in applications where accuracy directly affects the usability of the final product, such as in dental models for tooth- or implant-retained restorations; any deviation could lead to poorly fitting prosthetics that cannot be used. Moreover, several new printable materials have entered the market, such as different acrylics and ceramic-containing resins, but their accuracy and clinical applicability are unclear. Consequently, further evidence is required to establish the reliability of 3D printing as a replacement for conventional methods.

5.1.4 What would be the impact of our research results?

Our work findings will provide an assessment of the current state of additive manufacturing technology. These analyses will offer practitioners valuable insights into the capabilities and limitations of the technology in clinical practice. Furthermore, by assessing the accuracy of various techniques, practitioners will be better equipped to make decisions when selecting the most appropriate technology and materials for prosthodontic treatments. This, in turn, will enhance treatment planning and optimize patient outcomes.

5.2 Background of the topic

The arrival of CAD/CAM technology has revolutionized modern dentistry by providing precise and time-efficient manufacturing under controlled conditions (1, 2). CAD/CAM comprises three main components: data acquisition, processing, and manufacturing. Manufacturing can be divided into subtractive manufacturing (SM) and additive manufacturing (AM) (3). The representatives of subtractive manufacturing are milling machines, which use rotary tools to carve the blocks or discs into the desired shape. Additive manufacturing, or 3D printing or rapid prototyping, creates objects layer by layer from 3-dimensional data, minimizing material waste and enabling the production of complex designs without geometric constraints (4, 5). International Organization and Standardization (ISO/TC261) and the American Society for Testing and Materials (ASTM) defined additive manufacturing as “a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” (6). Both techniques aim to transform a virtual design into a tangible product. However, there are many differences between 3D printing and milling. While SM has been in use for almost 40 years, 3D printing, introduced in the late 1990s, is rapidly advancing and offers benefits such as reduced material waste, faster production, and the ability to create intricate and hollow objects (7, 8). Moreover, SM may suffer from limitations like tool wear, vibration-induced cracks, and restricted design capabilities due to milling constraints (9, 10).

The enormous development of additive technology has broadened the range of available procedures and machines, spanning various materials, including multiple resins, metals, and ceramics (11-13). Seven categories have been defined by ISO (ISO 17296-2:2015) for AM technologies: vat-polymerization, material extrusion, material jetting, binder jetting, powder-based fusion, sheet lamination, and direct energy deposition (6). The most used techniques are stereolithography (SLA) and digital light processing (DLP), which belong to the vat-polymerization category (14). These techniques can be used in nearly all areas of dentistry, such as dental casts, impression trays, aligners, surgical or preparation guides, and provisional or definite fixed and removable restorations. Due to their high resolution and smooth surface finish, fixed partial dentures (FPD), especially acrylic resin prostheses, are usually made with these techniques. (15). Ceramic fabrication through additive manufacturing (AM) has become a prominent focus in dentistry, leading to the development of various printing technologies. Among these is lithography-based ceramic manufacturing (LCM), a widely recognized SLA-based technique designed for producing high-strength ceramics (16-18). Other category representatives are liquid crystal display-based (LCD) printing, an emerging technology due to their speed, and continuous liquid interface (CLIP) technology (19). For metal fabrication, selective laser sintering (SLS), selective laser melting (SLM), direct metal laser sintering (DMLS), and direct metal laser melting (DMLM) are the main techniques from the powder-based fusion category (20). PolyJet/MultiJet and nanoparticle jetting (NPJ) use inkjet technologies by multiple nozzles to print an object belonging to the material jetting category (21). These are also used in maxillofacial surgery, orthodontics, and restorative dentistry (22). Material extrusion category contains fused deposition modeling (FDM) or fused filament fabrication (FFF) for dental models and impression trays, 3D gel deposition/printing (3DGP), and 3D slurry printing (3DSP) for FPDs (23, 24).

Though 3D printing is already integrated into routine dental practices, a thorough analysis of its accuracy remains essential. Several studies have been published about printing accuracy and the factors influencing the printing process (5, 14, 25). Our research focused on dental models and FPDs, and we observed that the results in the literature are conflicting. Individual studies often have smaller sample sizes compared to systematic reviews and meta-analyses, which are better suited to detect the true impact of an intervention. Combining studies and including various index tests can provide more substantial evidence for practical application. Consequently, we aimed to evaluate the accuracy of additive manufacturing through dental models and fixed dental restorations.

5.3 Importance of 3D printed dental models

The current gold standard is a tangible gypsum cast created from elastomeric impressions using custom or stock trays, with vinyl polysiloxane in custom trays providing the highest accuracy (26-29). CAD/CAM technology advances have introduced digital impressions, virtual designs, and computer-controlled manufacturing, enabling cost-effective workflows and reducing storage needs (30-32). Despite these innovations, physical casts remain essential in various dental fields - orthodontics, prosthodontics, implantology, and oral surgery - for diagnostics, treatment planning, communication, and education (33-35). Dental casts are crucial for accurately recording intermaxillary relationships and prosthodontics tasks like occlusal evaluation, veneering, and contact adjustments (36-39). Moreover, physical casts are still necessary for producing orthodontic appliances, such as trays for bracket bonding and clear aligners (40). Therefore, assessing the accuracy of 3D printed dental casts is an unmet need.

Various types of 3D printers are available, each utilizing different techniques and manufacturing parameters. How can we choose the most suitable printer for our needs? One of the most critical factors with every new technology is accuracy. Numerous studies have assessed the accuracy of 3D printed dental models, but their findings often conflict. For instance, Kim et al. compared four printing techniques and concluded that PolyJet and digital light processing (DLP) technologies were more precise than stereolithography (SLA) and fused filament fabrication (FFF), with PolyJet demonstrating the highest accuracy (41). Conversely, another study evaluating DLP and PolyJet technologies found that DLP models exhibited better trueness and significantly higher precision than PolyJet models (42). Similarly, Maura et al. examined SLA and DLP printers, reporting that SLA offered superior trueness and precision compared to DLP (43). These inconsistencies highlight the need for a comprehensive analysis. A quantitative synthesis can formally assess these discrepancies and identify their underlying causes. While a systematic review addressing this topic was published in 2020, it provided only qualitative analysis (44). Since then, additional studies have emerged. Incorporating these newer studies into a network meta-analysis could enhance the reliability and precision of conclusions regarding the accuracy of 3D printed dental models manufactured with different technologies.

5.4 Fixed partial dentures fabricated with CAD/CAM

The internal and marginal fit of indirect restorations is critical for their clinical success and long-term durability (45). As the marginal gap increases, more cement becomes exposed, raising the risk of cement dissolution. This exposure weakens the seal, fosters bacterial accumulation, and increases the likelihood of caries, periodontal inflammation, fractures, and marginal discoloration (45, 46). According to the American Dental Association (ADA) N.8 specification, zinc phosphate luting cement thickness should not exceed 25 µm for fine particle size (Type I) or 40 µm for medium particle size (Type II) agents (47). However, based on a widely cited study by McLean and Von Fraunhofer, a marginal fit of up to 120 µm is clinically acceptable. While there is no universal consensus on the ideal acceptable marginal gap, it remains the reference (48).

Numerous studies have been published comparing subtractively and additively fabricated short-span fixed partial dentures (FPDs) regarding internal fit, marginal fit, and accuracy; however, the results are opposing (49-52). Due to these disagreeing findings in the literature, a thorough analysis of the fit of 3D printed FPDs is needed to resolve these discrepancies. Several reviews have been published recently, including meta-analyses (14, 23, 53-58). Al Wadei et al. concluded that methacrylate-based 3D printed provisional prostheses offer superior marginal fit and internal adaptation compared to milled PMMA (polymethyl methacrylate) provisional restorations (57). Regarding dental ceramics, Al Hamad et al. found that AM provided lower accuracy than SM, especially in the marginal and occlusal areas (58). A meta-analysis also summarized that milled zirconia restorations had a better marginal fit than printed restorations. Still, both fabrication techniques generally resulted within the clinically acceptable adaptation limit (23). Regarding metal fabrication, additively manufactured removable partial dentures seem to perform within clinical acceptability, however the fit and trueness of metal fixed restorations is unclear (59, 60). Nevertheless, there is a need for a comprehensive analysis of the fit and trueness of additively manufactured FPDs to address and resolve the ongoing controversies in the literature. An update on the current state of research is necessary to understand the strengths and limitations of AM in terms of accuracy across various materials, such as different polymers, ceramics, and metals.

6 OBJECTIVES

6.1 Study I – Clear guidance to select the most accurate technologies for 3D printing dental models – A network meta-analysis

We aimed to investigate the accuracy of 3D printed dental models fabricated with different technologies compared to digital reference models by reviewing the existing literature. In addition, the accuracy results were compared with the clinical acceptability threshold values of 120 μm for prosthodontic and 250 μm for orthodontic applications.

6.2 Study II – Comparison of fit and trueness of fixed dental restorations fabricated by additive and subtractive manufacturing – Systematic review and meta-analysis

Our aim was to compare the fit and trueness of additive manufacturing to subtractive technology on single-unit and short-span fixed dental restorations while considering the materials used.

7 METHODS

7.1 Study I

7.1.1 Literature search and eligibility criteria

Our systematic review and meta-analysis was structured according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Reporting Checklist (PRISMA) and the Cochrane Handbook (61, 62). The review protocol was registered in PROSPERO under the registration number CRD42021285863.

Based on the population-intervention-control-outcome (PICO) principle, the review question was the following: Do dental models (P) manufactured using different 3D printing technologies (I) provide the same accuracy (O) as the initial digital model (C)? Articles investigating partial dental models or complete mandibles with ramus and condyles and accuracy studies with coordinate measuring machines or calipers were excluded. An electronic search was performed across four databases: MEDLINE (via PubMed), CENTRAL (The Cochrane Central Register of Controlled Trials), Embase, and Web of Science on the 3rd of November 2021. A manual search was also performed on the reference lists of previous reviews and included records. The search queries are detailed in the original publication (63).

7.1.2 Study selection and data extraction

The following data were collected from each eligible article for Study I: title, first author, year of publication, 3D printers with the technology used, layer thickness, model design, sample size, postprocessing method, reference scanner, assessment software, outcomes (trueness, precision).

All relevant studies were collected using a reference manager software (EndNote X9; Clarivate Analytics, Philadelphia, PA, USA). After removing the duplicates, two investigators independently screened the publications based on their titles, abstracts, and full texts, and a third investigator resolved disagreements. Data extraction was performed individually by two investigators using a standardized data collection sheet, and a third independent investigator resolved disagreements.

7.1.3 Quality assessment

Potential sources of bias and applicability concerns in the included studies were evaluated using the Quality Assessment of Diagnostic Accuracy-2 (QUADAS-2) tool. Each study was classified as high risk, low risk, or unclear risk across four domains: model selection, index test, reference standard, and flow and timing (64). To assess the certainty of evidence, the GRADEpro tool was used by the "Grades of Recommendation, Assessment, Development, and Evaluation (GRADE)" considering the following domains: risk of bias, inconsistency, indirectness, and imprecision (65, 66).

7.1.4 Data synthesis and analysis

The accuracy of 3D printed models was evaluated in terms of trueness and precision. As defined by the International Organization for Standardization (ISO 5725-1), trueness is the closeness between the mean of test results and the true reference value, while precision indicates the closeness between individual test results (67).

Three outcomes were extracted from the articles: trueness (RMS), absolute mean deviation, and precision (RMS). Six subgroups were defined and analyzed separately to address clinical heterogeneity due to varying printing parameters, with the overall results synthesized from these subgroup analyses. Network characteristic tables summarized key statistics for each subgroup. A Bayesian Network Meta-Analysis method was employed for pairwise meta-analyses and network meta-analyses (NMA) using a random-effects model with a 95% confidence level (68, 69). All measurements were conducted in micrometers, with the initial standard tessellation language (STL) file as the reference. When articles lacked mean and standard deviation (SD) values for reference scans, literature values were used, setting trueness at 0 ± 10 µm and precision at 15 ± 10 µm to assess 3D printing performance conservatively (70). Statistical analyses were performed using R software (ver. 4.1.3) with the BUGSnet package (71). Consistency was evaluated through node-splitting analysis by comparing consistency and inconsistency models to visualize data heterogeneity.

Subgroup analysis was conducted based on factors impacting printing accuracy, including layer thickness (≤50 µm or >50 µm), model design (horseshoe, cross-arch plate, full model), measurement level (arch or tooth), and calculation method (RMS or absolute mean deviation). Based on layer thickness, models were divided into two ranges, one for models with a layer thickness of 50 µm or less and one for models with a layer thickness of over 50 µm (≤50 µm or >50 µm) because these are the two most commonly used values (72-74, 75). The second parameter is model design. Shin et al. and Camardella et al. found that the accuracy was significantly higher in models with a cross-arch plate design than in the horseshoe-shaped models (76, 77). Considering this background, the different model designs were assessed separately. Only horseshoe-shaped models were included in this quantitative analysis because this type of model had enough data for statistical analysis. We distinguished between accuracy values that examined the accuracy of the full-arch model and those that evaluated smaller segments. Measuring level as the third influencing factor was divided into „arch level" and „tooth level." Finally, we separately assessed the publications according to the measuring method and expressed value. The CAD software making the superimposition and comparison between the digital reference file and the printed model's digital file can express the discrepancy with different metrics, absolute mean deviation, or root mean square (RMS). Both formulas express the deviation between the two files in micrometer; however, we can't combine them because of different calculation methods. In recent articles, RMS values have been used to measure accuracy because they magnify differences and provide more information about 3-dimensional deviation. Therefore, the articles were evaluated separately in subgroups named „RMS" and „Deviation".

7.2 Study II

7.2.1 Literature search and eligibility criteria

The protocol for this study was registered in PROSPERO as a meta-analysis and systematic review under registration number CRD42022323090. The manuscript was prepared following the PRISMA guidelines and the Cochrane Handbook (61, 62).

Based on the PICO principle, the review question for Study II was: What is the accuracy (O) of fixed dental restorations (P) made by additive manufacturing (I) compared to subtractive manufacturing (C)? Articles measuring prostheses fabricated from milled or printed castable patterns and studies using coordinate measuring machines were excluded. An electronic search was conducted in four databases—MEDLINE (via PubMed), CENTRAL (The Cochrane Central Register of Controlled Trials), Embase, and Web of Science—using a predefined search strategy on September 6, 2023. Additionally, a manual search was carried out by reviewing the reference lists of previous reviews and included studies. The exact search keys are detailed in the original publication (67).

7.2.2 Study selection and data extraction

The following data were collected from each eligible article for Study II: title, first author, year of publication, 3D printers with the technology and material used, milling machines with the material used, sample size, examination method, and outcomes as marginal fit, internal fit, and trueness.

The relevant studies were compiled using reference management software (EndNote X9; Clarivate Analytics, Philadelphia, PA, USA). After removing duplicates, two investigators independently screened the titles, abstracts, and full texts of the publications, with a third investigator resolving any discrepancies. Data extraction was conducted independently by two investigators using a standardized data collection form, and a third independent investigator resolved disagreements.

7.2.3 Quality assessment

The potential sources of bias and applicability concerns in the included studies were evaluated using the Quality Assessment for In Vitro Studies (QUIN Tool) *(68).* Each article was assessed against 12 criteria, with scores assigned as follows: adequately specified = 2 points, inadequately specified = 1 point, not specified = 0 points, and not applicable = exclusion. The individual scores were summed to calculate a total score, which was then converted into a percentage for the specific in vitro study. Using a defined formula, these percentages were applied to classify studies as high, medium, or low risk (68). To assess the certainty of evidence, the GRADEpro tool was used (65, 66).

7.2.4 Data synthesis and analysis

The accuracy of restorations was expressed using the terminology of Holmes et al.: internal fit/gap (µm) as the perpendicular distance from the internal surface to the axial wall, marginal fit/gap (µm) as the distance from the restoration margin to the preparation margin, and absolute marginal discrepancy (µm), combining the marginal gap and extension errors (69). Trueness (µm) was defined as the closeness between the mean of test results and the reference value (ISO 5725-1) (70). Subgrouping was based on the material used (metals, acrylic resins, ceramics, and composites), and further subgrouping considered the measurement area (axial, occlusal, and marginal).

Given the substantial between-study heterogeneity, a random-effects model was used to pool effect sizes. All outcomes were continuous, so the difference between the mean differences (MD) was used for the effect size measure with a 95% confidence interval (CI). Sample size, mean, and standard deviation (SD) were extracted for each group to calculate the study MDs and pooled MDs. Results were expressed as subtractive group minus additive group values. To account for the use of multiple data points from the same articles—where a single study contributed more than one data point in each forest plot—a multilevel meta-analytic approach was employed to produce conservative confidence interval (CI) estimates. This approach required the assumption that effects within the same study were more closely related than effects from different studies. Consequently, a three-level model was implemented using study ID as a random factor, per Viechtbauer's method (71). Results were significant if the pooled CI excluded the null value. Forest plots summarized outcomes, and prediction intervals were reported when sufficiently large studies with low heterogeneity were available. Heterogeneity was measured using Higgins & Thompson's I^2 statistics (72). Publication bias was assessed via Funnel plots and Egger's test for MD effect size, with a bias suspected if $p < 0.10$ (73). All analyses were performed using R (R Core Team 2023, v4.3.0) with the meta (Schwarzer 2023, v6.2.1) and metafor (Viechtbauer 2023, v4.2.0) packages (74-76).

8 RESULTS

8.1 Study I: Clear guidance to select the most accurate technologies for 3D printing dental models – A network meta-analysis

8.1.1 Search and selection, characteristics of the included studies

The initial search identified 20,024 studies, with 16,303 remaining after duplicate removal. Following the title and abstract screening, 104 papers were chosen for full-text reading. One additional publication was found through manual searching. Eventually, 11 publications met the criteria and were included in the network meta-analysis (63). The PRISMA flowchart illustrating the study selection process is shown in **Figure 1.**

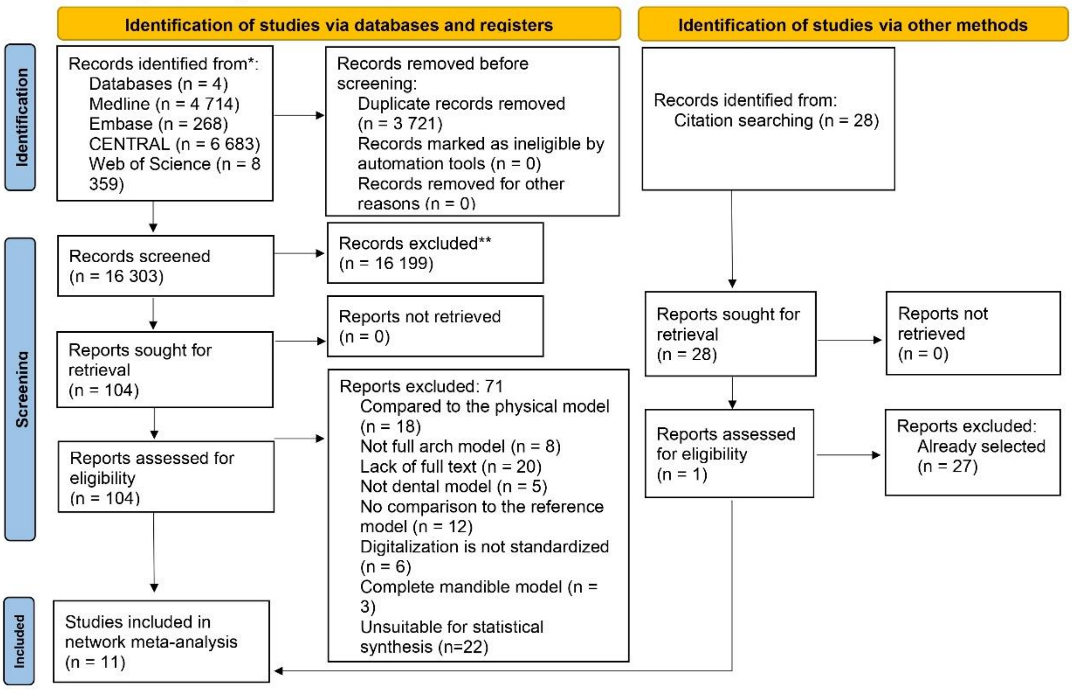


Figure 1. *PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses Reporting Checklist) Flow Diagram of the screening and selection process for Study I (63)*

Characteristics of the included studies for the systematic review and meta-analysis are detailed in **Table 1**.

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Table 1. Main characteristics of the included studies for Study I (63)

Author (year)	3D printing technology	3D printer details	Layer thickness (μm)	Model design	Post-processing method	Sample size	Reference scanner	Assessment software	Outcome
Emir et al. 2021 (77)	SLA	Ultra SP Ortho, (EnvisionTEC)	50	horseshoe shaped mandibular arch model with 6 abutments to resemble prepared teeth	2 min (isopropanol alcohol bath); 3 min postcure	10	ATOS Core 200 5M, GOM GmbH, Braunschweig, Germany	Geomagic Control, 3D Systems	trueness, precision
	DLP	Perfactory Vida (EnvisionTEC)	50		2 min (isopropanol alcohol bath); 3 min postcure	10			
	PolyJet	Objet30 Prime, Stratasys Ltd.	16-28		2 min (waterjet)	10			
Abduo et al. 2019 (78)	MJ	ProJet, 3510 DP Pro, 3D systems, Rock Hill, SC, USA	< 50	maxillary typodont with 16 teeth	unclear	10	D-640 scanner, 3Shape Dental System, Copenhagen, Denmark	Geomagic Studio, 3D systems, Rock Hill, SC, USA	trueness, precision
Shin et al. 2020 (79)	DLP	Phrozen Shuffle, Phrozen, Hsinchu, Taiwan	100	maxillary tooth dentiform U-shaped model	washed with 90% isopropyl alcohol (Formwasher, Formlabs, Somerville, MA, USA), polymerized using ultraviolet post-curing unit (CureM D102, Sona Global, Seoul, Korea)	40	Identica T500, Medit, Seoul, Korea	Geomagic Control X, 3D Systems, Rock Hill, SC, USA	trueness, precision
Giudice et al. 2021 (80)	LCD	Elegoo Mars Pro (Shenzhen Elegoo Technology Co., Shenzhen, China)	50, 100	horseshoe shaped maxillary dental typodont model	2-propanol baths (10 min each), air drying (30 s), curing (15 min): Elegoo Mercury Plus machine (Shenzhen Elegoo Technology Co.)	20	T710 desktop scanner (MEDIT, Seoul, Korea)	Geomagic Control X software (3D Sistems, version 2018.1.1, 3D Systems, USA)	trueness, precision

	LCD	Anycubic Photon S (Anycubic Technology Co., Shenzhen, China)	50, 100		2-propanol baths (10 min each), air drying (30 s), curing (15 min): Anycubic Wash & Cure Machine (Anycubic Technology Co.)	20			
	SLA	Vector 3SP (EnvisionTEC, Dearborn, MI)	50, 100		2-propanol baths (10 min each), air drying (30 s), curing (10 min): Ultra/Xtrem UV Light Curing Apparatus (EnvisionTEC, Dearborn, MI)	20			
Emir et al. 2021 (42)	DLP	Perfactory Vida (EnvisionTEC Inc., Dearborn, Michigan, US)	50	horse-shoe shaped mandibular arch model with 6 abutments to resemble prepared teeth	soaked into isopropyl alcohol (2 min), waited for post-cure (3 min)	10	ATOS Core 200 5M (GOM GmbH, Braunschweig, Germany)	Geomagic Control (3D Systems, Rock Hill, SC, USA)	trueness, precision
	PolyJet	Objet30 Orthodesk (Stratasys Ltd., Eden Prairie, Minn, and Rehovot, Israel)	28		cleaned with a waterjet (2 min) and no additional post-cure process	10			
Kim et al. 2018 (41)	SLA	ZENITH (Dentis, Daegu, Korea)	50	pair of typodont horse-shoe shaped models with half-ball markers	unclear	5	Identica Hybrid (MEDIT, Seoul, Korea)	Geomagic Control (3D Systems, Rock Hill, SC)	trueness, precision
	DLP	M-One (MAKEX Technology, Zhejiang, China)	75			5			
	FFF	Cubicon 3DP-110F (HyVISION System, Sungnam City, Korea)	100			5			

	PolyJet	Objet Eden 260VS; Stratasys, Eden Prairie, Minn	16			5			
Choi et al. 2019 (81)	SLA	ZENITH U (Dentis, Daegu, Korea)	50	horseshoe shaped maxillary typodont model including complete dentition and four prepared teeth	cleaned with ethanol (10 min) and post-cured (10 min) in an UV curing machine (DIO PROBO Cure, Dentis, DIO, Busan, Korea)	10	Identica Blue (Medit, Seoul, Korea)	Geomagic Control X (3D systems, Rock Hill, SC, USA	trueness
	DLP	DIO PROBO (DIO, Busan, Korea)	50		cleaned with ethanol (10 min) and post-cured (10 min) in an UV curing machine (DIO PROBO Cure, Dentis, DIO, Busan, Korea)	10			
Burde et al. 2017 (82)	FDM	Creatr HS (Leapfrog, Alphen aan den Rijn, Netherlands)	100	mandibular and maxillary horse-shoe shaped model	No post-processing was required	20	InEos X5 (Sirona Gmbh, Bensheim, Germany)	Geomagic Qualify 13 (Geomagic, Morrisville, USA)	trueness
	FDM	RepRap FDM printer based on a PrusaI3 kit	100		No post-processing was required	20			
	SLA	Form 1+ (Formlabs Gmbh, Berlin, Germany)	25		cleaning the excess resin with isopropyl alcohol, a 20-minute exposure per model to UV light	20			
	DLS/CLIP	M2 Printer (Carbon)	75	horseshoe shaped	unclear	20	Ortho Insight 3D laser scanner	Geomagic Control	trueness

Akyalcin et al. 2021 (83)	DLP	Juell 3D Flash OC (Park Dental Research, NY)	100	maxillary and mandibular dental arch models		20	(Motionview Software, Hixson, Tenn)	(version 2015.3.1, 3D Systems, Rock Hill, SC, USA)	
	SLA	Form 2 (Formlabs Inc., Somerville, Mass)	100			20			
	PolyJet	Objet Eden 260VS (Stratasys, Eden Prairie, Minn)	16			20			
Zhang et al. 2019 (84)	DLP	EvoDent (UnionTec, Shanghai, China)	50, 100	horseshoe shaped maxillary and mandibular dental arch models	unclear	2	D2000 desktop model scanner (3Shape, Copenhagen, Denmark)	Geomagic Qualify 12.0 (3D Systems, Rock Hill, SC, USA)	trueness
	DLP	EncaDent (Encashape, WuXi, China)	20, 30, 50, 100			4			
	DLP	Vida HD (EnvisionTec, Dearborn, MI, USA)	50, 100			2			
	SLA	Form 2 (Formlabs, Somerville, MA, USA)	25, 50, 100			3			
Mangano al. 2020 (85)	DLP	Sheraprint 40 (Shera, Lemforde, Germany)	50- 100	horseshoe shaped maxillary model	washed as prescribed by the manufacturer and then cured or polymerized	3	Freedom UHD desktop scanner	engineering software program (Studio 2012)	trueness
	DLP	Solflex 350 (Voco, Cuxhaven, Germany)	25- 200			3			
	SLA	Form 2 (Formlabs,	25- 50- 100			3			

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		Somerville MA, USA)							
	DLP	Vida HD (Envisiontec, Gladbeck, Germany)	25- 150			3			
	SLA	XFAB 2000 (DWS Systems, Thiene, Vicenzam Italy)	60- 100			3			
	DLP	MOONRAY D75 (Sprintray Inc., LA, CA, USA)	20- 50- 100			3			

AM: additive manufacturing; CLIP: continuous liquid interface production; DLP: digital light processing; DLS: digital light synthesis; FDM: fused deposition modeling; FFF: fused filament fabrication; IPA: isopropyl alcohol; LCD: liquid crystal display; MJ: MultiJet; SLA: stereolithography; UV: ultraviolet

8.1.2 Results of the quantitative analysis

Results are presented according to six subgroups: Trueness RMS arch level 0–50 µm, Trueness RMS arch level >50 µm, Trueness RMS tooth level 0–50 µm, Precision RMS arch level 0–50 µm, Precision RMS arch level >50 µm, and Trueness Deviation arch level >50 µm.

8.1.2.1 Trueness RMS arch level 0–50 µm

Seven studies were analyzed in this subgroup, encompassing five 3D printing technologies: stereolithography (SLA), digital light processing (DLP), PolyJet, MultiJet (MJ), and LCD technology (41, 42, 77, 78, 80-82). **Figure 2/A** displays the league heat plot, showing the mean difference of trueness: PolyJet (76.9 µm), DLP (81.8 µm), SLA (106.7 µm), MJ (138.7 µm), and LCD (200.2 µm), all significantly different from the reference. The forest plot (**Figure 2/B**) highlights these differences, where the null effect line represents the value of the control group set at zero. The ranking of the interventions is shown on the SUCRA (Surface Under the Cumulative Ranking) plot **(Figure 2/C**), showing that PolyJet technology has the highest likelihood of being in the top or one of the top ranks. Secondly, DLP, and thirdly, SLA is the most likely to reach one of the top ranks.

Clinical tolerance levels were established from the literature. A 250 µm accuracy threshold is necessary for orthodontic applications to ensure an aligner exerts the proper force on the teeth (83). For prosthodontic use, a 120 µm limit is set as the maximum acceptable marginal gap for restorations (86). This subgroup's results indicated that all evaluated technologies fell within the orthodontic tolerance range; however, only PolyJet, DLP, and SLA met the clinical requirements for prosthodontics.

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A)

	control	PolyJet	DLP	SLA	MJ	LCD
control		**76.87** (9.38, 142.32)	**81.77** (18.54, 144.76)	**106.73** (54.41, 160.00)	**138.65** (18.00, 260.89)	**200.19** (92.12, 308.35)
PolyJet	**-76.87** (-142.32, -9.38)		4.90 (-68.33, 78.19)	29.86 (-41.85, 98.98)	61.78 (-75.17, 200.64)	123.32 (-0.37, 246.18)
DLP	**-81.77** (-144.76, -18.54)	-4.90 (-78.19, 68.33)		24.97 (-46.71, 93.72)	56.88 (-79.29, 193.34)	118.43 (-3.82, 238.66)
SLA	**-106.73** (-160.00, -54.41)	29.86 (-98.98, 41.85)	-24.97 (-93.72, 46.71)		31.92 (-99.11, 164.81)	93.46 (-18.00, 199.32)
MJ	**-138.65** (-260.89, -18.00,)	-61.78 (-200.64, 75.17)	-56.88 (-193.34, 79.29)	31.92 (-164.81, 99.11)		61.54 (-103.37, 225.42)
LCD	**-200.19** (-308.35, -92.12)	-123.32 (-246.18, 0.37)	-118.43 (-238.66, 3.82)	-93.46 (-199.32, 18.00)	-61.54 (-225.42, 103.37)	

B)

C)

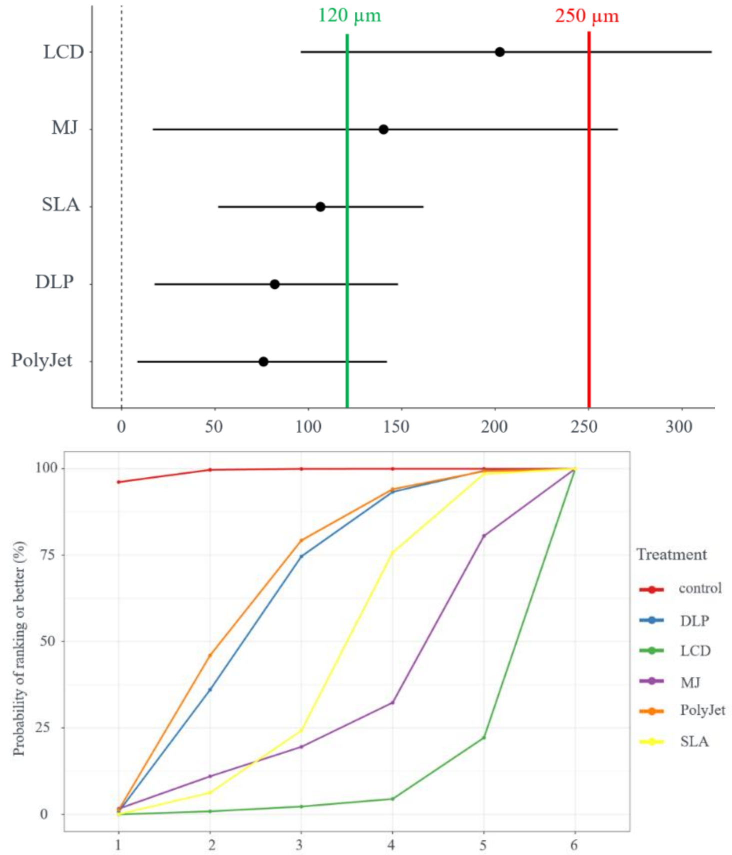

Figure 2. *The mean difference of RMS trueness at arch level using layer thickness 0-50 µm*

A) *League-heat plot contains mean difference with a 95% confidence interval for all possible treatment pairs.* ***B)*** *The forest plot shows the first line of the league-heat plot and highlights the 120 µm and 250 µm tolerance thresholds for prosthodontic and orthodontic* *applicability.* ***C)*** *The SUCRA (Surface Under the Cumulative Ranking) plot, ranging from 0 to 100%, ranks the hierarchy of treatments. SUCRA plot. PolyJet technology is most likely to be at the top or one of the top ranks. Secondly, DLP, and thirdly, SLA is the most likely to reach one of the top ranks (63) DLP= digital light processing; SLA= stereolithography; MJ= MultiJet; LCD= liquid crystal display*

8.1.2.2 Trueness RMS arch level over 50 µm

Four studies assessed four technologies within this subgroup (41, 79, 80, 82). No significant differences were noted between the reference and index tests. FDM/FFF, SLA, and DLP technologies achieved mean trueness differences of 196.8 µm, 209.2 µm, and 204.1 µm, respectively, meeting clinical standards for orthodontic use. However, none of the tested technologies met the 120 µm threshold required for prosthodontic applications (**Figure 3**).

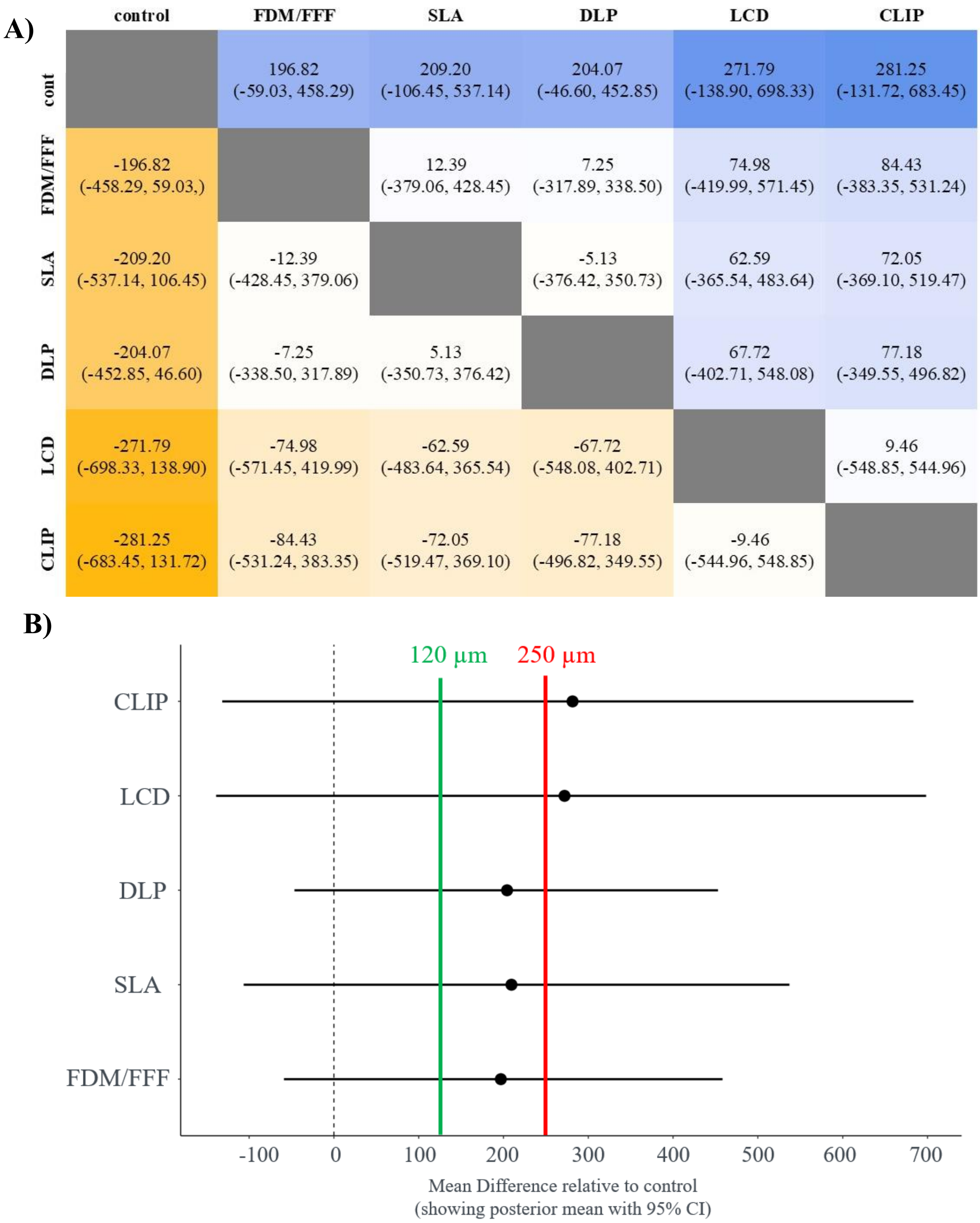

Figure 3. *Mean difference of RMS trueness at arch level using layer thickness over 50 µm*

A) *League-heat plot contains mean difference with 95% confidence interval for all possible treatment pairs.* ***B)*** *The forest plot shows the first line of the league-heat plot and highlights the 120 µm and 250 µm tolerance thresholds for prosthodontic and orthodontic applicability (63). FDM/FFF= fused deposition modeling/fused filament fabrication; SLA= stereolithography; DLP= digital light processing; LCD= liquid crystal display; CLIP=continuous liquid interface production*

8.1.2.3 Precision RMS arch level 0–50 µm and over 50 µm

Six interventions' repeatability across seven studies indicated low precision values (41, 42, 77-81). Among technologies using a layer thickness of 0–50 µm, PolyJet showed the highest precision with a mean difference of 31.3 µm, followed closely by DLP at 34.2 µm and SLA at 39.9 µm. LCD and MJ presented larger mean differences of 79.2 µm and 109.2 µm, respectively (**Figure 4**). For layer thicknesses exceeding 50 µm, SLA exhibited the best precision at 23.5 µm, followed by DLP at 57.5 µm, FDM/FFF at 74.4 µm, and LCD at 82.5 µm (**Figure 5**).

A)

	control	PolyJet	DLP	SLA	LCD	MJ
control		31.25 (-9.47, 69.87)	34.21 (-5.50, 74.84)	**39.89** (9.39, 86.80)	**79.21** (15.58, 155.20)	**109.21** (39.12, 183.76)
PolyJet	-31.25 (-69.87, 9.47)		2.96 (-40.01, 49.82)	8.64 (-29.33, 64.42)	47.96 (-19.26, 128.75)	77.96 (-5.38, 164.81)
DLP	-34.21 (-74.84, 5.50)	-2.96 (-49.82, 40.01)		5.68 (-33.09, 59.17)	45.00 (-25.38, 125.46)	75.00 (-11.70, 157.80)
SLA	**-39.89** (-86.80, -9.39)	-8.64 (-64.42, 29.33)	-5.68 (-59.17, 33.09)		39.32 (-32.03, 104.40)	69.32 (-21.32, 143.85)
LCD	**-79.21** (-155.20, -15.58)	-47.96 (-128.75, 19.26)	-45.00 (-125.46, 25.38)	-39.32 (-104.40, 32.03)		30.00 (-73.39, 125.41)
MJ	**-109.21** (-183.76, -39.12)	-77.96 (-164.81, 5.38)	-75.00 (-157.80, 11.70)	-69.32 (-143.85, 21.32)	-30.00 (-125.41, 73.39)	

B)

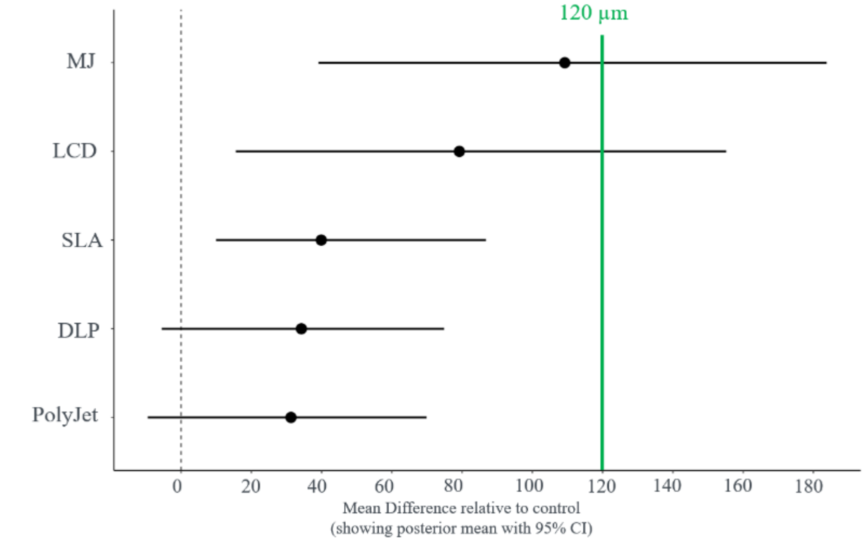

Figure 4. *Mean difference of RMS precision at arch level using layer thickness 0-50 µm **A)** League-heat plot contains mean difference with 95% confidence interval for all possible treatment pairs. **B)** The forest plot shows the first line of the league-heat plot and highlights the 120 µm and 250 µm tolerance thresholds for prosthodontic and orthodontic*

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applicability (63). DLP= digital light processing; SLA= stereolithography; LCD= liquid crystal display; MJ= MultiJet

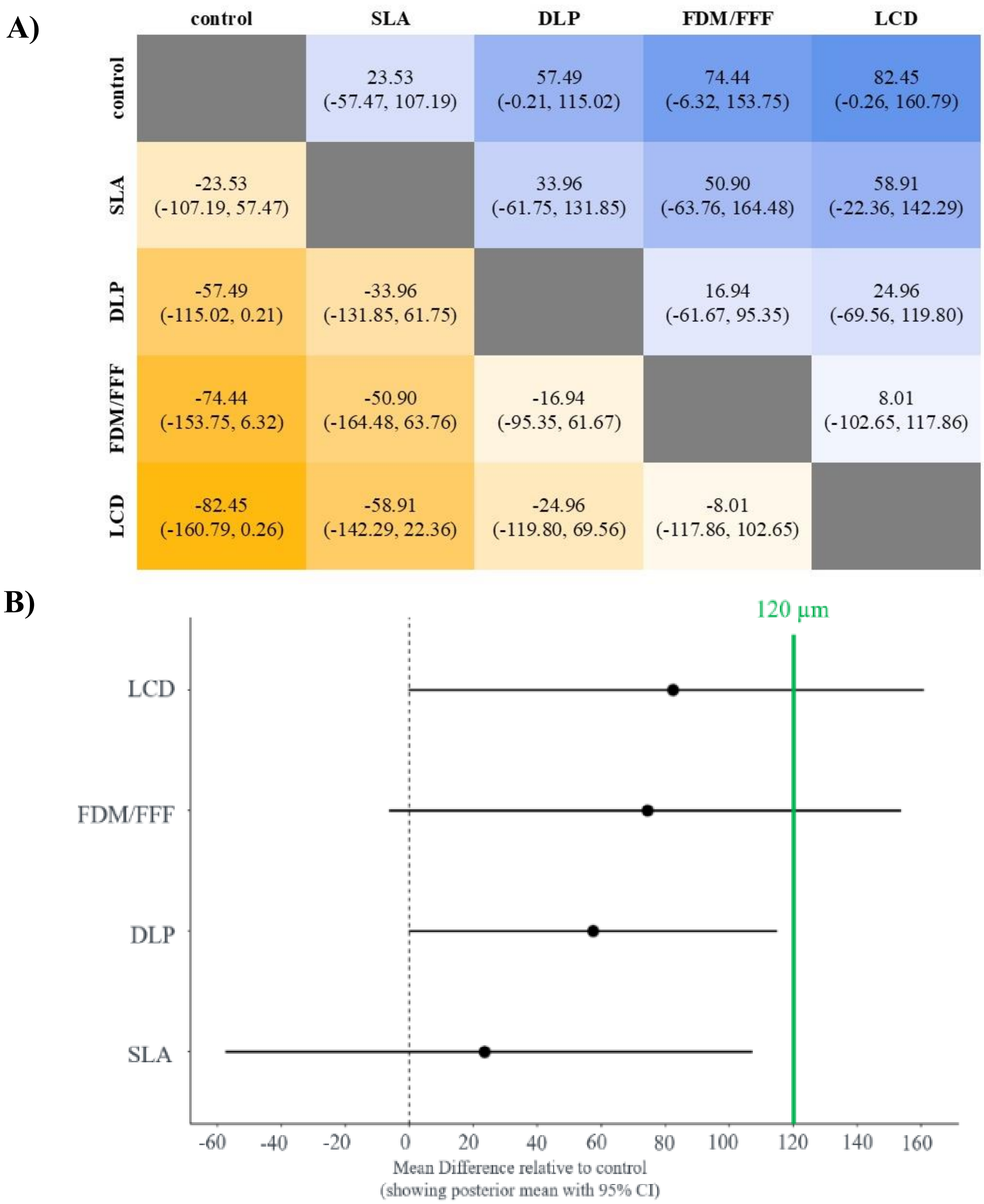

Figure 5. *Mean difference of RMS precision at arch level using layer thickness over 50 µm*

A) *League-heat plot contains mean difference with 95% confidence interval for all possible treatment pairs.* ***B)*** *The forest plot shows the first line of the league-heat plot and highlights the 120 µm and 250 µm tolerance thresholds for prosthodontic and orthodontic applicability (63). SLA= stereolithography; DLP= digital light processing; FDM/FFF= fused deposition modeling/fused filament fabrication; LCD= liquid crystal display*

8.1.2.4 Trueness RMS tooth level 0–50 µm

Three studies assessed the trueness of smaller arch segments using “tooth level” measurements (41, 78, 81). This subgroup included four technologies: MJ with a mean trueness difference of 37.0 µm, PolyJet at 67.9 µm, SLA at 86.7 µm, and DLP at 97.9 µm. The findings showed no significant statistical or clinical differences among the technologies, with all performing within the 120 µm clinical tolerance for prosthodontic applications (**Figure 6**).

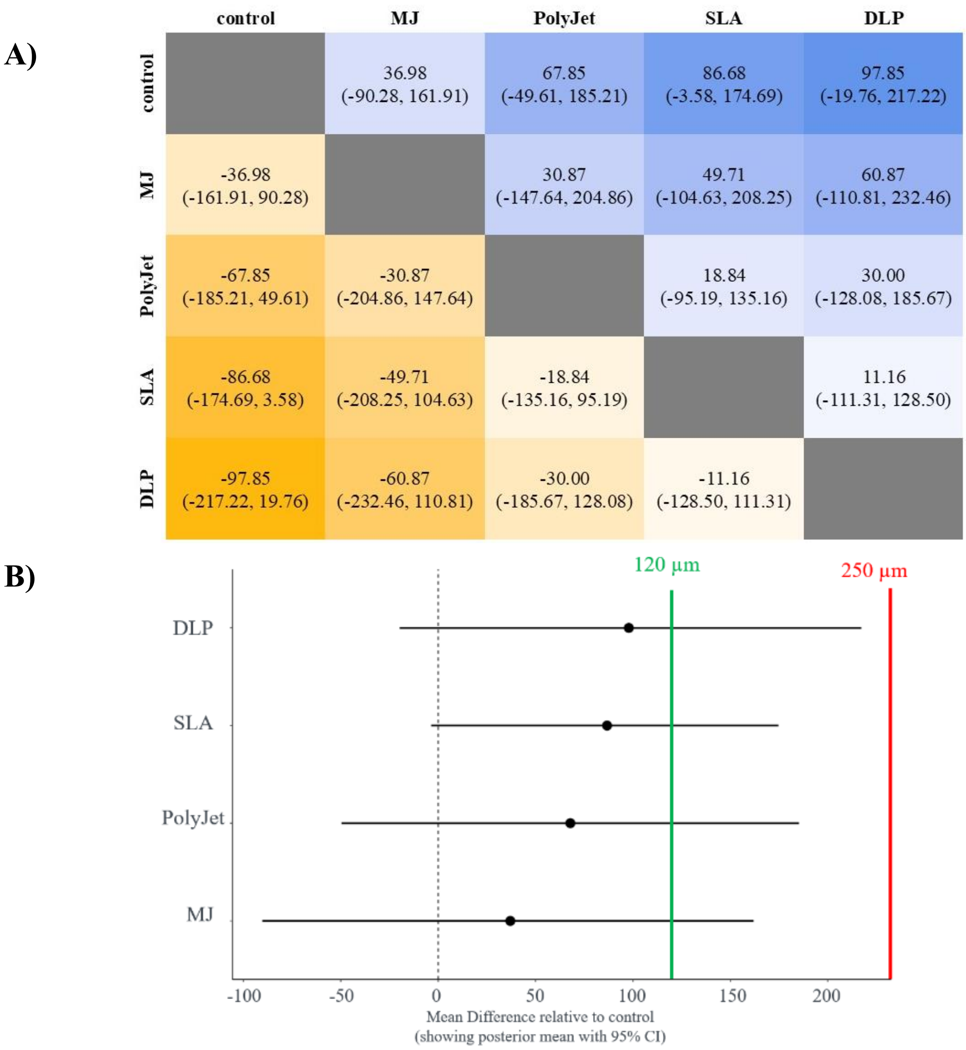

Figure 6. *Mean difference of RMS trueness at tooth level using layer thickness 0-50 µm* ***A)*** *League-heat plot contains mean difference with 95% confidence interval for all possible treatment pairs.* ***B)*** *The forest plot shows the first line of the league-heat plot and highlights the 120 µm and 250 µm tolerance thresholds for prosthodontic and orthodontic applicability (63). MJ= MultiJet; SLA= stereolithography; DLP= digital light processing*

8.1.2.5 Trueness Deviation arch level over 50 µm

In this subgroup, using layer thicknesses over 50 µm, DLP and SLA technologies emerged as the most accurate. In comparison, FDM/FFF exceeded the 120 µm clinical limit for prosthodontics, showing a mean trueness difference of 169.3 µm. Three studies featuring six different printers were included in this analysis (84, 85, 87). No significant differences were observed between reference values or among the treatment methods. DLP printers ranked highest, with mean absolute deviations of 46.1 µm, 49.6 µm, and 51.8 µm, followed by SLA at 73.9 µm. DLP and SLA technologies demonstrated clinical acceptability for prosthodontic use (**Figure 7**).

A)

	control	DLP2	DLP3	DLP1	SLA	FDM/FFF
control		46.13 (-128.06, 223.35)	49.59 (-133.89, 223.31)	51.81 (-118.99, 224.47)	73.93 (-53.03, 210.19)	169.27 (-10.91, 351.67)
DLP2	-46.13 (-223.35, 128.06)		3.46 (-185.41, 192.53)	5.68 (-182.82, 208.80)	27.80 (-148.65, 207.32)	123.14 (-120.39, 371.13)
DLP3	-49.59 (-223.31, 133.89)	-3.46 (-192.53, 185.41)		2.22 (-183.24, 198.90)	24.35 (-148.37, 195.56)	119.68 (-132.00, 371.55)
DLP1	-51.81 (-224.47, 118.99)	-5.68 (-208.80, 182.82)	-2.22 (-198.90, 183.24)		22.13 (-152.79, 201.97)	117.46 (-139.36, 367.84)
SLA	-73.93 (-210.19, 53.03)	-27.80 (-207.32, 148.65)	-24.35 (-195.56, 148.37)	-22.13 (-201.97, 152.79)		95.33 (-130.89, 315.94)
FDM/FFF	-169.27 (-351.67, 10.91)	-123.14 (-371.13, 120.39)	-119.68 (-371.55, 132.00)	-117.46 (-367.84, 139.36)	-95.33 (-315.94, 130.89)	

B)

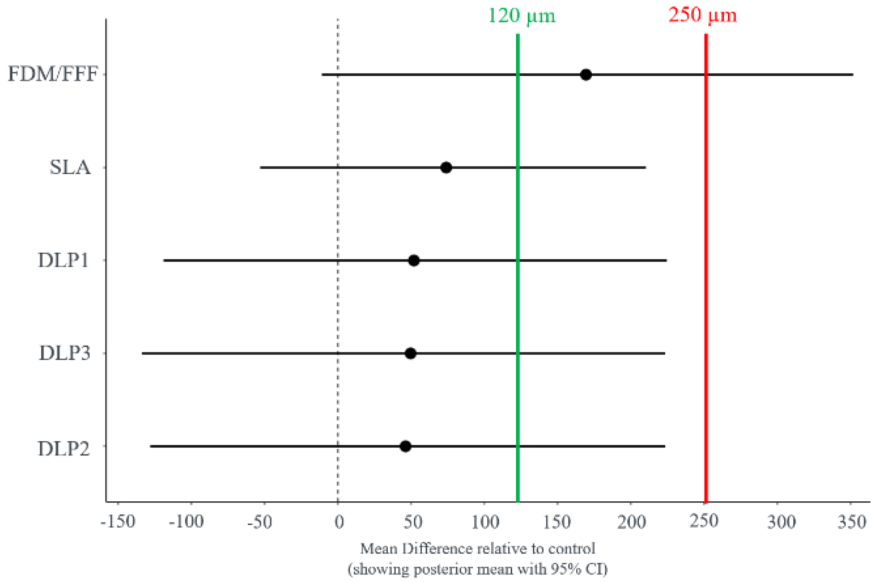

Figure 7. *The mean difference of Trueness deviation at arch level using layer thickness over 50 µm*

A) *League-heat plot contains mean difference with 95% confidence interval for all possible treatment pairs.* ***B)*** *The forest plot shows the first line of the league-heat plot and highlights the 120 µm and 250 µm tolerance thresholds for prosthodontic and orthodontic applicability (63). DLP= digital light processing; SLA= stereolithography; FDM/FFF= fused deposition modeling/fused filament fabrication*

8.1.3 Consistency analysis

Examining each outcome demonstrated that none of the data points deviated from the 45° consistency–inconsistency line, indicating no remarkable heterogeneity was observed in any of the examined subgroups. Detailed results are shown in the original publication (63).

8.1.4 Risk of bias and certainty evidence

Four domains were created to make a risk of bias assessment. In the domain of "model selection," nine studies were classified as low risk. In comparison, two studies were rated as unclear due to inconsistencies between the description and figures of the models or insufficient detail about the model design. In the "index test" domain, six studies were low-risk, four were high-risk due to missing information on postprocessing, and one was unclear because of insufficient data on layer thickness. All studies were low risk in the "reference standard" domain. However, the "flow and timing" domain was unclear across all studies, as none provided details regarding storage conditions or duration.

The quality of treatment-effect estimates was assessed using the GRADEpro tool, revealing moderate certainty in four subgroups (Trueness RMS arch level 0-50 µm, Trueness RMS tooth level 0-50 µm, Trueness RMS tooth level 0-50 µm) and low-risk in subgroup Trueness Deviation arch level over 50 µm and very low certainty in Trueness RMS arch level over 50 µm subgroup. The evidence was downgraded due to serious inconsistencies resulting from wide confidence intervals. The detailed results can be found in the original publication (63).

8.2 Study II: Comparison of fit and trueness of fixed dental restorations fabricated by additive and subtractive manufacturing – A systematic review and meta-analysis

8.2.1 Search and selection, characteristics of the included studies

The initial search produced 4,172 studies, with 3,505 remaining after removing duplicates. Screening of titles and abstracts led to 120 papers being selected for full-text reading. Four additional articles were identified through a manual search of reference lists from previous reviews and included records. Finally, 57 publications were included in both the qualitative and quantitative syntheses (67). **Figure 8.** shows the PRISMA flowchart of the study selection process.

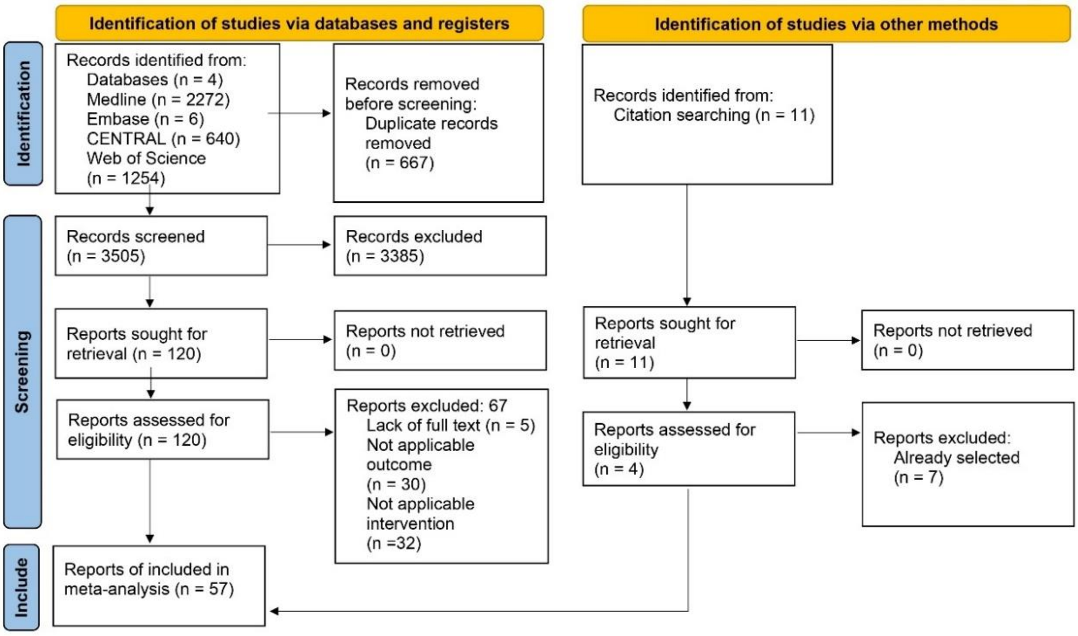

Figure 8. *PRISMA Flow Diagram of the screening and selection process for Study II (67)*

The characteristics of the included studies for the systematic review and meta-analysis are detailed in **Table 2.**

Table 2. Main characteristics of the included studies for Study II (67)

Author (year)	**Restoration**	**AM techn.**	**Material (AM)**	**SM techn.**	**Material (SM)**	**Sample size**	**Examination method**	**Outcome**
Peng et al. 2019 (88)	crown	MiiCraft 125; (Young Optics, Hsinchu, Taiwan) - DLP	methacrylic oligomer (NextDent C&B MFH; 3D System)	DWX-51D Milling Machine (Roland DGA Co, Irvine, CA)	PMMA resin blocks (ZCAD Temp Fix)	12	with cementation; μCT (X5000 CT system; North Star Imaging, Rogers, MN); vinyl polysiloxane (PVS) impression; measuring microscope (Measurescope 20; Nikon, Tokyo, Japan) 75 × magnification	internal fit (μm), AMD (μm)
Peng et al. 2020 (89)	crown	MiiCraft 125; (Young Optics, Hsinchu, Taiwan) - DLP	methacrylic oligomer (NextDent C&B MFH; 3D System)	DWX-51D (Roland DGA Co, Irvine, CA)	PMMA resin blocks (ZCAD Temp Fix 98; Harvest Dental)	16	with cementation; μCT (X5000 CT system; North Star Imaging, Rogers, MN)	internal fit (μm)

Wu et al. 2021 (90)	crown	cara® Print 4.0 (Kulzer North America, South Bend, IN, USA) - DLP	methacrylate material (Dima Denture teeth, Kulzer North America, South Bend, IN, USA)	DWX-51D (Roland DGA, Frenchs Forest, NSW, Australia)	resin nano ceramic material (Lava Ultimate, 3M ESPE, St. Paul, MN, USA)	16	with cementation; (PVS) impression technique; stereoscope (Measurescope 20; Nikon, Tokyo, Japan) 75 × magnification	AMD (µm)
Lee et al. 2017 (91)	crown	Stratasys – PolyJet; Dentis - SLA	VeroGlaze MED620 (Stratasys, USA); ZMD1000B (Dentis, Korea)	Zirkonzahn Milling system	Vipi block (VIPI,Brazil)	10	without cementation; silicone replica and image microscope system (EZVM-452M, SomeTech, Seoul, Korea) 300x magnification	internal fit (µm), margin al gap (µm)
Park et al. 2016 (92)	crown	Perfactory PixCera (EnvisionTEC Inc.) - DLP	PMMA (E-Dent; Envision TEC)	4-axial milling machine (Cendres & Metaux SA)	Pekkton milling blank (Pekkton Ivory; Cendres & Metaux)	40	without cementation; silicone replica technique and digital microscope (KH-7700; Hirox) ×160 magnification	internal fit (µm), margin al gap (µm)

Aldahian et al. 2021 (93)	crown	MiiCraft 125 (MiiCraft, Jena, Germany) - SLA	biocompatible resin (Freeprint Temp; DETAX GmbH & Co. KG, Ettlingen, Germany)	milling machine (Versamill; Axsys Dental Solutions, Wixom, MI, USA)	PMMA prefabricated blocks (Cercon base PMMA blocks; DeguDent GmbH, Hanau, Germany)	10	micro-CT (Skyscan 1173 high-energy spiral scan micro-CT; Skyscan NV, Kontich, Belgium)	internal fit (µm), margin al gap (µm)
Angwarawo ng et al. 2020 (94)	crown	Asiga Max (Asiga) - DLP	light-polymerized bis-acrylate resin (Freeprint Temp; DETAX GmbH)	5-axis milling machine (CORiTEC 250i; imes-icore GmbH)	PMMA resin block (Brylic Solid; Sagemax Bioceramics)	10	with cementation; traveling stereomicroscop e (Measurescope 20; Nikon)	margin al gap (µm)
Haddadi et al. 2021 (50)	crown	NextDent 5100 (3D Systems) - DLP	hybrid resin material (NextDent C&B, 3D systems)	MCX milling station (Dentsply Sirona)	hybrid resin block (Vita Enamic, Vita Zahnfabrik)	10	without cementation - silicone replica technique and loupes (2.3× magnification); with cementation - stereomicroscop e (Wild Macroscope M420, Wild) and digital camera (Zeiss AxioCam MRc5, Carl Zeiss Micro Imaging GmbH) 40× magnification	internal fit (µm), margin al gap (µm)

Revilla-León et al. 2018 (95)	onlay	Projet MJP 3600 XHD Dental, 3D System) - MultiJet	castable 3D printed pattern (Visijet M3DentCast, 3D System)	dental CNC machine (iMES-iCORE CORiTEC 250-I, iMES iCORE)	castable acrylic resin block (IPS AcrylCAD, Ivoclar Vivadent)	4	computed tomography (µCT)	internal fit (µm), margin al gap (µm)
Alharbi et al. 2017 (96)	crown	DW028D (DWS) - SLA	hybrid composite resin material (Temporis, shade A2, LOT: 040725, DWS)	5-axis milling machine (Wissner Ltd.; Germany)	PMMA-based acrylic resin (Polycon ae; Straumann; shade A2)	40	without cementation; micro-tomograpgy system scanner (Skyscan 1072, Bruker micro-CT, Kontich)	internal fit (µm), AMD (µm)
Karasan et al. 2022 (49)	3-unit bridge	FormLabs 2 (FormLabs, Somerville, MA, USA) – SLA;	acrylic-based composite (SHERA Werkstoff-Technologie GmbH & Co, Lemförde, Germany)	5-axis milling machine (Zenotec Select Hybrid, Wieland Dental, Forzheim, Germany)	PMMA (Telio CAD LT A2)	10	without cementation, modified triple scan method – optical laboratory scanner (Iscan D104i; Imetric 3D SA)	internal fit (µm), margin al gap (µm)
		P30 (RapidShapeHeimsh eim, Germany) - DLP						
Mugri et al, 2023 (97)	crown	Asiga 3D printer (Alexandria, Australia) - DLP	resin material (DentaTooth Shade A1, Asiga, Alexandria, Australia, Lot: MO/08782)	5-axis milling machine DWX-52D (DG SHAPE, Roland DGA, Irvine, CA, USA)	PMMA temporary crowns blocks (CopraTemp Shade A1, WhitePeaks Dental Solutions GmbH, Wesel, Germany)	10	with cementation; stereomicroscop e	margin al gap (µm)
Khanlar et al, 2023 (98)	crow	EnvisionTEC VIDA HD (EnvisionTEC Inc) – DLP;	resin material (E-Dent 400 C&B; Envision TEC Inc);	milling machine (ProgramMill P7; Ivoclar AG)	PMMA disc (ZCAD Temp Esthetic; Harvest Dental)	10	without cementation; silicone replica	internal fit (µm),

		Carbon M1 (DENTCA) - DLS	Crown & Bridge (DENTCA)				technique and digital microscope (Olympus SZX16; Olympus Corp.) x70 magnification	margin al gap (µm)
Son et al. 2022 (99)	crown	Zenith U (Dentis) – SLA RayDENT Studio (Ray) - DLP	ZMD-1000D (Dentis) RayDENT C&B (Ray)	CORiTEC 250i (iMES iCORE)	no data	20	without cementation; silicone replica technique and optical microscope (IT Plus 5.0, SOMETECH) x60	internal fit (µm), AMD (µm), margin al gap (µm)
Falahchai et al. 2022 (100)	3-unit bridge	MAX UV; (Asiga) - DLP	methacrylate oligomer resin (NextDent C&B, Vertex Dental)	milling machine (Ceramill; Amann Girrbach)	PMMA resin blocks (Ceramill TEMP light 71 L20 nm; Amanngirrba AG)	20	without cementation; silicone replica technique and video measuring machine (VMM, C-Class Vision Measurement Machine; Easson Optoelectronica technology Co.) at ×202.9 magnification	internal fit (µm), AMD (µm)
Al-Wahadni et al, 2023 (101)	crown	X-Fab 2500 (DWS Systems, Thiene, Italy) – SLA	Temporis (DWS, Italy)	Coritec 250i dry (iMES iCORE, Eiterfeld, Germany)	Ceramill A-temp (AmannGirrbach, Koblack, Audtria)	10	without cementation; Medit I700 scanner (Medit,	internal fit (µm), margin

		Asiga Max (Alexandria, Audtralia) - DLP	TEMP (PowerResins, Istambul, Turkey)				Seoul, Korea) and Meditlink crown gap tool (medit)	al gap (µm)
Revilla-León et al. 2020 (46)	crown	CERAMAKER 900 (3DCeram Co) - SLA	zirconia paste (3DMix ZrO2 ;3DCeram) - Zirconia stabilized with 3% yttria	5-axis milling machine	CARES zirconium-dioxide crown (Institut Straumann AG)	10	without cementation; silicone replica technique and digital microscope (VHX-2000 series; Keyence America) - ×100 magnification	internal fit (µm), margin al gap (µm)
Hsu et al. 2019 (102)	crown	3D slurry printing (3DSP)	resin mixed with ceramic powder, photoinitiator and a solvent	Coritec 245i, German	zirconia blank (Copran Zr-i Monolith A3 – Zirkonblank, Whitepeak Dental solution, Germany)	≥5	without cementation; desktop scanner (D800, 3Shape, Denmark) and superimposition	margin al gap (µm)
Li et al. 2022 (103)	crown	CSL 100 (Porimy) – SLA	47vol% zirconia suspension	milling machine (250i; imes-icore)	partially sintered zirconia blank (Katana ML A light; Kuraray Noritake)	6	without cementation; intraoral scanner (TRIOS 3; 3Shape A/S) and superimposition (Geomagic Studio 2013); Raindrop; triple scan method (D2000; 3Shape A/S)	internal fit (µm), margin al gap (µm), truenes s (µm)

Ioannidis et al. 2022 (104)	veneer	CeraFab 7500 (Lithoz GmbH) - LCM	3 mol% yttria-stabilized zirconia polycrystal dispersed in a photopolymerized monomer slurry	5-axis milling machine (Ceramill Motion2 5x; Amann Girrbach AG)	prefabricated zirconia disks (Ceramill Zolid FX; Amann Girrbach AG)	20	without cementation; intraoral scanner (TRIOS 3; 3Shape A/S) and superimposition (Geomatic verify 64Bit, ver. 2015.2.0; 3D Systems Inc)	internal fit (µm), marginal gap (µm)
Marouki et al, 2023 (45)	crown	3D gel deposition/printing – 3DGP	self-glazed zirconia (ErranTech Co Ltd).	milling machine (vhf K5; vhf Camfacture AG)	4 mol% yttria stabilized zirconia, CopraSupreme; Whitepeaks Dental Solutions GmbH)	10	without cementation; silicone replica technique and stereomicroscope (Nikon SMZ800; Nikon Corp);	internal fit (µm), marginal gap (µm)
Lyu et al. 2023 (105)	crown	J2 D140L CERAMICS; Junjing) – DLP;	ceramic suspension consisting of 80 wt% zirconia powder;)	5-axis milling machine (DWX 51D; Roland DG Corp)	partially sintered zirconia block (ST; Upcera)	10	without cementation; intraoral scanner (TRIOS 3; 3Shape A/S) and superimposition (Geomagic Studio 2013; 3D Systems)	internal fit (µm), marginal gap (µm), trueness (µm)
		Carmel 1400C; Xjet - NPJ	zirconia ceramic suspension (C800; Xjet					

Rues et al. 2023 (106)	veneer	CeraFab 7500 (Lithoz, Vienna, Austria) - DLP	3Y-TZP material (LithaCon 3Y 210, Lithoz, Vienna, Austria)	no data	3Y-TZP zirconia blank (Cercon ht, Cercon brain expert, Degudent, Hanau)	12	with cementation; digital microscope (Smartzoom 5, Zeiss, Jena, Germany) x130 magnification	internal fit (µm), marginal gap (µm)
Li et al. 2023 (107)	crown	csl-100 (Porimy 3D Printing Technology, Kunshan, China) - SLA	photosensitive ceramic slurry (Porimy Printing Technology), 47 vol% ceramic powders and 53 vol% photosensitive resin premix	milling machine (inlab MC x5, Sirona, Berlin, Germany)	zirconia ceramic block (Wieland, Munich, Germany)	10	without cementation; intraoral scanner (TRIOS 3; 3Shap) and superimposition (Geomagic Studio 2013; 3D Systems)	internal fit (µm), marginal gap (µm), trueness (µm)
Refaie et al. 2023 (108)	crown	CeraFab7500 printer (Lithoz GmbH, Vienna, Austria) - LCM	Lithoz 210 3Y (Lithoz GmbH, Vienna, Austria)	milling machine (DGSHAPE DWX-520, Roland, Willich, Germany)	IPS e.max ZirCAD LT (Ivoclar Vivadent, New York, USA)	10	without cementation; stereomicroscope (Wild Lecia M8, Leica Mikrosysteme, Heerbrugg, Switzerland) with digital camera (Leica DFC 420 C, Leica Mikrosysteme, Wetzlar, Germany) 50X magnification	marginal gap (µm)

Suksuphan et al. 2023 (109)	crown	Freeform Pro 2 (ASIGA; Anaheim Hills, USA) - DLP	Varseosmile (Bego; Bermen, Germany)	CEREC MCX (Dentsply Sirona; New Work, USA)	Vita Enamic (Vita Zahnfabrik; Bad Säckingen, Germany)	10	without cementation; micro-CT (Skyscan 1172; Bruker)	AMD (µm), margin al gap (µm)
Abualsaud et al. 2022 (110)	crown	CERAMAKER C900 Flex (3DCeram Sinto, Bonnac-la-Côte, France) - DLP	zirconia paste (3DMix ZrO2, 3DCeram Sinto, France)	5-axis milling machine (PrograMill PM7, Ivoclar Vivadent, Schaan, Liechtenstein)	Copran® Zri zirconia disc, shade A1 (Whitepeaks Dental Solutions GmbH, Wesel, Germany)	10	without cementation; 3Shape TRIOS 3 scanner (3Shape, Copenhagen, Denmark) and superimposition (Geomagic Control X software, V 2018, 3D Systems Inc., Rock Hill, SC, USA)	internal fit (µm), margin al gap (µm), truenes s (µm)
Kakinuma et al. 2022 (111)	crown	MAX UV (Asiga, Sidney, Australia) - DLP	hybrid resin-composite liquid (TNG-GMP101, A2, GC)	wet milling machine (Aadva LW-I, GC)	hybrid resin-composite block (CERASMART Prime, A2LT, GC)	7	with cementation; laser microscope (VR-3200/3000, Keyence, Osaka, Japan)	internal fit (µm), margin al gap (µm)

Lim et al. 2023 (112)	inlay	Bio3D L12 Dental Professional (BIO3D, Seoul, Republic of Korea) - DLP	NextDent C&B resin (3D Systems, Soesterberg, Netherlands)	milling equipment (Ceramill Motion 2, Amann Girrbach)	hybrid blocks (LU, 3M ESPE, St. Paul, Minnesota, United States)	13	without cementation; silicone replica and digital microscope (KH-7700, Hirox, Tokyo, Japan) 160× magnification; Identica Blue (Medit, Seoul, Republic of Korea) and Geomagic Verify (3D Systems Inc., United States)	internal fit (µm), margin al gap (µm), truenes s (µm)
Demirel et al. 2023 (113)	crown	MAX UV (Asiga, Sidney, Australia) - DLP	composite resin (Crowntec, Saremco Dental AG, Rebstein, Switzerland); hybrid composite resin (VarseoSmile Crown Plus, Bego, Bremen, Germany)	5-axis milling device (CEREC inLab MCX5; Dentsply Sirona, Bensheim, Germany)	Reinforced composite resin (Brilliant Crios, Coltène AG, Altstätten, Switzerland);	10	without cementation; CEREC Primescan (SW 5.2; Dentsply Sirona, Bensheim, Germany) and 3D analysis software (Medit Link v3.0.6; Medit, Seoul, Korea)	internal fit (µm), truenes s (µm)

Chang et al. 2019 (114)	crown	EOSINT M270 with (EOS M270, Munich, Germany) - SLS	Co—Cr—Mo SP2 powder (Co: 63.9%, Cr: 24.7%, W: 5.4%, Mo: 5%, and Si ≤ 1%) (BEGO Wirobond, Bremen, Germany)	no data	Co—Cr—Mo alloy	10	without cementation; light-body silicone and IScan L1 dental scanner and MIRDC Dental software (Metal Industry Research Development Centre, Kaohsiung, Taiwan)	margin al gap (µm)
Dahl et al. 2017 (115)	3-unit bridge	no data - SLS	Dentware CoCr (Dentware, Kristianstand, Sweden)	no data	ED Kera-Disc CoCr (Eisenbacher Dentalwaren, Germany)	3	without cementation; triple scan method (ATOS III; GOM, Brunschweig, Germany) and GOM Inspect	internal fit (µm)
Kim et al. 2014 (116)	crown	EOSINT M270 (EOS GmbH) - SLS	Co-Cr alloy powder (Co, 61.8%-65.8%; Cr, 23.7%-25.7%; tungsten, 4.9%-5.9%; molybdenum, 4.6%-5.6%; silicon, 0.8%-1.2%; iron, maximum 0.5%; manganese, maximum 0.1% [EOS Cobalt Chrome SP2; EOS GmbH]	Ceramill Motion 2 (AmannGirrbach AG)	Co-Cr alloy (Co, 66%; Cr, 28%; molybdenum, 5%, manganese; silicon; iron, <1%; organic binder, 1%-2% [Ceramill Sintron 71 XXS; AmannGirrbach AG])	10	without cementation; light-body silicone and 3-dimensional analysis (CopyCAD; Delcam)	internal fit (µm)

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Savencu et al. 2020 (117)	crown	PXS Dental (Phenix System, Rion, France) – SLS; no data- SLM	cobalt-chronium dental alloy powder (Starbond CoS Powder 16, S&S Sheftner GmbH, Mainz, Germany)	no data	no data	24	without cementation; silicone replica technique and optical microscope (Leica DM500, Leica, Wetzlar, Germany)	internal fit (µm), margin al gap (µm)
Kim et al. 2018 (118)	crown	SLM-50 (Realizer, ReaLizer GmbH, Borchen, Germany) - SLM	CoCr powder (Starnond CoS powder 55, S&S Sheiftner GmbH, Mainz, Germany)	CORiTec 450i (Imes-icore GmbH, Eiterfeld, Germany)	soft metal block (SoftMetal, LHK, Chilgok, Korea)	15	without cementation; silicone replica technique and digital microscope (KH-7700, Hirox, Tokyo, Japan) x160	internal fit (µm), margin al gap (µm)
Chou et al. 2021 (119)	crown	metal printer (ConceptLaser, Germany) - DMLM	cobalt-chromium alloy	Ceramill Sintron (Amann Girrbach AG)	cobalt-chromium alloy	10	without cementation; silicone replica technique and dental microscope (Zumax, Jiangsu, China) was used at a magnification of 23X	internal fit (µm), margin al gap (µm)

Kaleli et al. 2020 (120)	3-unit bridge	MLab Cusing 200R (Concept Laser GmbH, Lichtenfels, Germany) - DMLM	Co-Cr metal powder (Remanium Star CL, Dentaurum GmbH, Ispringen, Germany)	milling machine (Redon Hybrid, Redon, Istanbul, Turkey)	Co-Cr hard blanks (Starbond CoS Disc Basic, S & S Scheftner GmbH, Mainz, Germany)	10	with cementation; stereomicroscope (SZX16, Olympus, Tokyo, Japan) x40 equipped with a digital camera (DP73, Olympus, Tokyo, Japan)	marginal gap (µm)
Gunsoy et al. 2014 (121)	crown	laser sintering machine (Concept Laser M1 cusing, Hofmann, Lichtenfells, Germany) - DMLS	Co-Cr alloy powder (Dentaurum Remanium Star CL, Pforzheim, Germany)	Ceramill Sintron System (Amann Girrbach, Pforzheim,Germany)	CoCr block (Amann Girrbach, Ceramill Sintron System, Pforzheim,Germany)	16	with cementation; model sectioning and stereomicroscope x24	internal fit (µm), marginal gap (µm)
Dayan et al. 2019 (122)	crown	laser-sintering machine (Concept Laser GmbH, Lichtenfels, Germany) - DMLM	cobalt-chromium alloy	Ceramill Sintron (Amann Girrbach AG)	cobalt-chromium alloy	10	without cementation; direct view technique, stereomicroscope (SMZ800N, Nikon Instruments Inc., Tokyo, Japan); and silicone repcila technique and stereomicroscope x100	internal fit (µm), marginal gap (µm)

Önöral et al. 2020 (123)	3-unit bridge	EOSINT M 270 (EOS GmbH, Krailling, Munich) - SLS	Co-Cr-Mo powder (Co, 61.8-65.8%; Cr, 23.7-25.7%; Mo, 4.6-5.6%; W, 4.9-5.9%; Si, max. 0.8-1.2%; Mn, max. 0.50%; Fe, max. 0.1%/CobaltChrome SP2; EOS GmbH, Krailling, Munich)	5-axis milling device (inLab MC X5, Sirona Dental System GmbH, Germany)	Co-Cr block (CopraSintec K, Whitepeaks Dental Solutions GmbH and Co. KG, Germany)	15	without cementation; silicone replica technique and stereomicroscope (Leica S8 APO, Leica Microsystems GmbH, Wetzlar, Germany) x80	marginal gap (µm)
Kim et al. 2017 (124)	crown	EOSINT M 270 (EOS GmbH) - SLS	EOS Cobalt Chrome SP2 (SLM-ES)	Zenotec T1 (Wieland Dental + Technik GmbH & Co KG)	Soft Metal (MS-SM, LHK)	10	without cementation; light body polyvinyl siloxane impression and µCT system (SkyScan 1272, Bruker)	marginal gap (µm)
Alquahtani et al. 2021 (125)	crown	Concept Laser Machine (metal laser melting system; GE Additive company, Boston, MA, USA) - SLM	CoCr alloy (Starbond Easy Powder 30; Scheftner GmbH, Mainz, Germany) (composition, Co Appl. Sci. 2021, 11, 8328 4 of 12 61%, Cr 27.5%, W 8.5%, Si 1.6%, C, Fe and Mn < 1%)	Cercon Brain (DeguDent GmbH, Hanau-Wolfgang, Germany)	Ceramill Sintron alloy blanks (Co-Cr-Amann Girrbach AG, Herrschaftswiese, Koblach, Austria)	10	without cementation; Bruker micro CT (Skyscan 1173 high-energy spiral scan micro-CT; Skyscan NV, Kontich, Belgium)	marginal gap (µm)

Majeed et al. 2023 (126)	crown	ProX DMP 100, 3D Systems Inc., Rock Hill, SC) - SLM	metal powder (LaserForm CoCr (C), 3D Systems Inc., Rock Hill, SC)	milling machine (Arum 5X-500, Doowon, Daejeon, South Korea)	metal blanks (KERA®-DISC; Eisenbacher Dentalwaren ED GmbH, Rhine-Main, Germany)	12	without cementation; optical scanner (Medit T710 desktop scanner, Seoul, South Korea) and superimposition (Geomagic Control X, 3D Systems Inc., Rock Hill, SC)	internal fit (µm), truenes s (µm)
Kang et al. 2018 (127)	crown	Zenith U, Dentis) - SLA	PMMA-only liquid (Zmd1000B, Dentis)	five-axis milling machine (DWX-50, Roland DG Corporation, Shizuoka, Japan)	PMMA block (VipiBlock PMMA, Vipi, Pirassununga, Brazil)	11	blue light scanner (Identica Blue, Medit, Seoul, Korea) and superimposition (Verify, Geomagic GmbH, Stuttgart, German)	truenes s (µm)
Son et al. 2021 (128)	crown	ZENITH U (Dentis, Daegu, Korea) – SLA; RAYDENT Studio (Ray, Seoul, Korea) - DLP	photopolymer resin (ZMD-1000B; Dentis, Daegu, Korea); RAYDENT C&B (Ray, Seoul, Korea)	milling machine (CORITEC 250i, imes-icore GmbH, Eiterfeld, Germany)	prefabricated resin block (PMMA DISK; Yamahachi dental mpg, Aichi Pref, Japan)	15	desktop scanner (E1, 3Shape, Copenhagen, Denmark) and superimposition (Geomagic Control X v2018.0.0, 3D Systems Inc., Rock Hill, SC, USA)	truenes s (µm)

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Giannetti et al. 2021 (129)	crown	ProMaker LD10 Dental Plus (Prodways) - DLP	polymethylmethacrylate (PMMA) resin (NextDent C&B MFH, NextDent)	5-axis simultaneous milling machine (CORiTEC 350i, imes-icore GmbH)	Polymethylmethacrylate (PMMA) disks (Vipi Block Trilux ø 98.5 mm, Dental VIPI Ltda)	15	desktop scanner (E1, 3Shape, Software Dental System™, version 19.0, 3Shape) and superimposition (Dental System™, version 19.0, 3Shape)	trueness (µm)
Li et al. 2021 (130)	crown	CSL 100 (Porimy, China) - SLA	47 vol% 3 mol zirconia suspension	milling machine (AK-D4, Aidite, China)	partially sintered zirconia blank (SHT, Aidite, China)	30	intraoral scanner (3Shape Trios 3, 3Shape A/S, Denmark) and superimposition (Geomagic Studio, 2013; Raindrop, USA)	trueness (µm)
Wang et al. 2019 (131)	crown	CERAMAKER 900 (3DCeram Co) - SLA	ZrO2 paste (3DMIXZrO2L; 3DCeram Co) mixed with liquid photosensitive resin	5-axis milling machine (DWX-50; Roland DG Corp)	ZrO2 block (Zenostar; Wieland Dental)	10	blue light scanner (DS100; Shining 3D Corp) and superimposition (Geomagic Qualify 2013; Geomagic Inc)	trueness (µm)
Lerner et al. 2021 (52)	crown	Cerafab S65® (Lithoz, Vienna, Austria) - LCM	LithaCon 3Y 210® (Lithoz, Vienna, Austria), a ceramic suspension consisting of 3 mol% Yttria stabilized Zirconia (3-TZP) ceramic powder	5-axis milling machine (DWX-52D®, DGShape, a Roland Company, Hamamatsu, Japan)	no data	10	industrial optical scanner (ATOS Q®) and superimposition (Control X®, Geomagic, Morrisville, NC, USA)	trueness (µm)

Cakmak et al. 2022 (132)	3-unit bridge	MoonRay S100 (SprintRay Inc) - DLP	ZrO2 paste (3DMIXZrO2L; 3DCeram Co) mixed with liquid photosensitive resin	Zenotec mini (Wieland Dental+Technik GmbH & Co KG)	PMMA block (Upcera; Shenzhen Upcera Dental Technology Corp)	10	intraoral scanner (i500; Medit) and superimposition (Medit Link; Medit)	trueness (µm)
Cakmak et al. 2022 (133)	crown	MAX UV (ASIGA) - DLP	Crowntec; Saremco Dental AG	5-axis milling unit (PrograMill PM7; Ivoclar AG)	PMMA (breCAM.monoCOM, bredent)	10	intraoral scanner (CEREC Primescan SW 5.2; Dentsply Sirona) and superimposition (Medit Link v2.4.4; Medit)	trueness (µm)
Thomas et al. 2023 (134)	crown	Anycubic Photon D2 (Anycubic) - DLP	photopolymer resin (3D ACCUPRINT; D-tech)	5-axis milling machine (IvoryMill 5XW; Kelkar Dynamics LLP)	PMMA block (PMMA Blank for CAD-CAM applications; BILKIM TIBBI URUNLER SAN. VE TIC.LTD.STI)	10	laboratory scanner (Medit T500) and superimposition (CloudCompare)	trueness (µm)
Cho et al. 2023 (135)	crown	Octave Light R1 (Octave Light Ltd.) - DLP	zirconia suspension (Cera-P; M.O.P) containing nanometer-sized 3Y-TZP powder, polyfunctional acrylates, and dispersant	5-axis milling machine (Arum 5X-300; Doowon)	milling block (Luxen ML Multi A3; Dentalmax Co)	10	intraoral scanner (i500; Medit) and superimposition (Geomagic Control X; Geomagic Inc)	trueness (µm)
Lüchtenborg et al. 2022 (51)	4-unit	Ceramaker900 (3DCeram, Limoges, France) – SLA;	3Y-TZP paste (3D Mix ZrO2 Zr-P03 grade, 3DCeram);	no data	Zirconia GC ST	16	intraoral scanner (TRIOS 4, 3shape, Copenhagen,	trueness (µm)

		XJET (Rehovot, Israel) – MJ;	3Y-TZP ink (C800 zirconia model dispersion grade 7250001, XJET);				Denmark; Primescan, DentsplySirona, York, USA) and superimposition Geomagic Control X (Geomagic, 3DSystems)	
		405 nm Prototype DLP-Printer (University of Birmingham, UK) – DLP;	3Y-TZP material;					
		CeraFab System Medical (Lithoz, Vienna, Austria) - DLP	3Y-TZP slurry (LithaCon 3Y 230, Lithoz)					
Camargo et al. 2022 (136)	crown	Carmel 1400 (Xjet) inkjet printer - Inkjet	commercial ZrO2 suspension (C800 zirconia model dispersion grade 7250001, XJET), which contains about 45 wt% ZrO2 powder in a proprietary mixture of glycol ethers and dispersing agent	Matsuura LX-O 5 axis (Matsuura Machinery, Leicestershire, England)	pre-sintered Initial High Translucency (HT) (GC, Tokyo, Japan) zirconia disks	10	industrial visible-light GOM compact 5 M (GOM branch Benelux, Leuven, Belgium) and superimposition (3-Matic, Materialise, Leuven, Belgium)	truenes s (µm)

Kim et al. 2022 (137)	crown	Octave Light R1 (Octave Light Limited, Shatin, N.T., Hong Kong) – DLP	zirconia suspension (3Y-TZP; M.O.P, Seoul, Korea)	5-axis milling machine (Arum 5X-300; Doowon, Daejeon, Korea)	partially sintered 4-mol% yttria-stabilized zirconia (4Y-PSZ; KATANA STML, Kuraray Noritake Dental Inc., Tokyo, Japan); partially sintered 5-mol% yttria-stabilized zirconia (5Y-PSZ; KATANA UTML, Kuraray Noritake Dental Inc., Tokyo, Japan)	14	intraoral scanner (i500; Medit, Seoul, Korea) and superimposition (Geomagic Control X; Geomagic Inc., Morrisville, NC, USA)	trueness (µm)
		C100 EASY FAB (3D Ceram, Limoges, France) - SLA	zirconia suspension (3Y-TZP; 3D Ceram, Limoges, France)					
Moon et al. 2022 (138)	crown	INNI-II (AON, Gunpo, Korea) - DLP	INNI-Cera, AON, Gunpo, Korea	5X-500L (Arum Co., Daejeon, Korea)	Luxen Zirconia 1200 Zr (Dentalmax Co., Seoul, Korea)	10	model scanner (Identica Blue, Medit Co., Seoul, Korea) and superimposition (Geomagic Control X, 3D Systems Inc., Rock Hill, SC, USA)	trueness (µm)

3DGP: 3-dimensional gel deposition/printing; 3DSP: 3-dimensional slurry printing; AM: additive manufacturing; AMD: absolute marginal discrepancy; bis-GMA: bisphenol A-glycidyl methacrylate; DLP: digital light processing; DLS: digital light synthesis; DMLM: direct metal laser melting; DMLS: direct metal laser sintering; IPA: isopropyl alcohol; LCD: liquid crystal display; LCM: lithography-based ceramic manufacturing; micro-CT: micro-computed tomography; MJ: MultiJet; NPJ: nanoparticle jetting; OCT: optical coherence tomography; PMMA: polymethyl methacrylate; SEM: scanning electron microscope; SLA: stereolithography; SLM: selective laser melting; SLS: selective laser sintering; SM: subtractive manufacturing; UV: ultraviolet

8.2.2 Results of the quantitative analysis

8.2.2.1 Internal fit

Axial and occlusal gap values (µm) were analyzed separately to evaluate the internal fit of prostheses. For axial gap measurements, the mean differences (MD) were -2.68 µm (95% CI: -19.92 to 14.55) for metal restorations, -4.21 µm (95% CI: -17.82 to 9.40) for ceramics, and -6.74 µm (95% CI: -25.46 to 11.99) for acrylic resin restorations, with no statistically significant differences observed (**Figure 9**). Conversely, milled acrylic resin fixed restorations exhibited a significantly larger occlusal gap than 3D printed prostheses, with an MD of 39.12 µm (95% CI: 12.44 to 65.79). For occlusal gap measurements, metals had an MD of -50.93 µm (95% CI: -128.83 to 26.97), and ceramics had an MD of 13.45 µm (95% CI: -97.13 to 124.03), both showing no statistically significant differences (**Figure 10**).

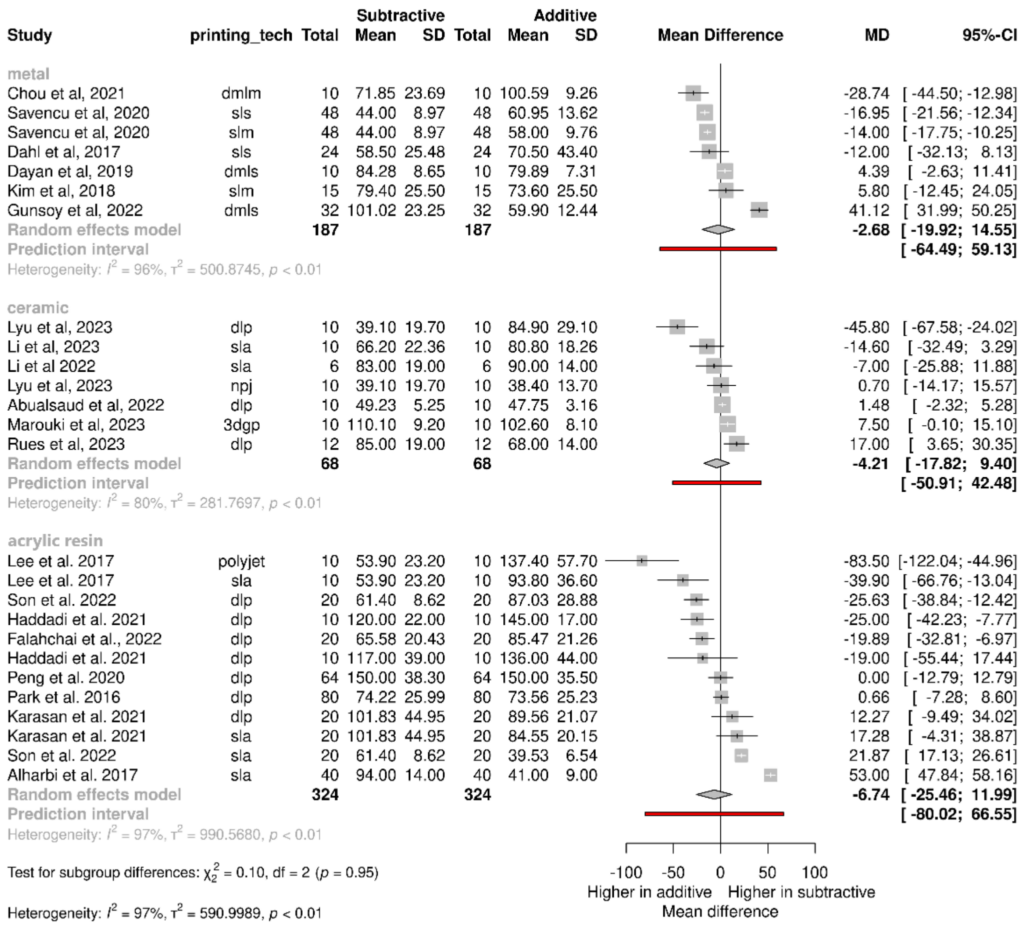

Figure 9. *Forest plot for the axial internal fit (µm) (67)*

No statistical difference is shown between AM and SM FPDs in either subgroup. 3DGP= 3-dimensional gel deposition/printing; DLP= digital light processing; DMLM=

direct metal laser melting; DMLS= direct metal laser sintering; NPJ= nanoparticle jetting; SLA= stereolithography; SLM=: selective laser melting; SLS= selective laser sintering

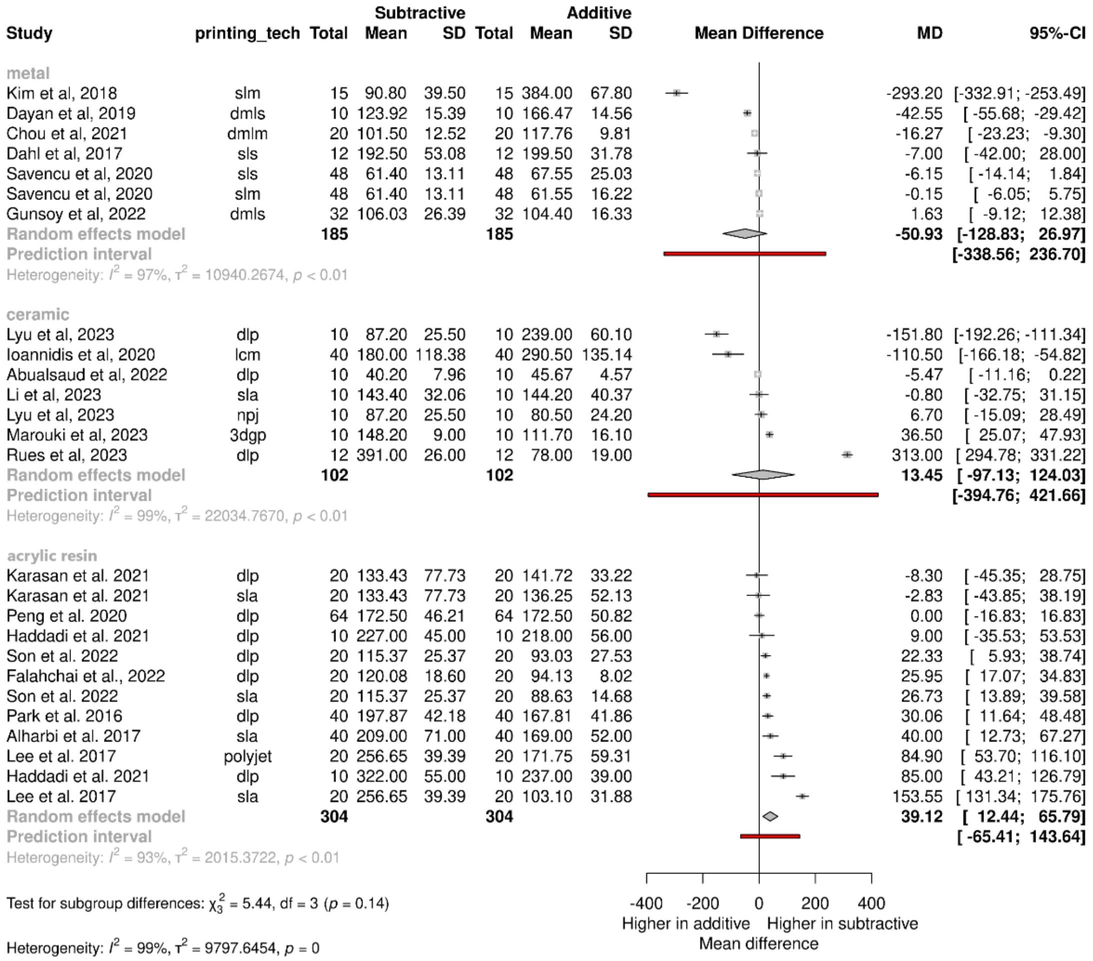

Figure 10. *Forest plot for the occlusal internal fit (µm) (67)*

SM Acrylic resin restorations demonstrated a significantly larger occlusal gap compared to AM restorations. 3DGP= 3-dimensional gel deposition/printing; DLP= digital light processing; DMLM= direct metal laser melting; DMLS= direct metal laser sintering; LCM= lithography-based ceramic manufacturing; NPJ= nanoparticle jetting; SLA= stereolithography; SLM=: selective laser melting; SLS= selective laser sintering

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8.2.2.2 Marginal fit

The marginal gap showed no significant differences across subgroups, with mean differences (MD) of -16.10 µm (95% CI: -47.37 to 15.18) for metals, -11.6 µm (95% CI: -23.19 to 1.07) for ceramics, and 0.61 µm (95% CI: -16.06 to 17.29) for acrylic resin restorations (**Figure 11**). For absolute marginal discrepancy (AMD), only data from studies on acrylic resin restorations were eligible, revealing no statistically significant difference between techniques, with an MD of 4.16 µm (95% CI: -12.04 to 20.37) (**Figure 12**).

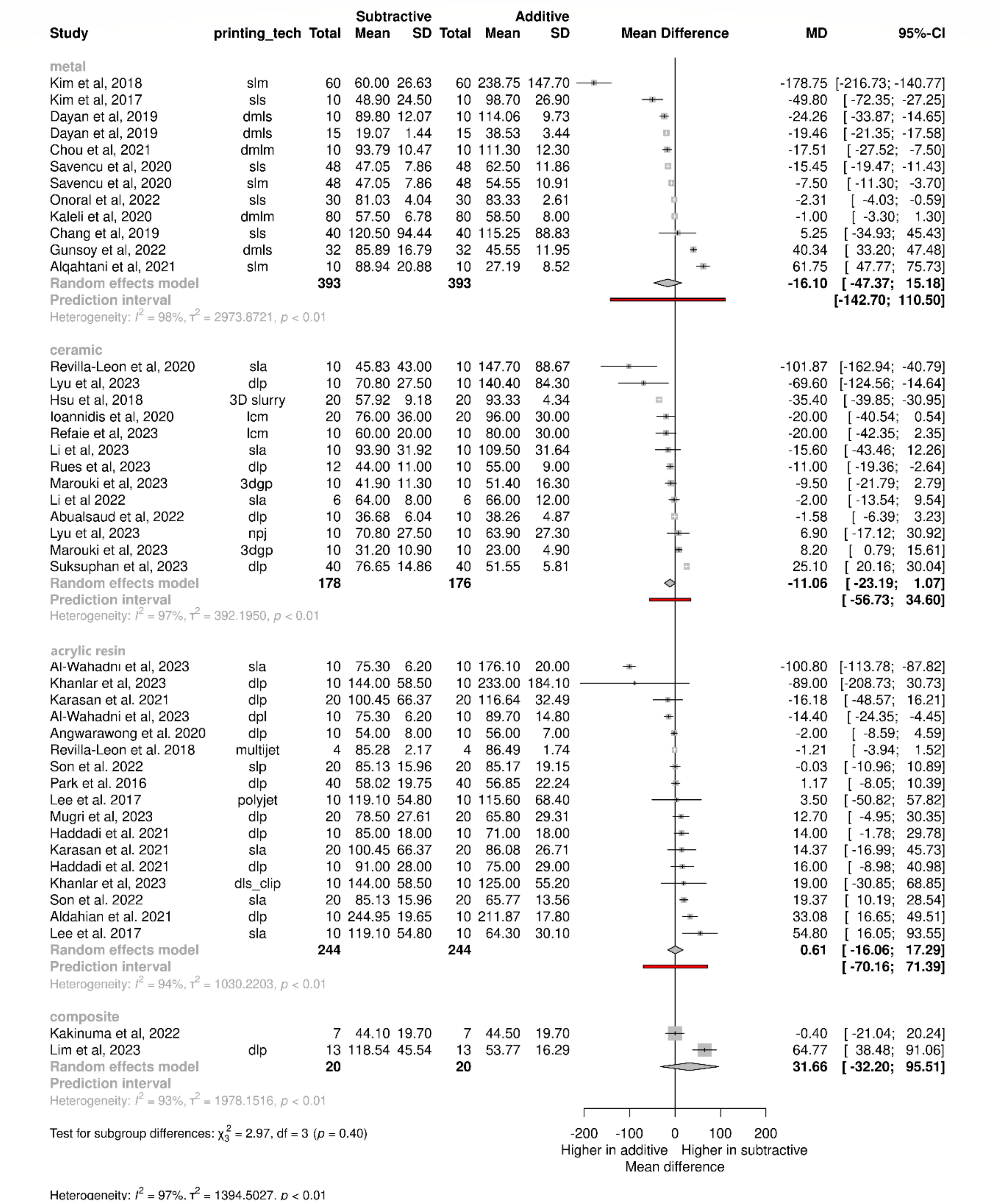

Figure 11. *Forest plot showing the marginal fit (μm) (67)*

There were no statistically significant differences across the subgroups.3DSP= 3-dimensional slurry printing; 3DGP= 3-dimensional gel deposition/printing; CLIP= continuous liquid interface production; DLP= digital light processing; DLS= digital light *synthesis; DMLM= direct metal laser melting; DMLS= direct metal laser sintering; LCM= lithography-based ceramic manufacturing; NPJ= nanoparticle jetting; SLA= stereolithography; SLM=: selective laser melting; SLS= selective laser sintering*

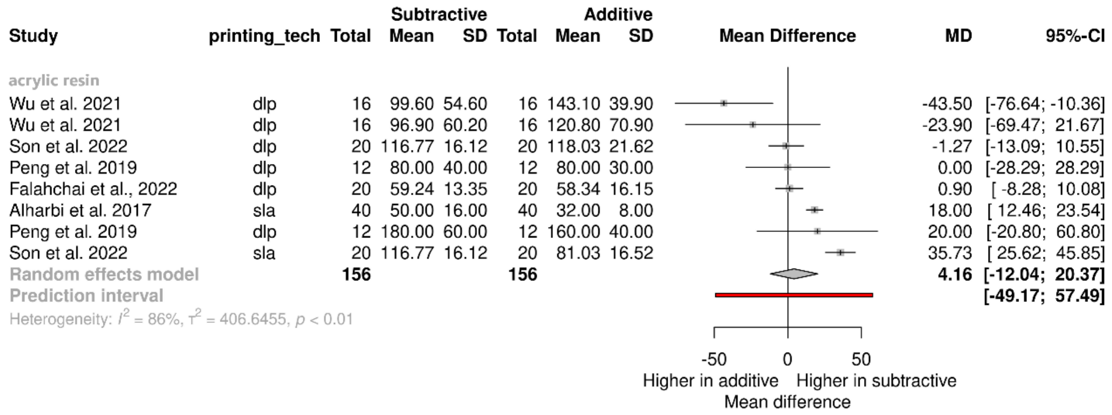

Figure 12. *Forest plot showing the absolute marginal discrepancy (AMD) (µm) (67) Acrylic resin restorations showed no significant difference between AM and SM technologies. DLP= digital light processing; SLA= stereolithography*

8.2.2.3 Trueness

Trueness was assessed across different regions of the restorations, with the marginal area identified as the most clinically relevant. AM ceramics showed a significant mean difference in trueness of -47.76 µm (95% CI: -95.51 to -0.00), although this difference is not clinically relevant (**Figure 13**). For acrylic resin restorations, the mean difference was 11.78 µm (95% CI: -0.65 to 24.21), showing no statistical significance (**Figure 13**).

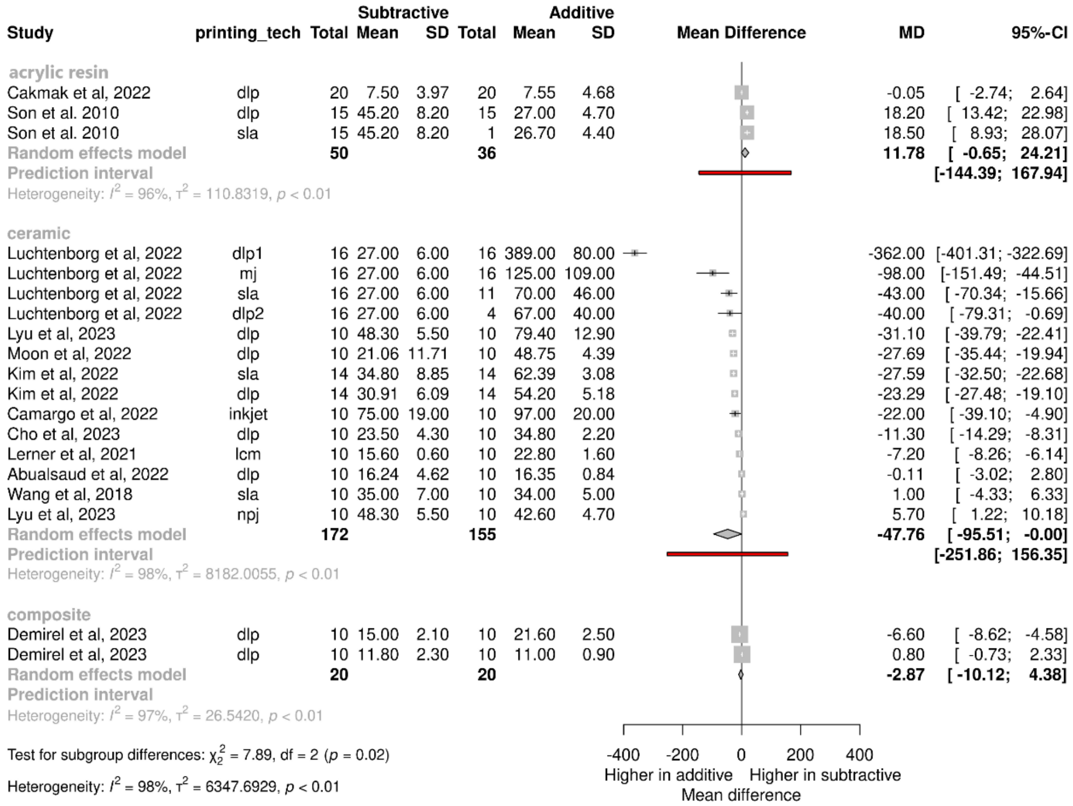

Figure 13. *Forest plot showing the marginal trueness (µm) (67)*

AM ceramic restorations showed significantly worse trueness than SM with no clinical relevance. DLP= digital light processing; LCM= lithography-based ceramic manufacturing; MJ= MultiJet; NPJ= nanoparticle jetting; SLA= stereolithography;

Due to insufficient data on composite restorations, it was impossible to draw conclusions regarding their fit and accuracy. Detailed results from all supplementary analyses are provided in the supplementary documents of the original publication (67).

8.2.3 Risk of Bias in Studies and Certainty of Evidence

The risk of bias was assessed using the QUIN tool. Nine studies were categorized as having a low risk, 47 as medium risk, and one as high risk. The high risk was attributed to the lack of specification in the statistical analysis.

The level of evidence for each outcome was evaluated using the GRADEpro tool. The certainty of the outcomes was generally low, except for the marginal fit of ceramics, which was classified as having very low certainty due to the potential for publication bias. The complete results can be found in the original publication (67).

9 DISCUSSION

The rapid advancement of 3D printing has introduced a wide array of printing methods and materials, revolutionizing clinical workflows and treatment possibilities. Despite its potential, the literature reveals conflicting findings regarding the technology's accuracy, creating uncertainty for practitioners. These studies aimed to address these inconsistencies by comprehensively evaluating the accuracy of various printing techniques and materials. This research aimed to enhance clinical decision-making, improve treatment planning, and optimize patient outcomes by identifying the most suitable technologies and materials for prosthodontic applications.

9.1 Summary of findings, international comparisons of Study I

Our first meta-analysis aimed to evaluate the accuracy of 3D printed dental models compared to a digital reference model. Significant differences were shown between the printed models and the reference; notable differences were observed among various printing technologies. Additionally, the findings highlight the impact of factors such as layer thickness and measurement methods on the accuracy.

9.1.1 Accuracy tolerance levels

Currently, there is no consensus on accuracy tolerance levels for additive manufacturing applications, although tolerances ranging from 50 to 500 μm have been reported in the literature (83, 84, 139-145). The required accuracy depends on the intended use of the printed models. For diagnostic, educational, or preoperative purposes, tolerances between 300–500 μm are acceptable, as they do not compromise outcomes *(139, 146).* In orthodontics, stricter limits are necessary; studies suggest that models for aligner fabrication should have deviations below 250 μm to ensure proper orthodontic force on the teeth (41, 83, 139). Higher precision is essential for prosthodontic applications as they are used to adjust articulation and occlusion and create appropriate occlusal and proximal contacts (37, 38). McLean and von Fraunhofer's study shows that the clinically acceptable marginal gap for prosthodontics is 120 μm, which many authors have adopted as a limit for their studies (86). Accordingly, this meta-analysis defined acceptable clinical limits of 250 μm for orthodontic and 120 μm for prosthodontic application.

9.1.2 Accuracy in the subgroups

Based on our results, DLP, SLA, and PolyJet are the most accurate 3D printing technologies regarding trueness and precision. These findings align with a previous systematic review, which reported that DLP and SLA printers achieved error measurements under 100 µm for full-arch dental models, indicating high trueness (44). In subgroups “Trueness RMS arch level 0–50 µm”, “Trueness RMS tooth level 0–50 µm”, “Precision RMS arch level 0–50 µm” and “Precision RMS arch level over 50 µm” all three technologies achieved below 120 µm falling within clinically acceptable limits for prosthodontic applications. Stereolithography (SLA) is generally considered more accurate than digital light processing (DLP) due to its point-by-point laser curing, which allows for more complete polymerization and leaves less residual monomer (147). However, our findings revealed that DLP surpassed SLA in four subgroups (“Trueness RMS arch level 0–50 µm”, “Trueness RMS arch level over 50 µm”, “Precision RMS arch level 0–50 µm” and “Trueness Deviation arch level over 50 µm”). This may be attributed to the slower movement of SLA’s laser beam, which can introduce errors, whereas DLP uses a faster projector-based process, reducing potential inaccuracies associated with repeated printing cycles (41). "Tooth level" measurements demonstrated greater trueness compared to "arch level" measurements, consistent with previous studies suggesting that measurement level can impact trueness outcomes (41, 81). For example, trueness improved from 106.7 µm to 86.7 µm for SLA and from 138.7 µm to 37.0 µm for MJ in the "tooth level" subgroup. This improvement likely results from the section-based alignment method used in quality control software, which enhances alignment accuracy and reduces measurement errors in smaller sections (148-150).

Our findings suggest that reducing the printing height improves trueness. In the "Trueness RMS tooth level 0–50 µm" subgroup, MJ and PolyJet demonstrated the best accuracy, with mean RMS values of 37 µm and 68 µm, respectively, utilizing the smallest layer thicknesses of 30 µm and 16 µm. It supports the results of previous studies, which define that layer height affects accuracy and surface quality, and decreased layer thickness improves both (143, 151, 152). In the "Trueness RMS arch level over 50 µm", subgroup results were notably higher with wide confidence intervals. Our study indicates that printing with a layer thickness of 0–50 µm achieves better accuracy, particularly in the "Trueness RMS arch level 0–50 µm" subgroup, compared to using thicker layers above

50 µm. For example, SLA and DLP technologies showed a mean difference exceeding 200 µm when using layer thicknesses over 50 µm, whereas they remained below 120 µm when using a layer thickness of 0–50 µm. Printing resolution in the x- and y-dimensions is set by the manufacturer, but the z-dimension (printing height) can be adjusted by the operator. Most printers are capable a minimum layer thickness of 25 µm, with PolyJet achieving 16 µm. Thinner layers lead to more layers, producing smoother and more detailed surfaces, while thicker layers cause increased boundary distances, resulting in rougher surfaces, lower quality, and a stare-stepping effect (84). Park et al. observed that FDM/FFF-printed models exhibit significantly larger deviations and rougher surfaces when compared to SLA models, as evidenced by scanning electron microscope (SEM) images and photographs (153). However, Zhang et al. found that reducing the layer thickness from 50 µm to 20 µm with DLP technology can reduce the printing accuracy (84). This suggests that while selecting the smallest printing height can improve surface characteristics, it does not necessarily guarantee higher accuracy. A significant reduction in layer height increases the likelihood of manufacturing errors, such as deviations from the expected print boundary, artifacts, and inconsistencies during the printing process (83, 84). Additionally, minimal shrinkage in each layer during polymerization can result in the accumulation of these errors (78).

DLP printers from different manufacturers, yet using the same technology, showed similar high trueness results with no significant differences. In the "Trueness Deviation arch level over 50 µm" subgroup, three different DLP printers were evaluated, enabling a comparison across manufacturers. Zhang et al. assessed three DLP printers: EvoDent (UnionTec, Shanghai, China), EncaDent (Encashape, Wuhan, China), and Vida HD (Envisioned, Dearborn, MI, USA) (84). The results revealed that the difference in mean absolute deviations among these printers was only 6 µm. Overall, the accuracy of these printers was great, meeting the clinical standards for both prosthodontic and orthodontic applications.

9.1.3 Root mean square (RMS) versus absolute mean deviation

The included studies expressed accuracy using two different methods: RMS and absolute deviation. Due to differences in calculation methods, accuracy expressed in RMS tends to yield higher values than absolute mean deviation. The analysis software used to compare the models generates three-dimensional deviation data, including RMS and positive and negative mean deviations. When positive and negative values are evenly distributed, their average as the total deviation will approach zero, minimizing the real discrepancy (41, 77). Unlike absolute deviation, RMS is less affected by offset errors, as it accounts for the magnitude of both positive and negative deviations without compensating for them (80). This makes RMS a preferred metric in recent studies for evaluating mean differences in datasets with aligned coordinate systems, as it amplifies differences more effectively (80). This distinction was noticeable in our comparisons: in the "Trueness RMS arch level over 50 µm" subgroup, SLA and DLP technologies showed mean RMS trueness values of 209 µm and 204 µm, respectively. In contrast, the "Trueness Deviation arch level over 50 µm" subgroup achieved 74 µm and 46 µm. Despite identical parameters like model design, layer thickness, and measurement level, RMS values were substantially higher, likely due to the differing calculation formulas.

9.2 Summary of findings, international comparisons of Study II

The aim of our second meta-analysis was to compare the fit and trueness of additive manufacturing to subtractive technology on single-unit and short-span fixed dental restorations while considering the materials used. Our findings support the application of 3D printing in fabricating FPDs since the results indicated no significant differences between AM and SM restorations, with one exception, where SM provided a significantly larger occlusal gap.

9.2.1 Metals

The use of additive techniques for creating metal frameworks and removable partial dentures (RPDs) is well-established in dentistry (25). Previous reviews have shown that AM techniques can produce RPD frameworks within clinically acceptable ranges (59, 60). The findings of our analysis indicated no significant differences between AM and SM techniques, where 13 studies were included evaluating fixed metal restorations made of cobalt-chrome (Co-Cr) alloy for internal and marginal fit. Nevertheless, outliers were observed for occlusal internal fit and marginal fit. Kim et al. reported exceptionally high values for AM (384.00 ± 67.8 µm and 238.75 ± 147.7 µm) (118). It was possibly due to the use of SLM technique with a larger powder size (55 µm) compared to other studies using smaller powder sizes of 16 and 30 µm (117, 125). Larger powder sizes and partially melted particles in SLM may contribute to higher misfits and rough surfaces (154). Overall, our findings align with previous meta-analyses on implant-supported frameworks, affirming AM as a reliable method for producing metal frameworks (155). In addition, in everyday dentistry, AM has already replaced milling to produce metal components, except for titanium implant abutments. Milling became inefficient and uneconomical for such applications due to rapid tool wear and the high cost of metal alloys (156).

9.2.2 Acrylic resins

Provisional restorations play a crucial role by offering protection and giving functional and esthetic insights for the patient while serving as templates for final prostheses. Their main functions include protecting the pulp, managing soft tissues, and providing therapeutic and functional support. Proper internal fit and marginal sealing are critical for maintaining periodontal health and avoiding complications such as cement dissolution, bacterial invasion, pulpal irritation, and secondary caries (157). Provisional restoration materials fall into two categories: methacrylic and bis-GMA-based resins. PMMA, a widely used acrylic resin, is popular for long-term temporary restorations due to its durability, cost-effectiveness, and high flexural strength. However, it is associated with polymerization shrinkage and exothermic reactions during setting (158, 159). Polymerization shrinkage is a common cause of dimensional inaccuracies and increased marginal gaps, particularly in conventionally fabricated temporary restorations (160, 161). However, CAD/CAM technology minimizes these issues as blocks used in these systems are pre-polymerized, and 3D printed resin polymerization is conducted under controlled conditions in every cross-section (94, 162). Systematic reviews and meta-analyses indicate that AM interim materials exhibit great mechanical properties compared to milled and conventionally fabricated restorations (163). A total of 22 studies assessed acrylic resin restorations concerning internal fit, marginal fit, and trueness. There were no significant differences between additive and subtractive manufacturing for these parameters, except for occlusal internal fit. SM restorations exhibited a significantly larger occlusal gap of 39.12 μm (95% CI: 12.44; 65.79). The accuracy of the occlusal surface is particularly important for the structural durability of crowns (92). However, the precise fabrication of uneven intaglio surfaces is challenging for SM due to limitations in the size and angulation of cutting tools (90, 91, 162). This issue, known as drill compensation, involves adjusting the internal geometry of the restoration to align with the capabilities of the milling burs. Factors such as tool shape, tool diameter, and the hardness of the substrate can influence the extent of this compensation (164). Proper preparation designs can mitigate this issue by minimizing the effects of drill compensation and reducing the likelihood of overmilling (165). These findings suggest that AM is better suited to reproduce the detailed anatomy of inner surfaces and occlusal features in temporary restorations than milling. This conclusion aligns with earlier systematic review and meta-analysis, which reported that 3D printed provisional FPDs exhibit superior marginal fit and internal adaptation compared to those fabricated using CAD/CAM milling or conventional methods (57). In axial internal fit measurements, Lee et al. reported an outlier gap of 137.4 (± 67.8) µm for AM. This deviation was likely caused by using a material designed for models, try-ins, and impression trays (VeroGlaze MED620, Stratasys, USA) instead of temporary resin (91, 166). Similarly, Wu et al. recorded a gap of 143.1 (± 39.9) µm for the absolute marginal discrepancy with AM. This higher value can be attributed to using denture teeth material (Dima Print Denture Teeth, Kulzer, North America, USA) instead of materials specifically intended for temporary restorations (90). These findings underscore the importance of material selection in achieving accurate fit measurements in printed restorations.

9.2.3 Ceramics

Nineteen studies focused on evaluating ceramic fixed prostheses for internal fit, marginal fit, and trueness, with the majority examining zirconia exclusively (109). The analysis revealed that AM ceramic restorations demonstrated significantly lower marginal trueness, with a difference of -47.76 µm (95% CI: -95.51; -0.00) compared to milled restorations. However, there were no statistically significant differences between AM and SM for other measurements. Given that 18 of the included studies investigated zirconia, the findings provide limited insight into the performance of other ceramic materials. Zirconia restorations are widely spread for their chemical stability, biocompatibility, mechanical strength, and optical properties (167). While subtractive manufacturing is the traditional fabrication method, its shortcomings have spurred interest in additive manufacturing as a cost-effective, precise alternative capable of producing complex geometries (15, 168). However, AM faces challenges, for example, the composition of the ceramic suspension is a critical factor in the printing process, as it necessitates high solid loading, uniform dispersion, and low viscosity to achieve optimal results (169). High solid loading is essential for producing ceramic restorations with adequate densification while minimizing defects during debinding and sintering. However, increasing the ceramic content reduces flowability, potentially causing challenges during the layering process. Striking a balance in ceramic loading is therefore challenging, as it requires reducing viscosity to maintain flowability while ensuring higher density for improved mechanical properties and reduced shrinkage (170, 171). Additionally, light scattering from ceramic particles, particularly zirconia, which have a significant light scattering effect with a relative index of 20-27%, hinders photopolymerization and affects curing depth in vat-polymerization techniques like SLA and DLP (14, 168). Material jetting also struggles with issues like the coffee-stain effect, when the ceramic particles isolate to the edges during drying (172). Lyu et al. demonstrated extreme occlusal and marginal fit results in this subgroup using the DLP printer (J2 D140L CERAMICS, Junjing), while the NPJ printer produced acceptable results. This discrepancy may be due to the higher zirconia loading (80 wt%) in the DLP printer, which could increase suspension viscosity and lead to solid content segregation (170, 171). In contrast, the NPJ printer used 45% zirconia ink. Moreover, the J2 D140L CERAMICS DLP printer mentioned above could not be found on any website or source by the authors. Another outlier result was reported by Ioannidis et al., reaching 290.5 (± 145.14) µm in occlusal fit measurements with AM, likely due to an excessive layer thickness of 100 µm (63). Lüchtenborg et al. provided another outlier in trueness measurements (389.0 ± 80.00 µm) with a homemade DLP printer from the University of Birmingham (51). Similarly, Rues et al. found an unexpectedly large gap of 381.0 (± 26.0) µm in a milled zirconia veneer, attributed to drill compensation explained by the authors (106). Despite these challenges, additive manufacturing for zirconia shows great promise, though the optimal suspension consistency and suitable technology need further clarification and investigation, not to mention the long manufacturing time. Until advancements are made, subtractive manufacturing remains the preferred method to produce zirconia restorations in everyday practice.

9.2.4 Misfit evaluation techniques

Various techniques are available for evaluating the fit between restorations and abutments, including destructive and nondestructive methods and cemented and noncemented approaches. The silicone replica technique is widely used for assessing internal fit without damaging the tested sample (173). A low-viscosity silicone is applied during this method to fill the gap between the restorations and the master die. It is followed by heavy-body silicone to support the thin film forming a single piece (174). The silicone replica is then sectioned, and the thickness of the light body is measured under a microscope (175). Micro-computed tomography (micro-CT) provides a non-destructive, three-dimensional evaluation but may face limitations such as radiation artifacts due to differences in material absorption coefficients (96, 176). Optical coherence tomography (OCT) is another non-invasive option that employs partially coherent light to generate high-resolution, real-time imaging without ionizing radiation (177). Restorations are cemented, sectioned, and examined for destructive evaluations under light or electron microscopy to assess the tooth–prosthesis interface (53). Recent studies, particularly those published after 2022, measure the trueness of the printed and milled restorations (11). In these studies, the triple-scan method is used, which is a validated, non-destructive alternative to the replica technique (178). This process involves digitizing the prepared tooth, prosthesis, and their construction to provide analysis of cement space and overall accuracy (49, 179).

9.3 Strengths

The greatest strength of our work is that a rigorous methodology was used for both meta-analyses to ensure the highest standard of evidence and deliver a well-organized analysis of the findings reported in the literature.

9.3.1 Strength of Study I

This study was the first systematic review and meta-analysis evaluating the accuracy of 3D printed dental models using network meta-analysis. This approach enables the integration of both direct and indirect evidence across a network of studies, enhancing the practical applicability of the findings. Simultaneously assessing all available interventions facilitates the estimation of their relative rankings for specific outcomes, a feature not achievable through traditional meta-analyses.

9.3.2 Strength of Study II

Our second project includes a large number of publications, mainly from the last 5 years, so it gives a comprehensive picture of the present state of the technology, analyzing various materials, such as metals, polymers, and ceramics, and evaluating not only internal and marginal fit but trueness as well on axial, occlusal and marginal surfaces.

9.4 Limitations

Evaluating additive manufacturing is always challenging because numerous factors can affect printing accuracy, such as the printing technology, layer thickness, the material used, post-processing, etc. If we want to investigate the influence of one of the elements, all the other circumstances should be standardized. However, inconsistencies in printing parameters and testing protocols make comparisons challenging. Therefore, the biggest limitation of our analyses is the heterogeneity of the included studies.

9.4.1 Limitations of Study I

The main limitation of Study I was that only horseshoe-shaped models were investigated since sufficient data were only available about them. Therefore, the statistical analysis could not include the cross-arch plate and full models. In addition, subgroup sample sizes were small, reference scanners were inconsistent, and there was variability in dental model anatomy, which hindered comparability and certainty of results. This meta-analysis did not account for factors such as printing orientation, postprocessing procedures, storage conditions, and the potential for human error, which can significantly influence accuracy beyond the risk of bias assessment. However, these variables may impact the results.

9.4.2 Limitations of Study II

The major limitation of this study was that the scope of the study was extensive, encompassing various materials, technologies, and processes, which presents challenges in comparison due to differing parameters and testing protocols across included studies and creates heterogeneity across the studies. One shortcoming of the work is the lack of subgroup analysis based on material composition, such as variations in solid loading rates of zirconia suspensions, even though material properties like shrinkage, viscosity, and mechanical behavior significantly impact dimensional accuracy. Additionally, the analysis did not differentiate by prosthesis type or preparation style. Heterogeneity in printers, milling machines, restorations, software, and measurement techniques further complicates drawing unified assumptions. Therefore, these limitations should be considered when interpreting the study's conclusions.

10 CONCLUSIONS

Study I

1. Stereolithography (SLA), digital light processing (DLP), and PolyJet technologies are the most accurate methods for producing full-arch dental models for prosthodontic applications, offering high trueness values.

2. Conversely, FDM/FFF, LCD, and CLIP technologies proved to be unsuitable for fabricating dental devices requiring accuracy below 120 µm.

3. A layer thickness between 0–50 µm was identified as optimal for achieving clinically acceptable accuracy levels.

Study II

1. Fixed dental restorations fabricated with additive manufacturing are valid alternatives in the digital workflow regarding marginal fit, internal fit, and trueness compared to subtractive manufacturing.

2. No significant differences in adaptation were observed between additively manufactured (AM) and subtractively manufactured (SM) metal and ceramic restorations.

3. 3D printed acrylic resin restorations demonstrated a significantly more accurate occlusal fit compared to SM, while AM ceramic restorations exhibited significantly reduced marginal trueness. However, these differences were not clinically relevant.

4. Dental zirconia fabrication with 3D printing is still under development, and further improvements in current AM technologies are needed.

11 IMPLEMENTATIONS FOR PRACTICE

Implementing research results in everyday practice is essential and has major health and economic benefits (180, 181). Traditionally, dental devices require multiple tools and labor-intensive processes, but ongoing developments in 3D printing have led to innovative machines capable of producing a wide range of products using specialized resins, reducing the need for outsourcing and cutting material waste. Open-system printers further drive cost savings by allowing flexibility in material choices and lowering dependency on proprietary options. These innovations streamline workflows, improve efficiency, and boost profitability for dental labs and clinics, making 3D printing a cost-effective solution for modern dentistry.

Study I highlights the suitability of additive manufacturing technologies for 3D printed dental models. For prosthodontic and implantological applications, SLA, DLP, and PolyJet technologies are recommended as they reach the required accuracy level for full-arch model production. From an orthodontic perspective, FDM/FFF technologies are considered appropriate. To achieve clinically acceptable accuracy across both prosthodontic and orthodontic applications, a layer thickness of 0–50 µm is preferable.

Study II supports the application of additive manufacturing in prosthodontics, particularly for single-unit and short-term acrylic resin restorations and definitive metal FPDs, demonstrating favorable adaptation outcomes. However, additional research and advancements are essential for ceramic materials, especially zirconia dental products, to further optimize their application in clinical practice.

12 IMPLEMENTATION FOR RESEARCH

Printing accuracy is influenced by various factors that have to be described and clarified before assessing deviations accurately and accounting for potential limitations effectively. Therefore, a standardized reporting protocol for 3D printing details is essential. Authors must specify all evaluation parameters critical for interpreting results. Key factors for future studies include precise printing parameters, such as layer thickness, model design (e.g., horseshoe-shaped, cross-arch plate, or full model), material selection, and postprocessing procedures (e.g., support removal, cleaning, and post-curing). Storage conditions (temperature, humidity, and duration) and printing parameters like build angle and direction should be detailed.

The lack of universal guidelines for performing gap measurement of restorations results in inconsistencies across studies. Additionally, there is variation in terminology used by authors (e.g., marginal gap, marginal fit, cervical fit), although Holmes et al. provided a precise misfit terminology to standardize the measurement (69). Consequently, a standardized accuracy assessment protocol is necessary to evaluate printed objects consistently using similar methodologies adapted to the different appliances. For example, future studies should develop a standardized and reliable method for assessing internal and marginal fit, enabling consistent comparison across different research studies. In addition, regarding clinically acceptable accuracy, the authors still refer to a study from 1971 by McLean et al., where a rubber film technique was applied, and the evaluation was made with a microscope under low magnification (25x) (48). Since then, newer restorative materials and luting cements have been developed by the effect of CAD/CAM technology, and more modern and precise measuring techniques are available, as listed above. So, there is an unmet need to perform long-term randomized controlled trials (RCT) on FPDs to confirm clinical applicability, success, and survival.

13 IMPLEMENTATION FOR POLICYMAKERS

Policymakers should implement several actions to effectively manage and promote 3D printing in dentistry. This includes developing clear standards and guidelines for material specifications, printing parameters, and post-processing requirements to ensure consistent quality and accuracy across dental practices. Setting strict regulations for the safety and quality of materials used in 3D printing, particularly for biocompatible resins, is also essential. Promoting research and development in dental 3D printing technologies can foster innovation in material science and digital workflows. Providing education and training for dental professionals could enhance their understanding and effective use of these technologies. Continuous monitoring through post-market surveillance will track the impact of AM, allowing for adjustments to policies to maintain high standards of care and patient safety. These steps will create a supportive environment for integrating 3D printing into everyday practice, enhancing the quality, accessibility, and affordability of dental treatments.

14 FUTURE PERSPECTIVES

The future of 3D printing in dentistry holds excellent promise, mirroring the rapid advancements observed with intraoral scanners. As we have witnessed the emergence of different types of IOS with a wide range of features, newer 3D printing machines are arriving, featuring innovative and improved technologies. These range from budget-friendly options to high-end professional types, allowing users to select the most suitable device based on their clinical or laboratory needs.

Simultaneously, the market is expected to expand with a broader collection of printable materials, particularly restorative materials. These will exhibit improved aesthetics and enhanced mechanical properties, such as fracture toughness and surface roughness. These advancements position printed materials as strong competitors to millable alternatives. Among these, resin-based ceramic materials are anticipated to be a groundbreaking innovation. However, the next transformative leap in dental 3D printing will likely be the advent of printable zirconia, which holds immense potential for revolutionizing prosthetic dentistry within the next few years.

As AM continues to evolve, its role in dentistry will expand, paving the way for even more innovative applications, cost-effective solutions, and efficient workflows. These innovations will redefine the role of 3D printing in delivering high-quality, patient-centered treatment. This evolution underscores the need for ongoing research and development to explore and fully harness these emerging technologies' potential.

15 REFERENCES

1. Baroudi K, Ibraheem SN. Assessment of Chair-side Computer-Aided Design and Computer-Aided Manufacturing Restorations: A Review of the Literature. Journal of International Oral Health: JIOH. 2015;7(4):96-104.

2. Alghazzawi TF. Advancements in CAD/CAM technology: Options for practical implementation. Journal of prosthodontic research. 2016;60(2):72-84.

3. van Noort R. The future of dental devices is digital. Dental Materials. 2012;28(1):3-12.

4. Liaw CY, Guvendiren M. Current and emerging applications of 3D printing in medicine. Biofabrication. 2017;9(2):024102.

5. Tian Y, Chen C, Xu X, Wang J, Hou X, Li K, et al. A Review of 3D Printing in Dentistry: Technologies, Affecting Factors, and Applications. Scanning. 2021;2021:9950131.

6. ASTM CFoamt, West Conshohocken, Pa. Standard terminology for additive manufacturing - general principles and terminology. ISO/ASTM52900-15. 2009.

7. Davidowitz G, Kotick PG. The use of CAD/CAM in dentistry. Dental clinics of North America. 2011;55(3):559-70, ix.

8. Strub JR, Rekow ED, Witkowski S. Computer-aided design and fabrication of dental restorations: current systems and future possibilities. Journal of the American Dental Association (1939). 2006;137(9):1289-96.

9. Kim CM, Kim SR, Kim JH, Kim HY, Kim WC. Trueness of milled prostheses according to number of ball-end mill burs. The Journal of Prosthetic Dentistry. 2016;115(5):624-9.

10. Lebon N, Tapie L, Duret F, Attal JP. Understanding dental CAD/CAM for restorations - dental milling machines from a mechanical engineering viewpoint. Part A: chairside milling machines. International Journal of Computerized Dentistry. 2016;19(1):45-62.

11. Revilla-León M, Meyers MJ, Zandinejad A, Özcan M. A review on chemical composition, mechanical properties, and manufacturing workflow of additively manufactured current polymers for interim dental restorations. Journal of esthetic and restorative dentistry : official publication of the American Academy of Esthetic Dentistry [et al]. 2019;31(1):51-7.

12. Revilla-León M, Sadeghpour M, Özcan M. A Review of the Applications of Additive Manufacturing Technologies Used to Fabricate Metals in Implant Dentistry. Journal of Prosthodontics: official journal of the American College of Prosthodontists. 2020;29(7):579-93.

13. Revilla-León M, Meyer MJ, Zandinejad A, Özcan M. Additive manufacturing technologies for processing zirconia in dental applications. International Journal of Computerized Dentistry. 2020;23(1):27-37.

14. Della Bona A, Cantelli V, Britto VT, Collares KF, Stansbury JW. 3D printing restorative materials using a stereolithographic technique: a systematic review. Dental materials : official publication of the Academy of Dental Materials. 2021;37(2):336-50.

15. Alammar A, Kois JC, Revilla-León M, Att W. Additive Manufacturing Technologies: Current Status and Future Perspectives. Journal of Prosthodontics: official journal of the American College of Prosthodontists. 2022;31(S1):4-12.

16. Schwentenwein M, Schneider P, Homa JJAiS, Technology. Lithography-based ceramic manufacturing: A novel technique for additive manufacturing of high-performance ceramics. 2014;88:60-4.

17. Schönherr JA, Baumgartner S, Hartmann M, Stampfl J. Stereolithographic Additive Manufacturing of High Precision Glass Ceramic Parts. Materials (Basel, Switzerland). 2020;13(7).

18. Gatto ML, Groppo R, Furlani M, Giuliani A, Mangano C, Mangano F. Lithography-based Ceramic Manufacturing (LCM) versus Milled Zirconia Blocks under uniaxial compressive loading: An in vitro comparative study. Journal of Dentistry. 2022;116:103886.

19. Piedra-Cascón W, Krishnamurthy VR, Att W, Revilla-León M. 3D printing parameters, supporting structures, slicing, and post-processing procedures of vat-polymerization additive manufacturing technologies: A narrative review. Journal of Dentistry. 2021;109:103630.

20. Suzuki Y, Shimizu S, Waki T, Shimpo H, Ohkubo C. Laboratory efficiency of additive manufacturing for removable denture frameworks: A literature-based review. Dental materials journal. 2021;40(2):265-71.

21. Revilla-León M, Sadeghpour M, Özcan M. An update on applications of 3D printing technologies used for processing polymers used in implant dentistry. Odontology. 2020;108(3):331-8.

22. Cristache CM, Totu EEJR, materials FPVTA. 3D printing-processed polymers for dental applications. 2021:141-64.

23. Alghauli M, Alqutaibi AY, Wille S, Kern M. 3D-printed versus conventionally milled zirconia for dental clinical applications: Trueness, precision, accuracy, biological and esthetic aspects. Journal of Dentistry. 2024;144:104925.

24. Yang H, Liu Y. Accuracy of Models Fabricated by a Chair-side Fused Deposition Modeling (FDM) Printer in Stomatology. Operative dentistry. 2022;47(5):E233-e40.

25. Jeong M, Radomski K, Lopez D, Liu JT, Lee JD, Lee SJ. Materials and Applications of 3D Printing Technology in Dentistry: An Overview. Dentistry Journal. 2023;12(1).

26. Ender A, Mehl A. Accuracy of complete-arch dental impressions: a new method of measuring trueness and precision. The Journal of Prosthetic Dentistry. 2013;109(2):121-8.

27. Stober T, Johnson GH, Schmitter M. Accuracy of the newly formulated vinyl siloxanether elastomeric impression material. The Journal of Prosthetic Dentistry. 2010;103(4):228-39.

28. Kang AH, Johnson GH, Lepe X, Wataha JC. Accuracy of a reformulated fast-set vinyl polysiloxane impression material using dual-arch trays. The Journal of Prosthetic Dentistry. 2009;101(5):332-41.

29. Husein HA, Morad ML, Kanout S. Accuracy of Conventional and Digital Methods of Obtaining Full-Arch Dental Impression (In Vitro Study). Cureus. 2022;14(9):e29055.

30. Patzelt SB, Bishti S, Stampf S, Att W. Accuracy of computer-aided design/computer-aided manufacturing-generated dental casts based on intraoral scanner data. Journal of the American Dental Association (1939). 2014;145(11):1133-40.

31. Joda T, Zarone F, Ferrari M. The complete digital workflow in fixed prosthodontics: a systematic review. BMC Oral Health. 2017;17(1):124.

32. Tallarico M. Computerization and Digital Workflow in Medicine: Focus on Digital Dentistry. Materials (Basel, Switzerland). 2020;13(9).

33. Narita M, Takaki T, Shibahara T, Iwamoto M, Yakushiji T, Kamio T. Utilization of desktop 3D printer-fabricated "Cost-Effective" 3D models in orthognathic surgery. Maxillofacial Plastic and Reconstructive Surgery. 2020;42(1):24.

34. Nicot R, Druelle C, Schlund M, Roland-Billecart T, Gwénaël R, Ferri J, et al. Use of 3D printed models in student education of craniofacial traumas. Dental traumatology: official publication of International Association for Dental Traumatology. 2019;35(4-5):296-9.

35. Seifert LB, Schnurr B, Herrera-Vizcaino C, Begic A, Thieringer F, Schwarz F, et al. 3D printed patient individualised models versus cadaveric models in an undergraduate oral and maxillofacial surgery curriculum: Comparison of students' perceptions. European journal of dental education: official journal of the Association for Dental Education in Europe. 2020;24(4):809-10.

36. Davies S, Al-Ani Z, Jeremiah H, Winston D, Smith P. Reliability of recording static and dynamic occlusal contact marks using transparent acetate sheet. The Journal of Prosthetic Dentistry. 2005;94(5):458-61.

37. Dawood A, Marti Marti B, Sauret-Jackson V, Darwood A. 3D printing in dentistry. British Dental Journal. 2015;219(11):521-9.

38. Buda M, Bratos M, Sorensen JA. Accuracy of 3-dimensional computer-aided manufactured single-tooth implant definitive casts. The Journal of Prosthetic Dentistry. 2018;120(6):913-8.

39. Sim JY, Jang Y, Kim WC, Kim HY, Lee DH, Kim JH. Comparing the accuracy (trueness and precision) of models of fixed dental prostheses fabricated by digital and conventional workflows. Journal of pProsthodontic Research. 2019;63(1):25-30.

40. Yu X, Li G, Zheng Y, Gao J, Fu Y, Wang Q, et al. 'Invisible' orthodontics by polymeric 'clear' aligners molded on 3D-printed personalized dental models. Regenerative Biomaterials. 2022;9(1):rbac007.

41. Kim SY, Shin YS, Jung HD, Hwang CJ, Baik HS, Cha JY. Precision and trueness of dental models manufactured with different 3-dimensional printing techniques. American journal of orthodontics and dentofacial orthopedics : official publication of the American Association of Orthodontists, its constituent societies, and the American Board of Orthodontics. 2018;153(1):144-53.

42. Emir F, Ceylan G, Ayyildiz S. In vitro accuracies of 3D printed models manufactured by two different printing technologies. European Oral Research. 2021;55(2):80-5.

43. Rey-Joly Maura C, Godinho J, Amorim M, Pinto R, Marques D, Jardim L. Precision and trueness of maxillary crowded models produced by 2 vat photopolymerization 3-dimensional printing techniques. American journal of orthodontics and dentofacial orthopedics : official publication of the American Association of Orthodontists, its constituent societies, and the American Board of Orthodontics. 2021;160(1):124-31.

44. Etemad-Shahidi Y, Qallandar OB, Evenden J, Alifui-Segbaya F, Ahmed KE. Accuracy of 3-Dimensionally Printed Full-Arch Dental Models: A Systematic Review. Journal of Clinical Medicine. 2020;9(10).

45. Marouki C, Shamon A, Svanborg P. Evaluation of fit and accuracy of single crowns fabricated from self-glazed zirconia compared with milled zirconia. The Journal of Prosthetic Dentistry. 2023.

46. Revilla-León M, Methani MM, Morton D, Zandinejad A. Internal and marginal discrepancies associated with stereolithography (SLA) additively manufactured zirconia crowns. The Journal of Prosthetic Dentistry. 2020;124(6):730-7.

47. ADA. ANSI/ADA Specification No. 8 for zinc phosphate cement. Guide to dental materials and devices (ed 5), American Dental Association, Chicago (1970-1971).

48. McLean JW, von Fraunhofer JA. The estimation of cement film thickness by an in vivo technique. British Dental Journal. 1971;131(3):107-11.

49. Karasan D, Legaz J, Boitelle P, Mojon P, Fehmer V, Sailer I. Accuracy of Additively Manufactured and Milled Interim 3-Unit Fixed Dental Prostheses. Journal of Prosthodontics: official journal of the American College of Prosthodontists. 2022;31(S1):58-69.

50. Haddadi Y, Ranjkesh B, Isidor F, Bahrami G. Marginal and internal fit of crowns based on additive or subtractive manufacturing. Biomaterial investigations in dentistry. 2021;8(1):87-91.

51. Lüchtenborg J, Willems E, Zhang F, Wesemann C, Weiss F, Nold J, et al. Accuracy of additively manufactured zirconia four-unit fixed dental prostheses fabricated by stereolithography, digital light processing and material jetting compared with

subtractive manufacturing. Dental materials : official publication of the Academy of Dental Materials. 2022;38(9):1459-69.

52. Lerner H, Nagy K, Pranno N, Zarone F, Admakin O, Mangano F. Trueness and precision of 3D-printed versus milled monolithic zirconia crowns: An in vitro study. Journal of Dentistry. 2021;113:103792.

53. Boitelle P, Mawussi B, Tapie L, Fromentin OJJoor. A systematic review of CAD/CAM fit restoration evaluations. 2014;41(11):853-74.

54. Oliveira TT, Reis AC. Fabrication of dental implants by the additive manufacturing method: A systematic review. The Journal of Prosthetic Dentistry. 2019;122(3):270-4.

55. Saravi B, Vollmer A, Hartmann M, Lang G, Kohal RJ, Boeker M, et al. Clinical Performance of CAD/CAM All-Ceramic Tooth-Supported Fixed Dental Prostheses: A Systematic Review and Meta-Analysis. Materials (Basel, Switzerland). 2021;14(10).

56. Svanborg P, Hjalmarsson L. A systematic review on the accuracy of manufacturing techniques for cobalt chromium fixed dental prostheses. Biomaterial Investigations in Dentistry. 2020;7(1):31-40.

57. Al Wadei MHD, Sayed ME, Jain S, Aggarwal A, Alqarni H, Gupta SG, et al. Marginal adaptation and internal fit of 3D-printed provisional crowns and fixed dental prosthesis resins compared to CAD/CAM-milled and conventional provisional resins: A systematic review and meta-analysis. 2022;12(11):1777.

58. Al Hamad KQ, Al-Rashdan BA, Ayyad JQ, Al Omrani LM, Sharoh AM, Al Nimri AM, et al. Additive Manufacturing of Dental Ceramics: A Systematic Review and Meta-Analysis. Journal of prosthodontics : official journal of the American College of Prosthodontists. 2022;31(8):e67-e86.

59. Ahmed N, Abbasi MS, Haider S, Ahmed N, Habib SR, Altamash S, et al. Fit Accuracy of Removable Partial Denture Frameworks Fabricated with CAD/CAM, Rapid Prototyping, and Conventional Techniques: A Systematic Review. BioMed Research International. 2021;2021:3194433.

60. Yunizar MF, Watanabe M, Ichikawa T. Current development status of additive manufacturing technologies for fabricating removable partial denture frameworks: a literature review. International Journal of Computerized Dentistry. 2022;25(1):57-70.

61. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ (Clinical research ed). 2021;372:n71.

62. Cumpston M, Li T, Page MJ, Chandler J, Welch VA, Higgins JP, et al. Updated guidance for trusted systematic reviews: a new edition of the Cochrane Handbook for Systematic Reviews of Interventions. The Cochrane database of systematic reviews. 2019;10(10):Ed000142.

63. Németh A, Vitai V, Czumbel ML, Szabó B, Varga G, Kerémi B, et al. Clear guidance to select the most accurate technologies for 3D printing dental models - A network meta-analysis(☆). Journal of Dentistry. 2023;134:104532.

64. Whiting PF, Rutjes AW, Westwood ME, Mallett S, Deeks JJ, Reitsma JB, et al. QUADAS-2: a revised tool for the quality assessment of diagnostic accuracy studies. Annals of Internal Medicine. 2011;155(8):529-36.

65. Iorio A, Spencer FA, Falavigna M, Alba C, Lang E, Burnand B, et al. Use of GRADE for assessment of evidence about prognosis: rating confidence in estimates of event rates in broad categories of patients. BMJ. 2015;350:h870.

66. GRADEpro GDT: GRADEpro Guideline Development Tool [Software] McMaster University and Evidence Prime2022 [Available from: gradepro.org.

67. Németh A, Vitai V, Kelemen K, Teutsch B, Szabó B, Gerber G, et al. Comparison of fit and trueness of single-unit and short-span fixed dental restorations fabricated by additive and subtractive manufacturing - A systematic review and meta-analysis. Journal of Dentistry. 2024:105527.

68. Sheth VH, Shah NP, Jain R, Bhanushali N, Bhatnagar V. Development and validation of a risk-of-bias tool for assessing in vitro studies conducted in dentistry: The QUIN. The Journal of Prosthetic Dentistry. 2022.

69. Holmes JR, Bayne SC, Holland GA, Sulik WD. Considerations in measurement of marginal fit. The Journal of Prosthetic Dentistry. 1989;62(4):405-8.

70. 5725-1 I. Accuracy (trueness and precision) of measuring methods and results. Part-I: General principles and definitions. 1994.

71. Viechtbauer W. A general workflow for complex meta-analyses with dependent effect sizes Maastricht University2021 [Available from: https://www.wvbauer.com/.

72. Higgins JP, Thompson SG. Quantifying heterogeneity in a meta-analysis. Statistics in Medicine. 2002;21(11):1539-58.

73. Egger M, Davey Smith G, Schneider M, Minder C. Bias in meta-analysis detected by a simple, graphical test. BMJ (Clinical research ed). 1997;315(7109):629-34.

74. Team RC. R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. 2023 [Available from: https://www.r-project.org/.

75. Schwarzer G. General Package for Meta-Analysis 2024 [Available from: https://link.springer.com/book/10.1007/978-3-319-21416-0.

76. Viechtbauer W. Metafor: Meta-Analysis Package for R 2023 [Available from: https://cran.r-project.org/web/packages/metafor/index.html.

77. Emir F, Ayyildiz S. Accuracy evaluation of complete-arch models manufactured by three different 3D printing technologies: a three-dimensional analysis. Journal of Prosthodontic Research. 2021;65(3):365-70.

78. Abduo J. Accuracy of casts produced from conventional and digital workflows: A qualitative and quantitative analyses. J Adv Prosthodont. 2019;11(2):138-46.

79. Shin SH, Lim JH, Kang YJ, Kim JH, Shim JS, Kim JE. Evaluation of the 3D Printing Accuracy of a Dental Model According to Its Internal Structure and Cross-Arch Plate Design: An In Vitro Study. Materials (Basel, Switzerland). 2020;13(23).

80. Lo Giudice A, Ronsivalle V, Rustico L, Aboulazm K, Isola G, Palazzo G. Evaluation of the accuracy of orthodontic models prototyped with entry-level LCD-based 3D printers: a study using surface-based superimposition and deviation analysis. Clinical Oral Investigations. 2022;26(1):303-12.

81. Choi JW, Ahn JJ, Son K, Huh JB. Three-Dimensional Evaluation on Accuracy of Conventional and Milled Gypsum Models and 3D Printed Photopolymer Models. Materials (Basel, Switzerland). 2019;12(21).

82. Burde AV, Gasparik C, Baciu S, Manole M, Dudea D, Câmpian RS, editors. Three-dimensional accuracy evaluation of two additive manufacturing processes in the production of dental models. Key Engineering Materials; 2017: Trans Tech Publ.

83. Akyalcin S, Rutkowski P, Arrigo M, Trotman CA, Kasper FK. Evaluation of current additive manufacturing systems for orthodontic 3-dimensional printing. American journal of orthodontics and dentofacial orthopedics : official publication of the American

Association of Orthodontists, its constituent societies, and the American Board of Orthodontics. 2021;160(4):594-602.

84. Zhang ZC, Li PL, Chu FT, Shen G. Influence of the three-dimensional printing technique and printing layer thickness on model accuracy. Journal of orofacial orthopedics = Fortschritte der Kieferorthopadie : Organ/official journal Deutsche Gesellschaft fur Kieferorthopadie. 2019;80(4):194-204.

85. Mangano FG, Admakin O, Bonacina M, Biaggini F, Farronato D, Lerner H. Accuracy of 6 Desktop 3D Printers in Dentistry: A Comparative In Vitro Study. The European Journal of Prosthodontics and Restorative Dentistry. 2020;28(2):75-85.

86. McLean JJBdj. The estimation of cement film thickness by an in vivo technique. 1971;131:107-11.

87. Metlerski M, Grocholewicz K, Jaroń A, Lipski M, Trybek G. Comparison of Presurgical Dental Models Manufactured with Two Different Three-Dimensional Printing Techniques. Journal of Healthcare Engineering. 2020;2020:8893338.

88. Peng CC, Chung KH, Ramos V, Jr. Assessment of the Adaptation of Interim Crowns using Different Measurement Techniques. Journal of Prosthodontics : official journal of the American College of Prosthodontists. 2020;29(1):87-93.

89. Peng CC, Chung KH, Yau HT, Ramos V, Jr. Assessment of the internal fit and marginal integrity of interim crowns made by different manufacturing methods. The Journal of Prosthetic Dentistry. 2020;123(3):514-22.

90. Wu J, Xie H, Sadr A, Chung KH. Evaluation of Internal Fit and Marginal Adaptation of Provisional Crowns Fabricated with Three Different Techniques. Sensors (Basel, Switzerland). 2021;21(3).

91. Lee WS, Lee DH, Lee KB. Evaluation of internal fit of interim crown fabricated with CAD/CAM milling and 3D printing system. The Journal of Advanced Prosthodontics. 2017;9(4):265-70.

92. Park JY, Jeong ID, Lee JJ, Bae SY, Kim JH, Kim WC. In vitro assessment of the marginal and internal fits of interim implant restorations fabricated with different methods. The Journal of Prosthetic Dentistry. 2016;116(4):536-42.

93. Aldahian N, Khan R, Mustafa M, Vohra F, Alrahlah A. Influence of Conventional, CAD-CAM, and 3D Printing Fabrication Techniques on the Marginal Integrity and Surface Roughness and Wear of Interim Crowns. Applied Sciences-Basel. 2021;11(19).

94. Angwarawong T, Reeponmaha T, Angwaravong O. Influence of thermomechanical aging on marginal gap of CAD-CAM and conventional interim restorations. The Journal of Prosthetic Dentistry. 2020;124(5):566.e1-.e6.

95. Revilla-León M, Olea-Vielba M, Esteso-Saiz A, Martínez-Klemm I, Özcan M. Marginal and Internal Gap of Handmade, Milled and 3D Printed Additive Manufactured Patterns for Pressed Lithium Disilicate Onlay Restorations. The European Journal of Prosthodontics and Restorative Dentistry. 2018;26(1):31-8.

96. Alharbi N, Alharbi S, Cuijpers V, Osman RB, Wismeijer D. Three-dimensional evaluation of marginal and internal fit of 3D-printed interim restorations fabricated on different finish line designs. Journal of Prosthodontic Research. 2018;62(2):218-26.

97. Mugri MH, Dewan H, Sayed ME, Shaabi FI, Hakami HI, Jokhadar HF, et al. The Effect of a Digital Manufacturing Technique, Preparation Taper, and Finish Line Design on the Marginal Fit of Temporary Molar Crowns: An In-Vitro Study. Biomedicines. 2023;11(2).

98. Khanlar LN, Barmak AB, Oh Y, Mendha U, Yared S, Zandinejad A. Marginal and internal discrepancies associated with carbon digital light synthesis additively manufactured interim crowns. The Journal of Prosthetic Dentistry. 2023;130(1):108.e1-.e6.

99. Son K, Lee JM, Lee KB. Marginal and Internal Fit and Intaglio Surface Trueness of Temporary Crowns Fabricated with Stereolithography, Digital Light Processing, and Milling Technology. The International Journal of Prosthodontics. 2022;35(5):697-701.

100. Falahchai M, Rahimabadi S, Khabazkar G, Babaee Hemmati Y, Neshandar Asli H. Marginal and internal fit and fracture resistance of three-unit provisional restorations fabricated by additive, subtractive, and conventional methods. Clinical and Experimental Dental Research. 2022;8(6):1404-12.

101. Al-Wahadni A, Abu Rashed BO, Al-Fodeh R, Tabanjah A, Hatamleh M. Marginal and Internal Gaps, Surface Roughness and Fracture Resistance of Provisional Crowns Fabricated With 3D Printing and Milling Systems. Operative Dentistry. 2023;48(4):464-71.

102. Hsu HJ, Lee SY, Jiang CP, Lin R. A comparison of the marginal fit and mechanical properties of a zirconia dental crown using CAM and 3DSP. Rapid Prototyping Journal. 2019;25(7):1187-97.

103. Li R, Xu T, Wang Y, Sun Y. Accuracy of zirconia crowns manufactured by stereolithography with an occlusal full-supporting structure: An in vitro study. The Journal of Prosthetic Dentistry. 2022.
104. Ioannidis A, Park JM, Hüsler J, Bomze D, Mühlemann S, Özcan M. An in vitro comparison of the marginal and internal adaptation of ultrathin occlusal veneers made of 3D-printed zirconia, milled zirconia, and heat-pressed lithium disilicate. The Journal of Prosthetic Dentistry. 2021.
105. Lyu J, Yang X, Li Y, Tan J, Liu X. Dimensional accuracy and clinical adaptation of monolithic zirconia crowns fabricated with the nanoparticle jetting technique. The Journal of Prosthetic Dentistry. 2023.
106. Rues S, Zehender N, Zenthöfer A, Bömicke W, Herpel C, Ilani A, et al. Fit of anterior restorations made of 3D-printed and milled zirconia: An in-vitro study. Journal of Dentistry. 2023;130:104415.
107. Li B, Jiang Q, Meng D. Evaluation of the trueness and adaptation of zirconia crowns fabricated with stereolithography. Dental Materials Journal. 2023;42(3):441-8.
108. Refaie A, Fouda A, Bourauel C, Singer L. Marginal gap and internal fit of 3D printed versus milled monolithic zirconia crowns. BMC Oral Health. 2023;23(1):448.
109. Suksuphan P, Krajangta N, Didron PP, Wasanapiarnpong T, Rakmanee T. Marginal adaptation and fracture resistance of milled and 3D-printed CAD/CAM hybrid dental crown materials with various occlusal thicknesses. Journal of Prosthodontic Research. 2023.
110. Abualsaud R, Alalawi H. Fit, Precision, and Trueness of 3D-Printed Zirconia Crowns Compared to Milled Counterparts. Dentistry Journal. 2022;10(11).
111. Kakinuma H, Izumita K, Yoda N, Egusa H, Sasaki K. Comparison of the accuracy of resin-composite crowns fabricated by three-dimensional printing and milling methods. Dental Materials Journal. 2022;41(6):808-15.
112. Lim YA, Kim JM, Choi Y, Park S. Evaluation of Fitness and Accuracy of Milled and Three-Dimensionally Printed Inlays. European Journal of Dentistry. 2023;17(4):1029-36.
113. Demirel M, Diken Türksayar AA, Donmez MB. Fabrication trueness and internal fit of hybrid abutment crowns fabricated by using additively and subtractively manufactured resins. Journal of Dentistry. 2023;136:104621.

114. Chang HS, Peng YT, Hung WL, Hsu ML. Evaluation of marginal adaptation of Co-Cr-Mo metal crowns fabricated by traditional method and computer-aided technologies. Journal of Dental Sciences. 2019;14(3):288-94.

115. Dahl BE, Dahl JE, Ronold HJ. Internal fit of three-unit fixed dental prostheses produced by computer-aided design/computer-aided manufacturing and the lost-wax metal casting technique assessed using the triple-scan protocol. European Journal of Oral Sciences. 2018;126(1):66-73.

116. Kim KB, Kim JH, Kim WC, Kim JH. Three-dimensional evaluation of gaps associated with fixed dental prostheses fabricated with new technologies. The Journal of Prosthetic Dentistry. 2014;112(6):1432-6.

117. Savencu CE, Serban C, Porojan L. Adaptability Evaluation of Metal-Ceramic Crowns Obtained by Additive and Subtractive Technologies. Applied Sciences-Basel. 2020;10(16).

118. Kim DY, Kim JH, Kim HY, Kim WC. Comparison and evaluation of marginal and internal gaps in cobalt-chromium alloy copings fabricated using subtractive and additive manufacturing. Journal of Prosthodontic Research. 2018;62(1):56-64.

119. Chou WT, Chuang CC, Wang YB, Chiu HC. Comparison of the internal fit of metal crowns fabricated by traditional casting, computer numerical control milling, and three-dimensional printing. PloS one. 2021;16(9):e0257158.

120. Kaleli N, Ural C, Us YO. Evaluation of marginal discrepancy in metal frameworks fabricated by sintering-based computer-aided manufacturing methods. Journal of Advanced Prosthodontics. 2020;12(3):124-30.

121. Gunsoy S, Ulusoy M. Evaluation of marginal/internal fit of chrome-cobalt crowns: Direct laser metal sintering versus computer-aided design and computer-aided manufacturing. Nigerian Journal of Clinical Practice. 2016;19(5):636-44.

122. Dayan SC, Kiseri B, Gencel B, Kurt A. Evaluation of the Internal and Marginal Discrepancies of Co-Cr Metal Copings Prepared via CAD/CAM and Conventional Casting. European Journal of Prosthodontics and Restorative Dentistry. 2019;27(1):26-31.

123. Onoral O. Marginal discrepancy of 3-unit Co-Cr metal copings fabricated with additive and subtractive manners: A comparative study. Nigerian Journal of Clinical Practice. 2020;23(9):1274-80.

124. Kim EH, Lee DH, Kwon SM, Kwon TY. A microcomputed tomography evaluation of the marginal fit of cobalt-chromium alloy copings fabricated by new manufacturing techniques and alloy systems. The Journal of Prosthetic Dentistry. 2017;117(3):393-9.

125. Alqahtani AS, AlFadda AM, Eldesouky M, Alnuwaiser MK, Al-Saleh S, Alresayes S, et al. Comparison of Marginal Integrity and Surface Roughness of Selective Laser Melting, CAD-CAM and Digital Light Processing Manufactured Co-Cr Alloy Copings. Applied Sciences-Basel. 2021;11(18).

126. Ali Majeed Z, Hasan Jasim H. Digital Evaluation of Trueness and Fitting Accuracy of Co-Cr Crown Copings Fabricated by Different Manufacturing Technologies. Cureus. 2023;15(6):e39819.

127. Kang SY, Park JH, Kim JH, Kim WC. Accuracy of provisional crowns made using stereolithography apparatus and subtractive technique. The Journal of Advanced Prosthodontics. 2018;10(5):354-60.

128. Son K, Lee JH, Lee KB. Comparison of Intaglio Surface Trueness of Interim Dental Crowns Fabricated with SLA 3D Printing, DLP 3D Printing, and Milling Technologies. Healthcare (Basel, Switzerland). 2021;9(8).

129. Giannetti L, Apponi R, Mordini L, Presti S, Breschi L, Mintrone F. The occlusal precision of milled versus printed provisional crowns. Journal of Dentistry. 2022;117:103924.

130. Li R, Chen H, Wang Y, Sun Y. Performance of stereolithography and milling in fabricating monolithic zirconia crowns with different finish line designs. Journal of the Mechanical Behavior of Biomedical Materials. 2021;115:104255.

131. Wang W, Yu H, Liu Y, Jiang X, Gao B. Trueness analysis of zirconia crowns fabricated with 3-dimensional printing. The Journal of Prosthetic Dentistry. 2019;121(2):285-91.

132. Çakmak G, Cuellar AR, Donmez MB, Abou-Ayash S, Lu WE, Schimmel M, et al. Effect of printing layer thickness on the trueness of 3-unit interim fixed partial dentures. The Journal of Prosthetic Dentistry. 2022.

133. Çakmak G, Rusa AM, Donmez MB, Akay C, Kahveci Ç, Schimmel M, et al. Trueness of crowns fabricated by using additively and subtractively manufactured resin-based CAD-CAM materials. The Journal of Prosthetic Dentistry. 2022.

134. Thomas AA, Daniel AY, Gandhi N, Roy N, Varghese KG, Wadhwa S, et al. Surface trueness and precision of interim restorations fabricated by digital light processing and CAD-CAM milling systems. The Journal of Prosthetic Dentistry. 2023;130(4):611.e1-.e7.
135. Cho JH, Yoon HI, Oh JH, Kim DH. Effect of maximum support attachment angle on intaglio surface trueness of anatomic contour monolithic prostheses manufactured by digital light processing and zirconia suspension. The Journal of Prosthetic Dentistry. 2023;129(3):478-85.
136. Camargo B, Willems E, Jacobs W, Van Landuyt K, Peumans M, Zhang F, et al. 3D printing and milling accuracy influence full-contour zirconia crown adaptation. Dental Materials : official publication of the Academy of Dental Materials. 2022;38(12):1963-76.
137. Kim YK, Han JS, Yoon HI. Evaluation of intaglio surface trueness, wear, and fracture resistance of zirconia crown under simulated mastication: a comparative analysis between subtractive and additive manufacturing. The Journal of Advanced Prosthodontics. 2022;14(2):122-32.
138. Moon JM, Jeong CS, Lee HJ, Bae JM, Choi EJ, Kim ST, et al. A Comparative Study of Additive and Subtractive Manufacturing Techniques for a Zirconia Dental Product: An Analysis of the Manufacturing Accuracy and the Bond Strength of Porcelain to Zirconia. Materials (Basel, Switzerland). 2022;15(15).
139. Wesemann C, Muallah J, Mah J, Bumann A. Accuracy and efficiency of full-arch digitalization and 3D printing: A comparison between desktop model scanners, an intraoral scanner, a CBCT model scan, and stereolithographic 3D printing. Quintessence International (Berlin, Germany : 1985). 2017;48(1):41-50.
140. Ledingham AD, English JD, Akyalcin S, Cozad BE, Ontiveros JC, Kasper FK. Accuracy and mechanical properties of orthodontic models printed 3-dimensionally from calcium sulfate before and after various postprinting treatments. American journal of orthodontics and dentofacial orthopedics : official publication of the American Association of Orthodontists, its constituent societies, and the American Board of Orthodontics. 2016;150(6):1056-62.
141. Brown GB, Currier GF, Kadioglu O, Kierl JP. Accuracy of 3-dimensional printed dental models reconstructed from digital intraoral impressions. American journal of

orthodontics and dentofacial orthopedics : official publication of the American Association of Orthodontists, its constituent societies, and the American Board of Orthodontics. 2018;154(5):733-9.

142. Hazeveld A, Huddleston Slater JJ, Ren Y. Accuracy and reproducibility of dental replica models reconstructed by different rapid prototyping techniques. American journal of orthodontics and dentofacial orthopedics : official publication of the American Association of Orthodontists, its constituent societies, and the American Board of Orthodontics. 2014;145(1):108-15.

143. Favero CS, English JD, Cozad BE, Wirthlin JO, Short MM, Kasper FK. Effect of print layer height and printer type on the accuracy of 3-dimensional printed orthodontic models. American journal of orthodontics and dentofacial orthopedics : official publication of the American Association of Orthodontists, its constituent societies, and the American Board of Orthodontics. 2017;152(4):557-65.

144. Papaspyridakos P, Chen YW, Alshawaf B, Kang K, Finkelman M, Chronopoulos V, et al. Digital workflow: In vitro accuracy of 3D printed casts generated from complete-arch digital implant scans. The Journal of Prosthetic Dentistry. 2020;124(5):589-93.

145. Rungrojwittayakul O, Kan JY, Shiozaki K, Swamidass RS, Goodacre BJ, Goodacre CJ, et al. Accuracy of 3D Printed Models Created by Two Technologies of Printers with Different Designs of Model Base. Journal of Prosthodontics : official journal of the American College of Prosthodontists. 2020;29(2):124-8.

146. Wan Hassan WN, Yusoff Y, Mardi NA. Comparison of reconstructed rapid prototyping models produced by 3-dimensional printing and conventional stone models with different degrees of crowding. American Journal of Orthodontics and Dentofacial Orthopedics: official publication of the American Association of Orthodontists, its constituent societies, and the American Board of Orthodontics. 2017;151(1):209-18.

147. Dikova T, Dzhendov D, Ivanov D, Bliznakova KJAMSE. Dimensional accuracy and surface roughness of polymeric dental bridges produced by different 3D printing processes. 2018;94(2):65-75.

148. Revilla-León M, Gohil A, Barmak AB, Zandinejad A, Raigrodski AJ, Alonso Pérez-Barquero J. Best-Fit Algorithm Influences on Virtual Casts' Alignment Discrepancies. Journal of prosthodontics : official journal of the American College of Prosthodontists. 2022.

149. O'Toole S, Osnes C, Bartlett D, Keeling A. Investigation into the accuracy and measurement methods of sequential 3D dental scan alignment. Dental materials : official publication of the Academy of Dental Materials. 2019;35(3):495-500.

150. Revilla-León M, Pérez-Barquero JA, Barmak BA, Agustín-Panadero R, Fernández-Estevan L, Att W. Facial scanning accuracy depending on the alignment algorithm and digitized surface area location: An in vitro study. Journal of Dentistry. 2021;110:103680.

151. Loflin WA, English JD, Borders C, Harris LM, Moon A, Holland JN, et al. Effect of print layer height on the assessment of 3D-printed models. American journal of orthodontics and dentofacial orthopedics : official publication of the American Association of Orthodontists, its constituent societies, and the American Board of Orthodontics. 2019;156(2):283-9.

152. Ko J, Bloomstein RD, Briss D, Holland JN, Morsy HM, Kasper FK, et al. Effect of build angle and layer height on the accuracy of 3-dimensional printed dental models. American journal of orthodontics and dentofacial orthopedics : official publication of the American Association of Orthodontists, its constituent societies, and the American Board of Orthodontics. 2021;160(3):451-8.e2.

153. Park JM, Jeon J, Koak JY, Kim SK, Heo SJ. Dimensional accuracy and surface characteristics of 3D-printed dental casts. The Journal of Prosthetic Dentistry. 2021;126(3):427-37.

154. Al-Saleh S, Vohra F, Albogami SM, Alkhammash NM, Alnashwan MA, Almutairi NS, et al. Marginal Misfit of 3D-Printed (Selective Laser Sintered), CAD-CAM and Lost Wax Technique Cobalt Chromium Copings with Shoulder and Chamfer Finish Lines: An In-Vitro Study. Medicina (Kaunas, Lithuania). 2022;58(10).

155. Thakur J, Parlani S, Shivakumar S, Jajoo K. Accuracy of marginal fit of an implant-supported framework fabricated by 3D printing versus subtractive manufacturing technique: A systematic review and meta-analysis. The Journal of Prosthetic Dentistry. 2021.

156. Shah KK, Sivaswamy V. A Literature Review on Implant Abutment Types, Materials, and Fabrication Processes. Journal of long-term effects of medical implants. 2022;33(1):57-66.

157. Wiskott HAJP, Quintessence CL. Fixed prosthodontics2011.

158. Young HM, Smith CT, Morton D. Comparative in vitro evaluation of two provisional restorative materials. The Journal of Prosthetic Dentistry. 2001;85(2):129-32.

159. Schwantz JK, Oliveira-Ogliari A, Meereis CT, Leal FB, Ogliari FA, Moraes RR. Characterization of Bis-Acryl Composite Resins for Provisional Restorations. Brazilian dental journal. 2017;28(3):354-61.

160. Balkenhol M, Knapp M, Ferger P, Heun U, Wöstmann B. Correlation between polymerization shrinkage and marginal fit of temporary crowns. Dental Materials: official publication of the Academy of Dental Materials. 2008;24(11):1575-84.

161. Amin BM, Aras MA, Chitre V. A comparative evaluation of the marginal accuracy of crowns fabricated from four commercially available provisional materials: An in vitro study. Contemporary Clinical Dentistry. 2015;6(2):161-5.

162. Mai HN, Lee KB, Lee DH. Fit of interim crowns fabricated using photopolymer-jetting 3D printing. The Journal of Prosthetic Dentistry. 2017;118(2):208-15.

163. Jain S, Sayed ME, Shetty M, Alqahtani SM, Al Wadei MHD, Gupta SG, et al. Physical and Mechanical Properties of 3D-Printed Provisional Crowns and Fixed Dental Prosthesis Resins Compared to CAD/CAM Milled and Conventional Provisional Resins: A Systematic Review and Meta-Analysis. Polymers. 2022;14(13).

164. Örtorp A, Jönsson D, Mouhsen A, Vult von Steyern P. The fit of cobalt-chromium three-unit fixed dental prostheses fabricated with four different techniques: a comparative in vitro study. Dental Materials: official publication of the Academy of Dental Materials. 2011;27(4):356-63.

165. Barndt CPR, Sterlitz, S.J. and Fasbinder, D.J. Tooth preparation considerations for CAD/CAM materials in restorative dentistry [Available from: https://decisionsindentistry.com/article/tooth-preparation-considerations-for-cad-cam-materials-in-restorative-dentistry/.

166. Med 620 - Polyjet Technology Material, Stratasys [Available from: https://www.stratasys.com/en/materials/materials-catalog/polyjet-materials/biocompatible-veroglaze-med620/.

167. Piconi C, Maccauro G. Zirconia as a ceramic biomaterial. Biomaterials. 1999;20(1):1-25.

168. Su G, Zhang Y, Jin C, Zhang Q, Lu J, Liu Z, et al. 3D printed zirconia used as dental materials: a critical review. Journal of biological engineering. 2023;17(1):78.

169. Griffith ML, Halloran JWJJotACS. Freeform fabrication of ceramics via stereolithography. 1996;79(10):2601-8.

170. Wu H, Cheng Y, Liu W, He R, Zhou M, Wu S, et al. Effect of the particle size and the debinding process on the density of alumina ceramics fabricated by 3D printing based on stereolithography. 2016;42(15):17290-4.

171. Lian Q, Sui W, Wu X, Yang F, Yang SJRPJ. Additive manufacturing of ZrO2 ceramic dental bridges by stereolithography. 2018;24(1):114-9.

172. Majumder M, Rendall CS, Eukel JA, Wang JY, Behabtu N, Pint CL, et al. Overcoming the "coffee-stain" effect by compositional Marangoni-flow-assisted drop-drying. The Journal of Physical Chemistry B. 2012;116(22):6536-42.

173. El-Ashkar A, Taymour M, El-Tannir A. Evaluation of the marginal and internal gaps of partially crystallized versus fully crystallized zirconia-reinforced lithium silicate CAD-CAM crowns: An in vitro comparison of the silicone replica technique, direct view, and 3-dimensional superimposition analysis. The Journal of Prosthetic Dentistry. 2023;129(5):769-76.

174. Luthardt R, Weber A, Rudolph H, Schöne C, Quaas S, Walter M. Design and production of dental prosthetic restorations: basic research on dental CAD/CAM technology. International Journal of Computerized Dentistry. 2002;5(2-3):165-76.

175. Majeed MA, Al-Adel SKJJoG, conservation er. Evaluation of the marginal and internal fitness of full contour CAD/CAM crowns made from zirconia, lithium disilicate, zirconia-reinforced lithium silicate and hybrid dental ceramic by silicone replica technique (A comparative In vitro study). 2016;4(1):10-20.

176. Kim JH, Jeong JH, Lee JH, Cho HW. Fit of lithium disilicate crowns fabricated from conventional and digital impressions assessed with micro-CT. The Journal of Prosthetic Dentistry. 2016;116(4):551-7.

177. Al-Imam H, Michou S, Benetti AR, Gotfredsen K. Evaluation of marginal and internal fit of acrylic bridges using optical coherence tomography. Journal of Oral Rehabilitation. 2019;46(3):274-81.

178. Holst S, Karl M, Wichmann M, Matta RE. A new triple-scan protocol for 3D fit assessment of dental restorations. Quintessence international (Berlin, Germany : 1985). 2011;42(8):651-7.

179. Boitelle P, Tapie L, Mawussi B, Fromentin O. Evaluation of the marginal fit of CAD-CAM zirconia copings: Comparison of 2D and 3D measurement methods. The Journal of Prosthetic Dentistry. 2018;119(1):75-81.
180. Hegyi P, Erőss B, Izbéki F, Párniczky A, Szentesi A. Accelerating the translational medicine cycle: the Academia Europaea pilot. Nature Medicine. 2021;27(8):1317-9.
181. Hegyi P, Petersen OH, Holgate S, Erőss B, Garami A, Szakács Z, et al. Academia Europaea Position Paper on Translational Medicine: The Cycle Model for Translating Scientific Results into Community Benefits. Journal of Clinical Medicine. 2020;9(5).

16 BIBLIOGRAPHY

16.1 Publications related to the thesis

Németh, A., Vitai, V., Czumbel, M. L., Szabó, B., Varga, G., Kerémi, B., Hegyi, P., Hermann, P., & Borbély, J. (2023). Clear guidance to select the most accurate technologies for 3D printing dental models - A network meta-analysis. **Journal of Dentistry**, 134, 104532. https://doi.org/10.1016/j.jdent.2023.104532

D1, IF: 4.80

Németh, A., Vitai, V., Kelemen, K., Teutsch, B., Szabó, B., Gerber, G., Varga, G., Fazekas, R., Hegyi, P., & Borbély, J. (2024). Comparison of fit and trueness of single-unit and short-span fixed dental restorations fabricated by additive and subtractive manufacturing - A systematic review and meta-analysis. **Journal of Dentistry**, 105527. https://doi.org/10.1016/j.jdent.2024.105527

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16.2 Publications not related to the thesis

Vitai, V., **Németh, A.**, Sólyom, E., Czumbel, L. M., Szabó, B., Fazekas, R., Gerber, G., Hegyi, P., Hermann, P., & Borbély, J. (2023). Evaluation of the accuracy of intraoral scanners for complete-arch scanning: A systematic review and network meta-analysis. **Journal of Dentistry**, 137, 104636. https://doi.org/10.1016/j.jdent.2023.104636

D1, IF: 4.80

Vitai, V., **Németh, A.**, Teutsch, B., Kelemen, K., Fazekas, A., Hegyi, P., Németh, O., Kerémi, B., & Borbély, J. (2024). Color Comparison Between Intraoral Scanner and Spectrophotometer Shade Matching: A Systematic Review and Meta-Analysis. **Journal of esthetic and restorative dentistry**: *official publication of the American Academy of Esthetic Dentistry ... [et al.]*, 10.1111/jerd.13309. Advance online publication. https://doi.org/10.1111/jerd.13309

D1, IF: 3.2

Palaszkó, D., **Németh, A.**, Török, G., Vecsei, B., Vánkos, B., Dinya, E., Borbély, J., Marada, Gy., Hermann, P., Kispélyi, B. (2024). Trueness of five different 3D printing systems including budget- and professional-grade printers: An In vitro study. **Heliyon**. 10(5) https://doi.org/10.1016/j.heliyon.2024.e26874

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