Optimizing mandibular implant-overdentures based on 3D printing technologies and attachment systems

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Preface

This dissertation adheres to the manuscript format outlined in the guidelines of Graduate and Postdoctoral Studies at McGill University. It begins with a comprehensive introduction and literature review chapter, succeeded by five independent chapters, each corresponding to a distinct manuscript. Interspersed between these chapters are prefaces, functioning as connecting texts. These prefaces elucidate the interrelationships among the manuscripts and demonstrate their alignment within the overarching framework of a cohesive doctoral research program.

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Abstract

Background: Since 2002, the use of two-implant mandibular overdentures (IOD) has been advocated as the minimum standard of care for treating mandibular edentulism. Despite favorable patient-reported outcomes and satisfactory clinical performance, the existing IODs designed for mandibular edentulism come with inherent limitations. The primary disadvantages of these dental prostheses include the loss of attachment retention due to wear over time, necessitating regular maintenance appointments. Another significant hurdle for IODs lies in their time-consuming and expensive fabrication process. Although conventional denture-making techniques have been well-established for over a century, recent developments have brought computer-aided design and manufacturing (CAD/CAM) options to the forefront for dental professionals.

Objectives: The overall objective of this thesis has been to tackle the IODs' limitations, specifically the loss of retention in attachment systems and the lengthy and costly fabrication processes, by exploring methods for the optimization of this type of dental prostheses.

Methods: To address this objective, a combination of research methodologies was used. First, an *in vitro* study (manuscript I) was carried out to explore the retentive properties and structural integrity of two attachment systems (Novaloc and Locator attachments) for two-implant overdentures subjected to mechanical cycling representing masticatory forces for up to 12 months of use. Then, a scoping review (manuscript II), as well as a meta-analysis (manuscript III) were conducted to map the current literature regarding the CAD/CAM removable dental prosthesis. Through the fourth manuscript, a series of *in vitro* tests was performed to optimize the mechanical and surface properties of the 3D-printed denture base material through varying printing orientations and post-processing strategies before moving forward to the clinical trial phase.

Lastly, in manuscript V, a protocol for the first cross-over mixed-methods randomized controlled trial (RCT) comparing CAD/CAM IODs with the conventional ones was developed.

Results: The findings from the *in vitro* attachment study show that the Novaloc attachment system preserved retentive forces longevity relative to the Locator system, despite lower overall retentive force. The review and meta-analysis suggested that CAD/CAM dentures are comparable to conventional dentures regarding patient- and clinician-centered outcomes, yet they offer lower fabrication costs. In our set of experimental tests on 3D-printed denture base material, we found that both printing orientation and post-processing technique affect the mechanical and surface properties of these materials. Finally, we prepared a protocol for a cross-over mixed-methods RCT in comparing CAD/CAM IODs with the conventional ones, which has been approved by the Ethical Review Board at McGill University. The study is currently ongoing and began recruitment in January 2024.

Conclusions: Our scoping review and meta-analysis indicated the need to conduct more well-designed high-quality RCTs regarding the CAD/CAM dentures, particularly IODs. Through our series of *in vitro* tests, we found an ideal scenario for the attachment system and processing parameter for 3D-printed denture base material to use in the clinical setting. Our results, if confirmed in our RCT, will have significant effect on clinical practice, by improving the tested procedure and showcasing an opportunity for greater access to oral health care for the edentulous population.

Résumé

Contexte: Depuis 2002, l'utilisation de prothèses amovibles mandibulaires sur deux implants (IOD) est préconisée comme le standard minimal de soin pour le traitement de l'édentement mandibulaire. Malgré des résultats favorables rapportés par les patients et une performance clinique satisfaisante, les IOD existantes conçues pour l'édentement mandibulaire présentent des limites inhérentes. Les principaux inconvénients de ces prothèses dentaires incluent la perte de rétention des attachements due à l'usure au fil du temps, nécessitant des rendez-vous de maintenance réguliers. Un autre obstacle important pour les overdentures réside dans leur processus de fabrication long et coûteux. Bien que les techniques de fabrication de dentiers conventionnels soient bien établies depuis plus d'un siècle, les développements récents ont mis en avant les options de conception et de fabrication assistées par ordinateur (CAD/CAM) pour les professionnels dentaires.

Objectif : L'objectif global de cette thèse a été de s'attaquer aux limitations des IOD, notamment la perte de rétention dans les systèmes d'attache et les processus de fabrication longs et coûteux, en explorant des méthodes pour l'optimisation de ce type de prothèses dentaires.

Méthodes : Pour atteindre cet objectif, j'ai utilisé une combinaison de méthodologies de recherche. Tout d'abord, j'ai réalisé une étude *in vitro* (manuscrit I) explorant les propriétés de rétention et l'intégrité structurelle de deux systèmes d'attachements (Novaloc et les attaches Locator) pour les overdentures sur 2 implants soumises à un cyclage mécanique représentant les forces masticatoires jusqu'à 12 mois d'utilisation. Ensuite, j'ai mené une revue de portée (manuscrit II), ainsi qu'une méta-analyse (manuscrit III) pour cartographier la littérature actuelle concernant la prothèse dentaire amovible CAD/CAM. À travers le quatrième manuscrit, j'ai conduit une série de tests *in vitro* pour optimiser les propriétés mécaniques et de surface du matériel de base de la denture

imprimée en 3D à travers différentes orientations d'impression et stratégies de post-traitement avant de passer à la phase d'essai clinique. Enfin, dans le manuscrit V, j'ai développé un protocole pour le premier essai randomisé contrôlé (ERC) croisé à méthodes mixtes comparant les IODs CAD/CAM avec les conventionnelles.

Résultats : Les résultats de notre étude *in vitro* sur le système d'attache montrent que le système d'attache Novaloc a préservé la longévité des forces de rétention par rapport au système Locator, malgré une force de rétention globalement inférieure. La revue et la méta-analyse ont suggéré que les dentures CAD/CAM sont comparables aux dentures conventionnelles concernant les résultats centrés sur le patient et le clinicien, mais elles offrent des coûts de fabrication inférieurs. Dans notre ensemble de tests expérimentaux sur le matériau de base de la denture imprimée en 3D, nous avons trouvé que l'orientation de l'impression et la technique de post-traitement affectent les propriétés mécaniques et de surface de ces matériaux. Enfin, nous avons préparé un protocole pour un ERC croisé à méthodes mixtes comparant les IODs CAD/CAM avec les conventionnelles, qui a été approuvé par le comité d'éthique de l'Université McGill. L'étude est actuellement en cours et a commencé le recrutement en janvier 2024.

Conclusion : Notre revue de portée et méta-analyse ont indiqué la nécessité de mener davantage d'ERC bien conçus et de haute qualité concernant les dentures CAD/CAM, en particulier les IODs. À travers notre série de tests *in vitro*, nous avons trouvé un scénario idéal pour le système d'attache et le paramètre de traitement pour le matériau de base de la denture imprimée en 3D à utiliser dans le cadre clinique. Si nos résultats sont confirmés dans notre ERC, ils auront un effet significatif sur la pratique clinique, en améliorant la procédure testée et en démontrant une opportunité pour un accès plus large aux soins de santé bucco-dentaire pour la population édentée.

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I want to extend my deepest thanks to my supervisor, Dr. Raphael de Souza, whose kindness and understanding surpass what I could have imagined in a mentor. Your faith in me and the chance to be part of your team have been pivotal in my journey. Your unwavering support, encouragement, and the sharing of your extensive knowledge have been invaluable. I am profoundly thankful for your empathy and guidance throughout my graduate studies.

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Contribution to original knowledge

The content within this thesis constitutes original research, reflecting the integration of diverse skills I developed throughout my experience in clinical dentistry, dental material science, literature review, and epidemiology. This comprehensive body of work advances original knowledge towards improving the oral health of seniors using implant-based prosthesis.

In Manuscript I, an *in vitro* study was conducted to investigate the performance of a novel attachment system for implant-retained mandibular overdentures (IODs), and to assess the retentive properties of these attachments subjected to simulated masticatory forces. In Manuscript II, the literature was reviewed, with a focus on the digital computer-aided design and manufacturing (CAD/CAM) technology and its application in the fabrication of removable prostheses, including the IODs. This paper, published in the International Journal of Prosthodontics, has been the first scoping review in the field. In the third manuscript, a meta-analysis was carried out on the same topic, representing the first study to focus on the patient-reported outcomes. In Manuscript IV, the results of an *in vitro* study designed to determine the optimum printing parameters and post-processing techniques for the 3D printed denture base materials were presented. Lastly, in Manuscript V, a protocol was developed for a randomized clinical trial to investigate whether 3D-printed mandibular IODs are more satisfactory for edentulous seniors than those made through traditional methods.

Therefore, the aim of my PhD project has been to research and grasp a better understanding of IODs drawbacks, and to explore the ways to optimize these types of dental prostheses. The project is an example of an interdisciplinary approach that involves scoping review and meta-analysis

along with experimental *in vitro* studies ending with the preparation of a randomized clinical trial in humans to test my hypotheses.

Contribution of Authors

I was responsible for executing the research outlined in this thesis. This encompassed formulating the comprehensive Ph.D. project, identifying specific objectives, devising study designs, data collection, conducting statistical analysis, and conducting *in vitro* experiments. Additionally, I took charge of drafting the manuscripts, refining their final versions, and composing all the chapters incorporated into this dissertation. Throughout these endeavors, I worked under the guidance of Prof. Raphael de Souza. In the subsequent sections, I describe the distinct contributions of each author to the respective manuscripts included in this work.

Manuscript I: Retentive Properties of Novaloc and Locator Overdenture Attachments

Dana Jafarpour, PhD Candidate, Faculty of Dental Medicine and Oral Health Sciences, McGill University: conceptualization, *in vitro* experiment, data collection and analysis, original manuscript draft preparation, and review and editing of the final version.

Eric Krochmalnek, DMD student, Faculty of Dental Medicine and Oral Health Sciences, McGill University: data collection and analysis, original manuscript draft preparation.

Lei Wu, PhD Student, Dept. Mechanical Engineering, McGill University: *in vitro* experiment, review and editing of the final version.

Damiano Pasini, Professor, Dept. Mechanical Engineering, McGill University: critical review and editing of the final version.

Raphael Freitas de Souza, Associate Professor, Faculty of Dental Medicine and Oral Health Sciences, McGill University: candidate supervisor, design, critical review of manuscript and editing of final version, correspondence.

Manuscript II: Patient-reported outcomes and clinical performance of CAD/CAM removable dentures: A scoping review

Dana Jafarpour, PhD Candidate: conceptualization, search strategy development, original manuscript draft preparation, and review and editing of the final version.

Jocelyne S. Feine, Professor, Faculty of Dental Medicine and Oral Health Sciences, McGill University: co-supervision, manuscript critical review and editing of final version.

Martin Morris, Medical Librarian, Schulich Library of Science and Engineering, McGill University: database search, review and editing of manuscript.

Raphael de Souza, Associate Professor, Faculty of Dental Medicine and Oral Health Sciences, McGill University: candidate supervision, design, critical review of manuscript and editing of final version, correspondence.

Manuscript III: CAD/CAM vs traditional complete dentures: a systematic review and meta-analysis of patient and clinician-reported outcomes, post-insertion adjustments, and costs

Dana Jafarpour, PhD Candidate: design and conceptualization, search strategy development, database search, analysis and interpretation, original manuscript draft preparation, and review and editing of the final version.

Praveen Bhoopathi Haricharan, PhD candidate, Faculty of Dental Medicine and Oral Health Sciences, McGill University: analysis and interpretation, review and editing of the final version.

Raphael de Souza, Associate Professor, Faculty of Dental Medicine and Oral Health Sciences, McGill University: candidate supervision, critical review of manuscript and editing of final version, correspondence.

Manuscript IV: Post-processing of 3D printed denture base resins built in different printing orientations: An *in vitro* study of mechanical and surface properties

Dana Jafarpour, PhD Candidate, Faculty of Dental Medicine and Oral Health Sciences, McGill University: conceptualization, *in vitro* experiments, data collection and analysis, original manuscript draft preparation, and review and editing of the final version.

Raphael de Souza, Associate Professor, Faculty of Dental Medicine and Oral Health Sciences, McGill University: candidate supervision, design of the study, critical review of manuscript and editing of final version, correspondence.

Elizabeth Zimmermann, Assistant Professor, Faculty of Dental Medicine and Oral Health Sciences, McGill University: Advisory committee, resources, review of manuscript and editing of final version.

Kawkab Tahboub, PhD candidate, Faculty of Dental Medicine and Oral Health Sciences, McGill University: *in vitro* experiments, data collection, review and editing of the final version.

Nesma El-Amier, PhD student, Faculty of Dental Medicine and Oral Health Sciences, McGill University: *in vitro* experiments, data collection, review and editing of the final version.

Ana Carolina Pero, Associate Professor, Department of Dental Materials and Prosthodontics, Araraquara Dental School, São Paulo State University (UNESP), Araraquara, Brazil: design, review and editing of the final version.

Manuscript V: 3D printing vs traditional workflow for the fabrication of mandibular implant overdentures: Study protocol for a mixed-methods cross-over RCT

Dana Jafarpour, PhD candidate: conceptualization, original manuscript draft preparation, and review and editing of the final version.

Nesma El-Amier, PhD student, Faculty of Dental Medicine and Oral Health Sciences, McGill University: original manuscript draft preparation, and review and editing of the final version.

Jocelyne Feine, Professor, Faculty of Dental Medicine and Oral Health Sciences, McGill University: advisory committee, manuscript critical review and editing of final version.

Christophe Bedos, Associate Professor, Faculty of Dental Medicine and Oral Health Sciences, McGill University: study design and overseeing the qualitative data gathering and analysis.

Samer Abi-Nader, Associate Professor, Faculty of Dental Medicine and Oral Health Sciences, McGill University: advising in the prosthetic stages and integration phase/knowledge translation.

Shahrokh Esfandiari, Full Professor, Faculty of Dentistry, Université de Montréal, Montreal, QC, Canada: study design and overseeing the economic data collection and analysis.

Tibor Shuster, Associate Professor, Department of Family Medicine, McGill University: advisory committee member, advising in the data analysis plan.

Elizabeth Zimmermann, Assistant Professor, Faculty of Dental Medicine and Oral Health Sciences, McGill University: advisory committee member, advising in the technical part and methodology.

Raphael de Souza, Associate Professor, Faculty of Dental Medicine and Oral Health Sciences, McGill University: candidate supervision, study design and coordinating the trial.

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List of abbreviations

- ADLC: Amorphous Diamond-Like Carbon
- AM: Additive Manufacturing
- CAD/CAM: Computer-aided Design and Manufacturing
- CD: Complete Denture
- CI: Confidence Interval
- CNC: Computer Numerical Control
- CR: Centric Relation
- CTE: Coefficient of Thermal Expansion
- DLP: Digital Light Processing
- DSC: Differential Scanning Calorimetry
- ES: Effect Size
- FAD: Functional Assessment of Dentures
- FDM: Fused Deposition Modeling
- FS: Flexural Strength
- GEE: Generalized Estimating Equations
- ICER: Incremental Cost-Effectiveness Ratio
- IADR: International Association for Dental Research
- IOD: Implant-retained Mandibular Overdentures
- IOS: Intraoral Scanner
- IMO: Implant-retained Mandibular Overdentures
- ISO: International Standards Organization
- MeSH: Medical Subject Headings

- Micro-CT: Microcomputed Tomography
- MNAR: Missing Not At Random
- MOE: Modulus of Elasticity
- MDSQ: McGill Denture Satisfaction Questionnaire
- OHIP: Oral Health Impact Profile
- OHRQoL: Oral Health-Related Quality of Life
- OVD: Occlusal Vertical Dimension
- PEEK: Polyetheretherketone
- PICOS: Population, Intervention, Comparison, Outcomes, Study Design
- PMMA: Polymethyl Methacrylate
- PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
- PROM: Patient-Reported Outcome Measures
- RCT: Randomized Clinical Trial
- REB: Research Ethics Board
- RPD: Removable Partial Denture
- SD: Standard Deviation
- SEM: Scanning Electron Microscopy
- SIMO: Single-Implant Mandibular Overdenture
- SLA: Stereolithography
- SM: Subtractive Manufacturing
- SMD: Standard Mean Difference
- SPIRIT: Standard Protocol Items: Recommendations for Interventional Trials
- STL: Standard Tessellation Language

- TC: Trial Coordinator

- TGA: Thermogravimetric Analysis

- TiN: Titanium Nitride

- UV: Ultraviolet

- VAS: Visual Analogue Scale

- VHN: Vickers Hardness Number

- WHO: World Health Organization

1. Chapter 1: Introduction

The absence of all natural teeth (edentulism) is a common oral health issue, affecting around 30% of the elderly population globally (among individuals aged 65-74,) with predictions indicating its persistence in older demographics for the next decades (1, 2).

Previous research has found a link between edentulism and increased disability with a higher likelihood of earlier mortality (3). Thus, it is of importance to rehabilitate this condition in order to recuperate the function and quality of life for the patients. For decades, removable dentures, both complete and partial, have traditionally been the standard treatment for edentulism, offering a degree of functional restoration (4). However, issues like discomfort, poor retention, and instability, particularly with mandibular dentures, have been reported with these traditional treatment modalities (5). Over half of the mandibular dentures lack sufficient retention and stability (6). As a response to these challenges, the use of implants to support mandibular dentures and the adoption of implant-retained overdentures (IOD) emerged as an efficient alternative to the conventional dentures (7). In 2002, the McGill consensus announced the 2-implant mandibular overdenture as the minimum standard of care for treating mandibular edentulism (8, 9). While these overdentures offer a more cost-effective solution for an edentulous mandible compared to a 4-implant fixed prosthesis (10, 11), the current IODs for mandibular rehabilitation come with their own inherent limitations.

A significant issue with overdentures is the repetitive forces on the retentive component, namely attachments, leading to their deformation with hundreds of daily uses. During this process, attachment components between implants and the prosthesis are prone to fracture, distortion, and disengagement, resulting in a gradual loss of stability (12). Retention loss of attachments due to wear and tear during long-term use is a common concern, leading to frequent maintenance visits,

which are the primary drawbacks of these dental prostheses. The type of attachment used can significantly impact the retentive force of an overdenture and its maintenance over time (9, 13). To address the challenge of attachment retention loss and to optimize the treatment modality, this thesis explores the performance of an alternative to the traditionally used nylon attachments, represented here by the Locator system. This alternative, called the Novaloc system, is made of polyether ether ketone (PEEK) matrices and amorphous diamond-like carbon (ADLC)-coated cylindrical abutments to enhance wear resistance. The first part of this thesis (Manuscript I) includes an *in vitro* study exploring the retentive properties and structural integrity of Novaloc and Locator attachments for two-implant overdentures subjected to insertion-removal wear and compressive cyclic loading, simulating masticatory forces equivalent to 1 week, 1, 3, 6, and 12 months of use.

Another major challenge with overdentures is their lengthy and costly method of fabrication. Despite the long-standing establishment of traditional denture fabrication methods over the past century, recent advancements have introduced computer-aided design and manufacturing (CAD/CAM) alternatives to oral health professionals. These CAD/CAM technologies leverage software algorithms and data processing to generate virtual denture components, similar to the approach used for crowns and bridges, employing various manufacturing techniques. The integration of computer-assisted technologies holds the potential to enhance elderly individuals' access to oral healthcare significantly. The adoption of these technologies can lead to fewer appointments for denture treatment, thereby reducing costs for patients (14). Through the internet, patients can receive 3D images of their future dentures, making a clinical visit unnecessary (15). Additionally, elderly patients, particularly those with cognitive or physical impairments, face the risk of losing their dentures and requiring remakes. Digital files

allow for the replication of the same dentures even in the absence of the patient (16). This capability becomes particularly valuable with mandibular implant-retained overdentures, where there is a substantial risk of base fracture (17).

Therefore, in the second part of this thesis, the possibility of a change in IOD fabrication techniques was examined using the digital 3D printing methods. I addressed this objective through four manuscripts corresponding to four chapters. For this matter, I first appraised the state of current literature regarding the digital removable dental prosthesis through a scoping review (Manuscript II). I comprehensively mapped the current literature on CAD/CAM removable dental prosthesis and found that no randomized cross-over clinical trial has been conducted so far to compare the CAD/CAM implant-retained dentures with that of conventionally fabricated ones. Even of those newly published comparative studies on CAD/CAM conventional dentures, two were prospective clinical studies (18, 19), two were retrospective studies (20, 21), one was cross-sectional (22) (all five conducted in student clinics), and one was a non-randomized clinical study (23). Further, I carried out a meta-analysis, focusing on patient-reported outcomes of these CAD/CAM dentures (Manuscript III). I found that while there is some evidence showing that CAD/CAM complete dentures (CDs) are at least comparable to traditional CDs, there is a scarcity of well-designed randomized controlled trials evaluating the performance of specific CAD/CAM approaches for manufacturing implant-retained CDs. Through the fourth manuscript, I intended to optimize the mechanical and surface properties of the 3D printed denture base material through varying printing orientations and post-processing strategies before moving forward to the clinical trial phase. Lastly, in manuscript V, I developed a protocol for the first cross-over mixed-methods Randomized Clinical Trial (RCT) in comparing CAD/CAM implant-retained overdentures with conventional ones to fill this gap of knowledge.

2. Chapter 2: Literature Review

This part comprises three main sections. Section 2.1 summarizes the evidence on the definition, etiology, epidemiology, and impact of edentulism. Section 2.2. presents the evidence on the first-choice standard of care for edentulism, namely the implant-retained overdentures. Finally, section 2.3 presents the advancements in fabricating IODs, including the new CAD/CAM technology replacing the conventional fabrication methods of these types of dental prostheses.

2.1. Edentulism

2.1.1. Definition

Edentulism, or the condition commonly referred to as being edentulous, is defined as the absence of natural teeth (24). Complete edentulism signifies the absence of all teeth in the oral cavity. Maintaining proper dentition is crucial for overall well-being and quality of life. Among the elderly population, edentulism poses a significant public health challenge, profoundly impacting primary care practices. It is a severe and irreversible condition, often characterized as “the ultimate indicator of the disease burden for oral health” (24, 25).

2.1.2. Etiology

The factors contributing to edentulism are diverse. While predominantly influenced by genetic or microbial diseases with significant individual and behavioral impacts, complete tooth loss can also result from iatrogenic, traumatic, or therapeutic causes (26).

Various socio-economic factors, such as lower income and education levels, as well as compromised oral and general health, are associated with an increased incidence of tooth loss. The presence of higher periodontal disease indicators, perceived poor dental health, the need for

extractions, a history of smoking, and low ascorbic acid intake further contribute to this phenomenon (27).

Chronic systemic health issues such as uncontrolled diabetes (28), HIV (29), and obesity (30) can also lead to dry mouth, changes in oral microbiome, and immune system functionality, which in turn elevate the risk of periodontal diseases and dental caries. Both periodontal diseases and caries are significant causative factors directly associated with tooth loss (31, 32). In contemporary and developed societies where dental care is relatively accessible, the primary reason for tooth loss is predominantly dental caries, followed closely by periodontal diseases (33).

2.1.3. Epidemiology

Edentulism is a persistent condition with a prevalence that is expected to remain high, particularly exceeding 20% in certain socioeconomic segments of the population (26).

Literature presents conflicting perspectives on the trajectory of edentulism rates. The prevalence of complete edentulism varies between countries and regions, making cross-national comparisons challenging due to the influence of multiple factors. Khazaei *et al*. (34) suggested a consistent decline in edentulism rates in developed countries, while developing countries experience the opposite trend. The global prevalence of edentulism stands at approximately 30% among individuals aged 65-74 (1), with a concentration in elderly populations, and projections indicate its persistence at high levels for several decades (2). While some studies report that gender play a significant role, with a higher prevalence of edentulism in women compared to men (35), recent trends indicate an absence of gender bias in edentulism, with both men and women having almost the same likelihood of experiencing tooth loss (36). However, socioeconomic factors appear to influence the prevalence of this condition.

In the United States, Slade *et al.* (37) found an edentulism prevalence of 4.9% among adults over 15 years of age. In Canada, the overall rate in 2010 was ranging from 6.4% to 21.7% among adults aged 60-79 years (38). Regional disparities within a country are notable, such as the wide variation in edentulism rates between provinces in Canada (14% in Quebec to 5% in Northwest Regions), influenced by factors like access to fluoridated water and smoking habits (39).

2.1.4. Impact

Edentulism has direct implications for impairment, functional limitations, and various forms of disability, encompassing physical, psychological, and social aspects (40). In accordance with the criteria established by the World Health Organization (WHO), a completely edentulous patient aligns with WHO standards for being considered physically impaired, disabled, and handicapped (41). Therefore, all the key health dimensions, including physical symptoms, functional capacity, social functioning, and perception of well-being are impacted by edentulism (42). It is anticipated that all the mentioned aspects will progressively worsen the Oral Health-Related Quality of Life (OHRQoL) of edentulous individuals (42, 43).

Edentulism leads to heightened depressive symptoms (44), deteriorates oral functionality—particularly in chewing (45),—and fosters psychosocial issues like discomfort and lower self-esteem (46). Beyond its direct oral health impact, edentulism also correlates with broader health issues, such as increased disability and higher mortality rates in the elderly (47).

2.1.5. Treatment options for complete edentulism

The management of patients without teeth includes offering them either removable or fixed full-arch dental prosthetics. These prostheses include complete dentures, either conventional or implant-retained (48, 49).

2.1.5.1. Complete denture

Removable complete dentures (CDs) are categorized as the traditional and most prevalent treatment approach for individuals with total tooth loss (49). Despite being considered an accessible and cost-effective option for care, many patients express dissatisfaction with certain aspects of this treatment modality (50). Even though traditional denture fabrication methods have been firmly established over the past century (51), a significant number of individuals still encounter issues such as discomfort, inadequate retention/stability, and challenges, particularly with mandibular CDs, especially when consuming hard foods. These challenges often stem from the unique anatomical structure of the supporting mandibular arch (5).

Consequently, the introduction of implants to provide support for dentures and the adoption of implant-retained overdentures for edentulous jaws have emerged as an effective alternative to CDs (7).

2.1.5.2. Implant overdenture

The advent of osseointegrated implants and implant-retained prostheses has revolutionized the management of edentulism, particularly for cases of mandibular edentulism. This innovation addresses the significant challenge of dealing with advanced alveolar resorption, and the complexity of delivering retentive and functional prostheses (52).

The implant-supported prostheses have shown to preserve bone as opposed to the continuous bone loss experienced with traditional CDs, even suggesting that implants might encourage bone regeneration (53). When comparing traditional dentures to implant-supported overdentures regarding their impact on the resorption of the posterior mandibular residual ridge, it was found that the conventional denture wearers experienced an average decrease in alveolar height of 1.63 mm, while those with implant overdentures saw a reduction of just 0.69 mm over five years (54).

Several RCTs have shown that implant-retained overdentures lead to higher patient satisfaction and a positive effect on quality of life, including improved chewing ability and bite force, compared to traditional dentures in the mandible (55-57).

The enduring success of full arch implant-supported fixed complete dentures, which are anchored by four to six implants (58), allows for the rehabilitation of patients with compromised dentitions. However, the expense associated with fixed complete implant-supported prostheses is notably high. Research into the use of a reduced number of implants per arch has shown promising outcomes (57, 59).

2.2. Mandibular two-implant overdenture

According to Redford *et al*. (6), more than half of the mandibular complete dentures have limitations with regards to retention and stability. In 2002, the McGill Consensus Statement identified the mandibular two-implant overdenture as the first-choice standard care for patients without mandibular teeth (52). Feine and colleagues (52) acknowledged that while the two-implant overdenture comes at a higher initial cost compared to traditional dentures, it should be made accessible for edentulous patients. Similarly, the York Consensus of 2009 recommended that a two-implant-supported mandibular overdenture should be considered the minimum standard offered to edentulous patients as an initial treatment option (60).

In this section, we will first describe the different components of these types of prostheses. Then, the advantages and drawbacks of this treatment modality will be further discussed followed by the recent advancements to overcome these shortcomings.

2.2.1. Components

2.2.1.1. Attachment system

As defined in the Glossary of Oral and Maxillofacial Implants, an attachment system consists of a specific retentive mechanism design that utilizes matching matrix and patrix components. The matrix is the part of the system that serves as the receptacle (61). This female component, referred to as the matrix, consists of a housing embedded within the intaglio surface of the removable denture and includes a replaceable retention device. The male component, known as the patrix, is an abutment attached to the implant and is designed to fit snugly and engage with the matrix through friction (61, 62). Retention is achieved through the friction generated when the patrix and matrix components are interlocked, which is influenced by both the design of these parts and the materials from which they are made (62).

Attachment systems play a pivotal role in the success of implant treatments, significantly influencing the stability, retention, and functionality of complete dentures (63). The attachment systems vary in shape [e.g. bar-clip, magnet, and stud attachments (e.g. ball and O-ring attachments)], design [splinted or unsplinted], and material [metal or polymer] (62, 63).

A significant body of research on IODs has focused on stud attachments since the simplicity of these attachment systems on unsplinted implants has made them commonly used (59, 64-67).

Stud-type attachments in mandibular IODs are frequently chosen for their affordability, ease of use and processing, and the straightforwardness of future modifications or repairs. (68). These attachment systems can be categorized to two groups based on their abutment, which is either ball or cylindrical. Cylindrical attachment systems have been innovatively designed to accommodate clinical applications of attachment systems in limited prosthetic spaces. This development is attributed to their compact size and enhanced retention capabilities (62). Of these cylindrical

attachments, Locator is one of the most used. Recently, another cylindrical attachment system featuring an innovative material combination, known as Novaloc, was introduced.

2.2.1.1.1. Locator attachment system

The Locator attachment system has been widely recognized for its favorable retentive properties, making it an excellent choice for implant-supported overdentures, including cases of Single-Implant Mandibular Overdentures (SIMOs) (69). This consensus among researchers highlights the Locator system's advantages in terms of cost-effectiveness, durability, and biocompatibility, despite the acknowledged limitations of current attachment systems (70-72).

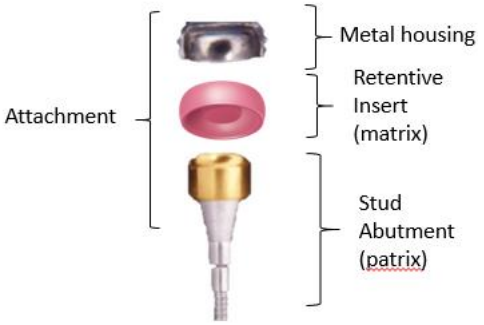

Figure 2-1. The locator attachment system. Reproduced from Zest Dental Solutions.

The Locator attachment is recommended for scenarios with short inter-arch distances or restricted vertical heights of the mandible (73). In cases with low vestibular height, significant transversal forces can impact the attachment, leading to mechanical wear and prosthodontic complications such as retention loss, insert dislodgement, and denture base fractures, as observed in clinical settings (74, 75).

2.2.1.1.2. Novaloc attachment system

Recently, a new retentive system featuring an innovative material combination, known as Novaloc, was introduced. This system includes a matrix made from polyetheretherketone (PEEK) and an abutment coated with amorphous diamond-like carbon (ADLC). This unique combination of materials could enhance the attachment system's mechanical durability, reducing susceptibility to mechanical wear, retention loss, and possible prosthodontic issues (76).

Previous studies have tried to compare Novaloc and Locator's performance. In a study by Arnold *et al.* (77), the Novaloc and Locator attachment systems were compared at different implant angulations. The researchers suggested that Novaloc can be an alternative to Locator attachments, due to comparatively continuous retentive force-curve over 10000 dislodging cycles.

Another study investigating the retentive force of Novaloc and Locator after 10000 insertion-removal cycles showed that Novaloc had the highest peak after 1,000 cycles, and maintained the retentive forces over the whole testing period (78).

2.2.1.2 Denture base

Denture bases are typically made from dental acrylic resins, which are selected for their mechanical durability, chemical stability, biocompatibility, and aesthetic appeal (79). Heat-cured acrylics, especially polymethyl methacrylate (PMMA), are favored for denture base production due to their excellent aesthetic properties. PMMA possess tensile strengths between 48 and 62 MPa, and a compressive strength of 75 MPa (80). It also boasts a Knoop hardness of 18 to 20 KHN (Knoop hardness number), and an elastic modulus around 2.4 GPa (80).

With the advent of three-dimensional (3D) printing technology, its use in denture fabrication has grown. However, 3D-printed denture bases are mechanically inferior to traditional acrylic ones

due to their monomers' reactivity in the curing process, and weaker interlayer bonds in printed layers, leading to lower flexural strength and toughness (80).

In a study examining the mechanical properties, such as flexural strength and surface hardness, of conventional, milled, and 3D-printed PMMA, the researchers found that 3D-printed materials exhibited the weakest flexural strength (81).

In another *in vitro* research, Gad *et al*. (82) assessed the 3D-printed denture base resin's flexural strength, impact strength, hardness, and surface roughness after subjecting it to thermal cycling. It was found that the 3D-printed resin had lower flexural strength, impact strength, and hardness compared to the heat-polymerized resin, although it demonstrated lower surface roughness.

In summary, the research consistently shows that 3D-printed resin materials have lower flexural strength compared to those produced by CAD/CAM and traditional PMMA resin processes. Therefore, enhancing the mechanical properties of 3D-printed materials is crucial to ensure their ability to endure the mechanical stresses encountered during chewing (83). There is no clinical study, in which the fracture incidence of 3D-printed dentures are compared to the conventional ones.

2.2.2. Advantages

The implant-supported overdenture offers several benefits, including a straightforward procedure, as well as excellent stability and retention, leading to enhanced functionality and higher patient satisfaction (84). Since the introduction of two-implant overdenture as the preferred standard of care for addressing mandibular edentulism, studies including an updated meta-analysis conducted in 2016, confirm the favorable patient-centered results with this treatment (85). The introduction of advanced tapered implant designs has broadened the potential to attain adequate primary stability, even in cases with poor bone quality. Primary stability, determined by the extent of

mechanical retention between an implant and the surrounding bone, serves as an initial indicator of the potential success of an implant. This enhancement may provide an opportunity for immediate loading of the implants and increase the applicability of two-implant overdentures to a wider range of patients (86). Moreover, recent studies indicate that the posterior ridge height tends to increase over time with the use of implant-supported prostheses, as compared to traditional dentures (87).

2.2.3. Drawbacks

Implant overdentures are often accompanied by the following limitations (50, 88):

1) The most frequent technical issues with implant overdentures are the loosening of the retentive mechanism or the screw in bar attachments (89). IOD attachments require significant maintenance, including frequent replacements, particularly within the first year of use. These attachments often face challenges such as wear and tear, reduced retention over time, and the need for regular maintenance, which could lead to increased costs (66). Other frequent occurrences involve the fracture of the denture base material along with the retentive anchor (90).
2) Traditional implant overdenture production methods, although established, are complex and time-consuming. The traditional method necessitates at least five clinical visits, involving tasks such as primary and secondary impressions, custom tray fabrication, recording the jaws' horizontal and vertical relationships, try-in appointment to confirm the esthetic aspects with the patient, denture delivery, and conducting necessary adjustments post-delivery (91). The laboratory procedures also require extensive steps, such as pouring stone, constructing a reline jig, and handling acrylic resin, which is prone to considerable

porosity and shrinkage (92). This complexity and the labor-intensive nature of analog processes might deter practitioners from providing this type of treatment (53).

2.2.4. Advancements in IODs

Since polymethylmethacrylate's debut in 1936, advancements have been made in acrylic resin's physical characteristics and polymerization methods. Yet, until recent years, the techniques for manufacturing dentures had not evolved significantly (53).

Recently, computer-aided design/computer-aided manufacturing (CAD/CAM) technology has made notable strides in dental practices, particularly in maxillofacial, fixed, and removable prosthodontics (93). CAD/CAM technology has been applied to complete denture fabrication, aiming to streamline clinical and laboratory processes, and to devise protocols that are both time and cost-efficient, enhancing the treatment outcomes for patients without teeth (94).

2.3. CAD/CAM fabrication techniques

Standard digital techniques for making removable dentures consist of three main steps. The first step is data collection through intraoral or desktop optical scanners. Digital scanners measure surface points with accuracy and define topography during data acquisition. The first intraoral scanner (IOS), developed by Brandestini and Moermann in the 1980s, evolved into a tool for Chairside Economical Restoration of Esthetic Ceramics (CEREC). Although IOS is the first step in a fully digital process, it faces linear stitching errors when moving along the dental arch. In contrast, extraoral desktop scanners in dental labs capture a broad view without stitching problems, making them more suitable for full-arch scanning. Both scanner types are effective for quadrant scanning (95,96). The second step is to design using a CAD software, and finally, the third step is employing the CAM strategies. These digital approaches are employed to fabricate components of

dentures, including bases and teeth for complete dentures, frameworks for removable partial dentures, and bars for overdentures, by either direct or indirect fabrication methods. Generally, the production of digital dentures (the CAM step) is categorized into two primary approaches: subtractive manufacturing (SM), and additive manufacturing (AM) (97).

2.3.1. Subtractive manufacturing

The subtractive manufacturing process involves shaping a product by removing material from a solid block using a CNC (Computer Numerical Control) machine. By removing material, the subtractive method customizes shapes through milling or machining processes (98). This process is facilitated by CAM software, which converts the CAD model into a series of tool paths for the CNC machine (98).

2.3.2. Additive manufacturing (3D printing)

The additive manufacturing or 3D printing involves the production of items by depositing material layer by layer based on digital designs (98). Additive manufacturing techniques encompass a variety of methods. These include (i) stereolithography (SLA), which utilizes laser technology to solidify liquid resin layer by layer; (ii) digital light processing (DLP), employing a digital light projector to cure resin similarly to SLA; (iii) fused deposition modeling (FDM), where thermoplastic filament is deposited layer by layer to construct objects; (iv) polyjet/multijet printing, which involves precise deposition of photopolymer droplets through inkjet nozzles; and (v) selective laser melting (SLM), which utilizes a high-power laser to melt and fuse metal powder, enabling the creation of intricate metal components layer by layer. Each of these techniques offers distinct advantages and applications across various industries, contributing to the diverse landscape of additive manufacturing (99). All these methodologies comprise several fundamental

stages: beginning with CAD, followed by conversion into a 3D image file format (such as .stl), then slicing, printing, and finally, post-processing (100).

3D printing offers advantages over subtractive methods including cost-effectiveness due to reduced prosthesis manipulation time, decreased material wastage, and less wear and fracture of the rotary instruments. Additionally, AM is simpler and allows for the simultaneous production of multiple restorations, while ensuring good strength and fit (101-103).

Optimal outcomes in 3D printing hinge on selecting suitable parameters, including material, AM technology, printing direction, layer thickness, and post-processing techniques. These factors collectively contribute to achieving the desired mechanical and surface properties of the printed objects (104-106).

2.3.2.1. Build Orientation

The printing orientation is a critical factor influencing both the mechanical and surface properties of 3D-printed dentures (107). This parameter dictates the surface geometry and the layer-by-layer structure of the material. There is controversy among the few studies that have examined the relationship between printing orientation and mechanical/surface properties. Alharethi (108) investigated the influence of build orientation (120° and 135°) on the surface roughness and flexural strength of 3D-printed denture base resin, and found that the tested build angles did not have any significant influence on the surface roughness or flexural properties of the 3D-printed denture base resin. Shim *et al.* (109) assessed the effect of printing orientation on the surface characteristics and flexural strength of the 3D-printed denture base resin. The authors found that the print orientation had a significant influence on the flexural strength, roughness, and *Candida albicans* attachment. The authors reported that flexural strength increased with statistical significance in the following printing orientation degrees: 90<45<0. Al-Dulaijan *et al*. (110) also

reported a higher FS with 0° printing angulation. On the other hand, the vertical print orientation showed the highest flexural strength compared to the 45˚ orientation group in a study by Wang (111). Ahmed Altarazi *et al*. (112) also showed that the flexural strength of the 3D-printed denture resin significantly increased when the printing orientation was changed from 0° to 90°.

2.3.2.2. Post-processing technique

The post-processing step in additive manufacturing plays a crucial role in determining the properties of 3D-printed materials (100, 113). It involves removing support structures, rinsing with isopropyl alcohol, and post-polymerization to enhance material characteristics (113). Post-polymerization is essential for improving biocompatibility and mechanical properties by facilitating cross-linking of monomers (114-116). Various Ultraviolet (UV) post-curing methods have been explored to strengthen 3D prints, with recent research highlighting the significant influence of post-polymerization strategies on flexural strength, attributed to differences in wavelengths emitted by curing devices (113).

There is a debate in the literature regarding the effect of increased UV curing time on the mechanical properties of 3D-printed resin. In a study by Aati *et al.* (117), the effect of post-curing light exposure time was inspected on the physical and mechanical properties of a 3D-printed denture base material. An improvement in the physio-mechanical properties of the 3D-printed material was reported as the post-curing time increased to 20 minutes. According to another study, the minimal post-curing time to reach optimum mechanical and physical properties is 30 minutes, and further curing was reported to have no significant effect on the properties of the material (112). On the other hand, some studies (110) reported that extended post-curing duration led to a rise in flexural strength. To enhance the overall clinical efficacy of the material, a minimum post-curing duration of 60 minutes is deemed necessary (115).

Nonetheless, research indicates that UV post-curing predominantly strengthens the material's outer layer, potentially leaving the interior 3D-printed components unaffected, a phenomenon known as the "candy-shell" effect (100). Consequently, thermal post-curing is suggested for achieving comprehensive material conversion. Up to now, no study has assessed the effects of thermal annealing on the mechanical properties of photopolymerized denture resins.

2.4. Rationale

Although IODs are considered as standard of care in rehabilitation of edentulism, there exist inherent limitations necessitating strategic intervention. There is an urge to explore avenues for optimizing attachment mechanisms and streamlining the protracted and expensive fabrication processes associated with removable dentures. The advent of CAD/CAM techniques introduces a paradigm shift in the fabrication of removable dentures, presenting a potential challenge to oral healthcare providers. Therefore, a comprehensive review of literature encompassing studies on CAD/CAM dentures with perspectives from both patients and clinicians is of paramount importance in informing decision-making processes and guiding future research endeavors and technical advancements.

Furthermore, the diverse array of post-processing methodologies and printing parameters proposed by manufacturers complicates the task for clinicians in identifying the optimal digital 3D printing technique. There exists a need to investigate the thermo-mechanical attributes of 3D-printed denture materials subjected to various printing and post-processing modalities prior to embarking on clinical trials.

Recognizing the significance of integrating patient preferences and experiences into treatment protocols, our proposed clinical trial aims to address this demand by investigating patient-reported

outcome measures (PROMs). Through a qualitative analysis, we endeavor to gain insights into the subjective experiences of patients undergoing treatment with digital mandibular implant overdentures, thereby enriching our understanding of the efficacy and patient acceptability of these innovative treatment modalities.

Therefore, the overarching goal of this thesis is to address the limitations of IODs, specifically the loss of retention in attachment systems and the lengthy and costly fabrication processes. This thesis explores methods to optimize these dental prostheses through a series of in vitro studies, literature review and knowledge synthesis, and the development of clinical trials that address the attachment component and the fabrication technique.

Despite their limitations, IODs have been proven effective in clinical settings. Rather than developing an entirely new approach, which could be costly and time-consuming, optimizing the existing IODs ensures that their efficacy is maintained while addressing the identified limitations. The goal is to make IODs more cost-effective and accessible, providing a reliable and efficient solution for patients who need dental prostheses.

2.5. Study objectives

The overarching goal of this thesis has been to tackle the IODs' limitations, and to explore the methods of optimizing these types of dental prostheses. The specific objectives are as follows:

i. To compare retentive forces of Novaloc and Locator abutments for two-implant overdentures in an *in vitro* study simulating masticatory forces equivalent to one week, one, three, six and 12 months of wear by undergoing insertion-removal and compressive cyclic loading

ii. To map the literature on CAD/CAM (computer-aided design and manufacturing) removable complete and partial dentures regarding patient and clinician-reported outcomes.

iii. To compare CAD/CAM CDs with the traditional ones in terms of patient and clinician-reported outcomes, post-insertion adjustment visits, and costs.

iv. To investigate the effect of post-processing technique and printing direction on the mechanical and surface properties of 3D printed photopolymerized denture base resins

v. To develop a cross-over RCT protocol which investigates whether 3D-printed implant-retained mandibular overdentures (IMO) are more satisfactory for edentulous seniors than those made through traditional methods.

3. Chapter 3: Manuscript I- Retentive Properties of Novaloc and Locator Overdenture Attachments

The two-implant overdenture's reliance on a reduced number of attachments requires routine reactivation or change in retentive components, which can be inefficient and burdensome. The Novaloc system matrices are made of PEEK, a material that is more resistant than traditionally used Nylon. While some studies have examined alterations in the retentive force of Novaloc and Locator two-implant abutments for compressive loading and insertion removal cycling, no study has assessed the structural integrity and thermal behavior of these attachments. Therefore, in our first manuscript, we designed an *in vitro* study to not only compare the performance of Novaloc and Locator after a large number of cycles, but also to inspect their thermal behavior and changes in crystallinity following insertion removal wear and compressive cyclic loading simulating masticatory forces equivalent to one week, one, three, six and 12 months of use. This manuscript is prepared for submission to the journal.

Title: Retentive Properties of Novaloc and Locator Overdenture Attachments

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Abstract

Purpose: To compare the *in vitro* retentive forces of Novaloc and Locator attachments for two-implant overdentures before and after insertion-removal and compressive cyclic loading, representing up to 12 months of wear.

Materials and Methods: Insertion-removal and compression cycles of two-implant Novaloc (Novaloc® Retentive System, Institut Straumann AG, Basel, Switzerland) and Locator overdenture attachments (Locator® Attachment System, Institut Straumann AG, Basel, Switzerland) embedded into 3D-printed acrylic blocks were performed (n=10 each). For compressive cycling, a force approximating 66.7-N was applied at the center of the blocks using a Bose ElectroForce Fatigue Testing machine over a sum of 300,000 cycles per sample. The retentive force was recorded at baseline and after certain insertion-removal (23, 270, 540, and 1080) and compression cycles (5k, 25k, 75k, 150k, and 300k). Deformation and crystallization were assessed using micro-computed tomography and differential scanning calorimetry coupled with thermal gravimetric analysis.

Results: Compressive cycling of the two-implant overdenture yielded a greater retentive force for the Locator attachments relative to the Novaloc system at simulated mastication equivalent to one week, one, three, six and 12 months of wear. However, Locator attachments displayed fluctuating retentive force throughout the 300,000-cycle duration. Retention forces for the Novaloc system had no significant differences between the baseline and following 300,000 cycles, indicating consistent retention throughout the cycling duration. Similarly, insertion-removal cycles resulted in retention loss for Locator, whereas Novaloc showed more consistency.

Conclusions: The Novaloc system offers superior durability following compressive and insertion-removal cycling. This indicates more longevity for retentive forces relative to the Locator overdenture attachments system, despite lower overall retentive force following insertion-removal and cycling tests.

Keywords. Denture retention, Implant supported denture, Implant supported dental prosthesis, attachment

Introduction

Edentulism is a chronic, devastating condition often described as the final disease burden marker in oral health (1). Edentulous individuals can exhibit impaired speech, mastication, and esthetics, directly impacting quality of life. Moreover, edentulism is steadily increasing in developing countries and remains a significant condition worldwide, particularly impacting individuals of advanced age, lower socioeconomic status, decreased education, poor oral health, limited social support and reduced overall health (2).

Since 2002, the two-implant mandibular overdenture has been recommended as the minimum standard of care for edentulism (3, 4). These overdentures are substantially more cost-effective for an edentulous mandible than a four-implant fixed prosthesis (5, 6). A significant challenge with overdentures involves the repetitive forces acting on attachments, causing them to be deformed hundreds of times daily. During use, the attachment components between the implants and the prosthesis can become liable to fracture, distortion, and disengagement with a gradual loss of stability (7). Different attachment types can impact on the retentive force of an overdenture and its maintenance over time (4, 8).

The frequent removal and insertion of two-implant overdentures and reliance on few attachments necessitates routine adjustment, reactivation or change in retentive components, which can be

costly and burdensome (3). More specifically, most patients experience retention loss of attachments due to wear and tear from long-term use. Lack of retention and frequent maintenance visits represent the main drawbacks frequently observed with dental prostheses, significantly contributing to patient dissatisfaction (9). Furthermore, the lower denture is the primary source of discomfort and poor chewing performance, causing the mandible to be the primary target for implant-assisted prosthetics (10).

The traditional Locator system, one of the most commonly used overdenture attachments, has several advantages, including a self-aligning feature, considerable resiliency, dual retention, and ease of nylon-retentive insert replacement (4). However, Locator attachments have been shown to loose retention following a few months of regular use due to considerable wear of its nylon matrices, eventually resulting in mechanical failure (7). Additionally, repeated insertion and removal results in abrasion of Locator matrices (11).

An innovative alternative to the traditionally used nylon is polyetheretherketone (PEEK), a semi-crystalline polyaromatic thermoplastic polymer from the high-performance polymer group of polyether aryl ketones (7). The introduction of PEEK in dentistry as a biocompatible material contributed to expanding the versatility of applications in removable prostheses such as dental implants, fixed partial dentures, and crowns. PEEK has high thermal stability, with a melting point of ≈343°C, density of 1.3-1.5 g/cm^3, and elastic modulus between 3-4 GPa. PEEK also has low water absorption and solubility, and has a biofilm formation comparable to other prosthodontic materials, such as zirconia (7). PEEK has good resistance to flexion, fatigue, creep, compression, and wear, and presents high chemical resistance, which are all desirable properties for prosthetic components with potential to reduce maintenance needs (12).

The Novaloc system combines PEEK matrices and amorphous diamond-like carbon (ADLC)-coated cylindrical abutments to enhance wear resistance. Previous studies with Novaloc show better resistance to retention loss caused by insertion-removal cycles (13, 14) compared to Locator. A randomized controlled trial showed general patient satisfaction (100-mm VAS) of 92% ± 8% with Novaloc versus 85% ± 13% with Locator, with the majority (7/10 patients) preferring Novaloc. In addition, patient-reported denture stability was better with the Novaloc system (5). While some studies have examined alterations in the retentive force of Novaloc and Locator two-implant abutments for compressive loading and insertion removal cycling, no study has assessed the structural integrity and thermal behavior of these attachments.

This *in vitro* study aims to explore the retentive properties and structural integrity of Novaloc and Locator attachments for two-implant overdentures after undergoing insertion-removal wear and compressive cyclic loading to simulate masticatory forces equivalent to one week, one, three, six and 12 months of use. Crystallization and morphological changes were assessed using differential scanning calorimetry (DSC) coupled with thermal gravimetric analysis (TGA) and micro-computed tomography (micro-CT), respectively. The null hypothesis was that the Novaloc and Locator attachment systems would perform similarly following the above-mentioned compressive and insertion-removal aging cycles.

Materials and Methods

To mimic the two-implant overdenture *in vitro*, specimens were prepared by placing the Novaloc and Locator attachments (Novaloc® Retentive System and Locator® Attachment System, Institut Straumann AG, Basel, Switzerland) over two parallel implant analogs embedded in an acrylic resin matrix (n=10/combination): 1) Two Novaloc abutments, with yellow PEEK matrices (medium); and 2) Two Locator abutments with pink nylon matrices (medium).

Polyjet 3D-printed acrylic blocks were used to embed the implant analogs and matrices. Half of the blocks were used for insertion-removal cycling. The other half served for simulated masticatory loading, as described by our previous study (6). In brief, analogs and matrices were placed 1 cm from the edge of the block, whereas the force was applied at the center of the blocks (13 mm away from the rotation axis between the two implant analogs). A 2-mm thick polyvinyl siloxane layer (Affinis Regular, Coltene, Altstätten, Switzerland) was applied around cuffs of the abutments and the blocks to simulate mucosal resiliency.

The retention force of each attachment was measured by a Bose ElectroForce 3500 testing machine (Bose Corporation, Eden Prairie, MN, USA), before and after simulated masticatory loading/compressive cycles corresponding to one week, one, three, six and 12 months of use (5k, 25k, 75k, 150k, and 300k, respectively). For the compression cycles, the Bose ElectroForce 3500 fatigue testing machine, capable of exerting a load approximating 66.7-N per specimen, was used. A sum of 300,000 cycles was applied for each sample, corresponding to a year (15).

Retention was also quantified after insertion-removal cycles corresponding to one week, three, six and 12 months (23 ,270, 540, and 1080 cycles, respectively). The cycling regimen was performed using the Bose ElectroForce 3500 fatigue tester. Previous studies have shown that the most retention loss is observable within the first year of use, which corresponds to the number of cycles used in our study (15, 16).

Differential Scanning Calorimetry (DSC) and Thermogravimetric (TGA) analysis

DSC was used to measure heat flow associated with polymer structure (amorphous and crystalline) and changes in structure (transitions) of retentive inserts as a function of time and temperature in a controlled atmosphere, before and after compressive cycling. Plastic inserts were carefully

removed from metallic housings using the manufacturers' demounting tool. DSC was conducted at the Material Characterization Research Facility – McGill University, Faculty of Engineering. A DSC 2500 calorimeter (TA Instruments, New Castle, DE, USA) was used to quantify the weight fraction crystallinity of different inserts before and after compressive cycling. The heating rate was 20°C/min and the maximum temperature was 350°C for Locator, and 450°C for Novaloc in N2-atmosphere. DSC was complemented by simultaneous thermogravimetric analysis (TGA) (TGA 5500; TA Instruments), to quantify the percentage of mass composed by water and other volatile components. For both phases, one specimen was randomly selected (pre- and post- cycling) and evaluated.

Micro-CT Analysis

Nylon inserts of Locator and PEEK inserts of Novaloc attachments were carefully removed from their metallic housings. The retentive inserts underwent micro-CT to observe deformation before and after compressive cycling. Images were obtained by a SkyScan 1172 micro-CT scanner (isotropic resolution: 9 μm) (Bruker, Antwerp, Belgium) and reconstructed by the proprietary software (Bruker Micro-CT Software (CTAn)).

Statistical analysis

Normality of data was confirmed with the Kolmogorov-Smirnov test. Since the test of Homogeneity of Variance showed significant heterogeneity among variances, generalized estimating equations (GEE) were used (α=0.05), followed by the Bonferroni post hoc test. Analyses were performed by the SPSS software, v.23 (IBM SPSS Inc., Chicago, IL, USA).

Results

Figure 3-1.A shows the results for compressive cycling tests, with evidently higher retention for Locator. The effect of cycling time was noticeable only for the Locator, whereas the retention forces of the Novaloc attachment did not change with time ($P>0.05$). The effect estimates of the GEE were 18.086 ($P=0.000$) for the attachment type, 13.992 ($P=0.016$) for time, and 11.935 ($P=0.036$) for the interaction of time and attachment type. Thus, the interaction between the type of attachment and time was significant. Overall, the mean retention force was 77.8 N [95% Confidence Interval (CI): 69.2 to 86.4 N] for the Locator attachment and 16.2 N (CI: 14.6 to 17.9 N) for Novaloc. The differences in retentive forces of the Locator attachment observed by the Bonferroni post hoc test within different compression cycles are shown in Table 3-1.

Figure 3-1.B presents results for insertion-removal tests. Similar to compressive cycling, Locator is clearly affected by time, whereas values for Novaloc fluctuate much less. The effect estimates of the GEE were 19.504 ($P=0.000$) for the attachment type, 17.222 ($P=0.002$) for time, and 18.219 ($P=0.001$) for the interaction of time and attachment type. Thus, the interaction between the type of attachment and time was statistically significant. The differences in retentive forces of the Locator attachment observed by the Bonferroni post hoc test within different insertion-removal cycles are indicated in Table 3-2. The retention forces of the Locator attachment at baseline was significantly higher than other time points ($P<0.05$). Conversely, the retention forces of the Novaloc attachment after 1,080 cycles was significantly higher than other time points ($P<0.05$).

DSC analysis

Figures 3-2, and 3-3 depict the heat flow curves observed for each attachment insert, before and after compressive and insertion-removal cycling. In brief, Locator showed more pronounced thermal events compared to Novaloc.

Post-cycling Locator inserts appear to begin thermal activity at a slightly lower temperature compared to the pre-cycling curves. This suggests some changes of the thermal properties of constituent materials after cycling. Locator inserts also suggest a trend of either increased crystallinity or pronounced thermal event after insertion and removal cycling, i.e., the post-cycling curves have a slightly sharper peak compared to the pre-cycling curves. On the other hand, the DSC curves for Novaloc at baseline, post compressive cycling, and post insertion are nearly superimposable, which implies that the material maintains its intrinsic characteristics quite well under these conditions, indicating that the Novaloc attachment is thermally stable and that its structural properties are not significantly affected by either compressive cycling or insertion-removal cycling.

TGA analysis

TGA was used to measure changes in weight percent in relation to a temperature increase over time in a controlled atmosphere (Figure 3-4). Both the Novaloc and Locator materials show weight loss as temperature increases, but they behave differently. The Locator material starts degrading at lower temperatures and loses weight more rapidly. The Novaloc material, on the other hand, is more thermally and structurally stable.

Both attachments were affected by cycling. The Novaloc post-insertion and removal curve overlaps with the baseline curve, showing that the insertion and removal cycling does not affect the material's thermal properties. The Novaloc post-compressive cycling curve has a similar onset of degradation but appears to lose weight more rapidly at higher temperatures, suggesting some post-cycling changes. The Locator pre-cycling curve begins its weight loss at a lower temperature compared to the post-cycling Locator and Novaloc curves. This suggests that the Locator material

starts degrading or evaporating its components at a lower temperature. The Locator post-cycling curve shows a similar trend but with a steeper decline, indicating a more rapid weight loss after cycling.

Micro-CT results

The results of Micro-CT analysis showed no major difference between the two attachments in terms of internal structure and porosity before and after compressive cycling (Figure 3-5). Locator inserts showed some evidence of surface degradation and slight dimensional changes on their intaglio, more specifically on the top of their central retentive projection.

Discussion

Novaloc, the innovative attachment system assessed in this *in vitro* study, was conceived with the intention to tackle the commonly reported issues related to implant overdentures. These issues include the gradual loss of retention, leading to the constant replacement of retentive inserts, and the necessity of replacing abutments due to excessive wear (17). We tried to explore this claim, comparing the retentive properties and structural integrity of Novaloc and Locator abutments after undergoing compressive cyclic loadings simulating masticatory forces and insertion-removal wear. The null hypothesis that the retentive forces would be the same for both attachments was rejected. The findings revealed that the Novaloc system performed more consistently over cycling time than Locator, although the latter showed a greater retentive force regardless of time.

Variations in design, materials, and surface treatment between the two attachment systems appear to significantly impact the retentive capabilities. Additionally, the insert design could potentially influence how the attachment system behaves, with systems featuring split-ring designs (e.g. Novaloc) likely exhibiting different responses compared to those with full-ring designs (e.g.

Locator) when dimensional changes occur. Comparing the findings of this study with previous research is challenging due to the wide range of variations in test setups, parameters, and pull-off speed, which could be responsible for the observed differences (18). In previous studies, the quantity of cycles spans from 3,000 to 30,000 (13, 14, 19-21). Furthermore, it is difficult to adequately replicate the individual patient behaviors and habits in our simulations. Still, in line with our findings, previous studies comparing individual Locator and Novaloc attachments also showed overall superior retention values for the Locator (13, 22, 23).

To simulate masticatory loading and wear, compressive cycling was performed on the attachments. Generally, wear is described as the loss of surface material caused by mechanical and, to some extent, chemical factors (24). These wear-induced surface alterations on color-coded matrices or abutments can change retention force (25). The mean retentive force of the models with the Locator attachments varied through the compressive cycles, with retention increasing until reaching a peak at 75k cycles, and thereafter decreasing to less than the initial level when reaching 300,000 cycles. A similar behavior has been reported for Locator by a previous paper following insertion and removal cycles (21). Other *in vivo* studies have also validated the vulnerability of the Locator attachment system to wear (26, 27).

Novaloc, on the other hand, showed consistent results with retention force after undergoing 300k compressive cycles. The results of DSC analysis revealed that, compared to Novaloc, Locator inserts seem to have more intense peaks (both endothermic melting and glass transition, and exothermic crystallization) pre- and post-cycling, suggesting a higher degree of crystallinity or a more pronounced thermal event. Changes in crystallinity are the likely the cause for the rise of Locator's retentive force with 75,000 compressive cycles. The coefficient of thermal expansion (CTE) of the matrix materials can impact the retentive properties by altering the matrices'

dimensions. In general, classic nylon materials, such as the one used in Locator, can demonstrate twice the CTE of PEEK. This could be a reason for Novaloc's relatively stable and repeatable retention forces, consisting of PEEK, in comparison with Locator.

Assuming that patients take out their removable dentures three times daily for cleaning, this study involved a total of 1,081 insertions and removals, which corresponds to approximately one year of wear (28). During the insertion-removal cycles, Locator showed a continuous, statistically significant loss of retention. According to previous literature, a range of 21% to 78.62% has been reported as the relative retention force losses following artificial ageing for Locator attachment systems (29, 30). Conversely, our results indicated that Novaloc had a consistent retention force with an increase following the final cycle. The same result was reported in previous studies, showing frequently repeated retention force values and more uniform force curves for Novaloc compared to the Locator system (13, 22, 23). The stiffness of PEEK likely contributed to the secure alignment of specimens' components, thus preventing undesired tilting – a known wear-inducing factor (22). The increased retention of Novaloc can also be explained based on the crystallinity of PEEK. As measured by DSC, PEEK crystallinity had a decreasing trend post-cycling, which might contribute to the increased resilience and retention of the polymer after cycling.

In line with this study, research has shown that wear signs emerge rapidly under load in the case of nylon, affecting retention properties (19, 31). In contrast, Novaloc inserts exhibit a lower reduction in retention, and studies have concluded that they remain clinically viable even after undergoing 10,000 cycles (14, 21).

Considering TGA results, the Locator inserts start degrading at lower temperatures compared to Novaloc. This discloses that nylon, the constituent material of Locator inserts, is less thermally

stable or contains components that evaporate or degrade at lower temperatures. The rate of weight loss appears to be faster for the Locator inserts, especially after cycling, compared to Novaloc. MicroCT analysis also showed some evidence of surface degradation and slight dimensional changes on the intaglio surface of Locator inserts post cycling.

Despite the homogeneity of the Novaloc results, the retentive force of Locator was always higher, regardless of the methodology used. However, the findings of our previous clinical trial on Novaloc showed that most of the patients preferred Novaloc due to better patient-perceived denture stability with Novaloc for the duration of the trial (5). This suggests that, rather than an initially high retentive force, patients tend to value consistency over time considerably. In other words, the primary reason for patients seeking attachment changes in the clinic is the significant drop in retention, rather than the absolute amount of retention initially provided.

We used medium-retention matrices for the Novaloc in the current study. Hence, to remain consistent with the Novaloc system, the "medium" strength (pink) insert was selected for the Locator specimens. If there is a noticeable decrease in retention force that is clinically significant, the color-coded matrices of both systems can be replaced chairside. Based on the current test results, it is suggested that replacements may be needed more frequently with the Locator attachment system compared to the Novaloc attachment system. We recommend further testing of matrices with different retention strengths to validate the obtained outcomes.

Although the retention force of Novaloc was less than Locator, it remained within the acceptable limits. Recent recommendations propose lower forces ranging from 8 to 10 N (32). In situations involving geriatric patients and those in palliative care, lower retention forces have been reported to be sufficient (33).

Although one might argue that our sample size (n=10) was small, based on previous studies, this sample size had enough statistical power to detect significant effects (13, 19, 34). Moreover, use of constant temperature without the presence of saliva, allowed for a controlled comparison of the attachments without introducing factors associated with individual patients.

One of the main limitations of this study is the *in vitro* setup of the study. As an *in vitro* investigation, some "parameters" of the clinical situations were inevitably lost. For instance, the application of unidirectional vertical forces is unlike the clinical situation, in which two-implant overdentures undergo rotational movements and thus multidirectional forces. This undoubtedly accelerates wear on the attachment components. As a result, the retention force measured *in vitro* at a specific cycling time cannot be directly extrapolated to a clinical setting, where increased wear can lead to even lower retentive forces. However, present results shed light on the wear mechanism of tested attachments.

Since all attachment systems examined maintained retention forces within a clinically satisfactory range throughout the study, it can be suggested that factors other than retention force may have a more significant influence on clinical treatment decisions. The more time-consistent retention forces of Novaloc might be one of the determining factors when choosing between these attachments. Further clinical studies are required to validate these *in vitro* findings.

Conclusions

The Novaloc system underwent minimal changes in retentive force with compressive and insertion-removal cycling, whereas Locator was largely affected by both cycling regimens. Structural changes in the polymeric matrix were minor but more pronounced with the latter. Locator presented higher retentive forces than Novaloc regardless of the time point.

Conflict of interest: None.

References

1. Cunha-Cruz J, Hujoel P, Nadanovsky P. Secular trends in socio-economic disparities in edentulism: USA, 1972–2001. Journal of dental research. 2007;86(2):131-6.

2. Al-Rafee MA. The epidemiology of edentulism and the associated factors: A literature Review. Journal of family medicine and primary care. 2020;9(4):1841-1843.

3. Feine J, Carlsson G, Awad M, Chehade A, Duncan W, Gizani S, et al. The McGill consensus statement on overdentures. Mandibular two-implant overdentures as first choice standard of care for edentulous patients. Gerodontology. 2002;19(1):3-4.

4. Ramadan RE, Mohamed FS. Retention of mandibular implant-retained overdentures with two different attachment designs: An in vitro study. The Journal of prosthetic dentistry. 2020;123(5): 738.e1-738.e6.

5. de Souza R, Jabbar A, Jafarpour D, Bedos C, Esfandiari S, Makhoul N, et al. Single-implant overdentures retained by a novel attachment: A mixed methods crossover randomized clinical trial. JDR Clinical & Translational Research. 2024;9(1):27-41.

6. Abi Nader S, De Souza R, Fortin D, De Koninck L, Fromentin O, Albuquerque Junior R. Effect of simulated masticatory loading on the retention of stud attachments for implant overdentures. Journal of Oral Rehabilitation. 2011;38(3):157-64.

7. Sharaf M, Eskander A, Afify M. Novel PEEK retentive elements versus conventional retentive elements in mandibular overdentures: a randomized controlled trial. International Journal of Dentistry. 2022;2022:6947756.

8. Setz J, Lee SH, Engel E. Retention of prefabricated attachments for implant stabilized overdentures in the edentulous mandible: an in vitro study. The Journal of prosthetic dentistry. 1998;80(3):323-9.

9. Ortegón SM, Thompson GA, Agar JR, Taylor TD, Perdikis D. Retention forces of spherical attachments as a function of implant and matrix angulation in mandibular overdentures: an in vitro study. The Journal of prosthetic dentistry. 2009;101(4):231-8.

10. Araujo R, Zancopé K, Moreira R, Barreto T, Neves F. Mandibular implant-assisted removable partial denture-Kennedy Class I to Class III modification–Case series with masticatory performance and satisfaction evaluation. Journal of Clinical and Experimental Dentistry. 2023;15(1):e71-e78.

11. Chae S-K, Cho W-T, Choi J-W, Bae E-B, Bae J-H, Bae G-H, et al. Comparison of retentive force and wear pattern of Locator® and ADD-TOC attachments combined with CAD-CAM milled bar. The Journal of Advanced Prosthodontics. 2022;14(1):12-21.

12. da Costa Valente ML, da Silva GG, Bachmann L, JA MA, Dos Reis C. An in vitro analysis of the physical and mechanical behavior of a polyetheretherketone (PEEK) component for an Implant-supported and retained removable dental prosthesis (I-RDP). The International Journal of Prosthodontics. 2023;36(5):612-619.

13. Arnold C, Stampa C, Schweyen R, Hey J, Boeckler A. Retentive characteristics of a new attachment system for hybrid dentures. Materials. 2020;13(15):3434.

14. Wichmann N, Kern M, Taylor T, Wille S, Passia N. Retention and wear of resin matrix attachments for implant overdentures. Journal of the mechanical behavior of biomedical materials. 2020;110:103901.

15. Fromentin O, Picard B, Tavernier B. In vitro study of the retention and mechanical fatigue behavior of four implant overdenture stud-type attachments. Practical periodontics and aesthetic dentistry: PPAD. 1999;11(3):391-7; quiz 398.

16. Gamborena JI, Hazelton LR, NaBadalung D, Brudvik J. Retention of ERA direct overdenture attachments before and after fatigue loading. International journal of prosthodontics. 1997;10(2):123-130.

17. Andreiotelli M, Att W, Strub J-R. Prosthodontic complications with implant overdentures: a systematic literature review. International Journal of Prosthodontics. 2010;23(3): 195-203.

18. Evtimovska E, Masri R, Driscoll CF, Romberg E. The change in retentive values of locator attachments and hader clips over time. Journal of Prosthodontics: Implant, Esthetic and Reconstructive Dentistry. 2009;18(6):479-83.

19. Reda KM, El-Torky IR, El-Gendy MN. In vitro retention force measurement for three different attachment systems for implant-retained overdenture. The Journal of the Indian Prosthodontic Society. 2016;16(4):380-385.

20. Sultana N, Bartlett DW, Suleiman M. Retention of implant-supported overdentures at different implant angulations: Comparing Locator and ball attachments. Clinical oral implants research. 2017;28(11):1406-10.

21. Maniewicz S, Badoud I, Herrmann FR, Chebib N, Ammann P, Schimmel M, et al. In vitro retention force changes during cyclic dislodging of three novel attachment systems for implant overdentures with different implant angulations. Clinical oral implants research. 2020;31(4):315-27.

22. Wakam R, Mawussi KB, Benoit A, Gorin C. Initial retention force of three attachment systems for implant retained-mandibular overdentures: An in vitro study. Journal of Prosthodontics. 2023.

23. Fugariu I, de Souza RF, Rosas E, Borie E. Using an Attachment System with PEEK Matrices for Single-Implant Overdentures: In Vitro Retention Force. Journal of Clinical Medicine. 2023;12(6):2159.

24. Anusavice KJ, Shen C, Rawls HR. Phillips' Science of Dental Materials, 12th ed. Elsevier Health Sciences; 2012.

25. Swain MV. Attachment systems for mandibular two-implant overdentures: a review of in vitro investigations on retention and wear features. Int J Prosthodont. 2009;22(5):429-40.

26. Jabbour Z, Fromentin O, Lassauzay C, Abi Nader S, Correa JA, Feine J, et al. Effect of implant angulation on attachment retention in mandibular two-implant overdentures: A clinical study. Clinical implant dentistry and related research. 2014;16(4):565-71.

27. Engelhardt F, Zeman F, Behr M, Hahmel S. Prosthetic Complications and Maintenance Requirements in Locator-attached Implant-Supported Overdentures: A Retrospective Study. The European Journal of Prosthodontics and Restorative Dentistry. 2016;24(1):31-5.

28. Besimo C, Guarneri A. In vitro retention force changes of prefabricated attachments for overdentures. Journal of oral rehabilitation. 2003;30(7):671-8.

29. Chung KH, Whiting D, Kronstrom M, Chan D, Wataha J. Retentive characteristics of overdenture attachments during repeated dislodging and cyclic loading. International Journal of Prosthodontics. 2011;24(2):127-9.

30. Rutkanas V, Mizutani H. Retentive and stabilizing properties of stud and magnetic attachments retaining manibular overdenture. Stomatol. 2004;6:85-90.

31. Kobayashi M, Srinivasan M, Ammann P, Perriard J, Ohkubo C, Müller F, et al. Effects of in vitro cyclic dislodging on retentive force and removal torque of three overdenture attachment systems. Clinical oral implants research. 2014;25(4):426-34.

32. Scherer MD, McGlumphy EA, Seghi RR, Campagni WV. Comparison of retention and stability of implant-retained overdentures based upon implant number and distribution. The International journal of oral & maxillofacial implants. 2013;28(6):1619-28.

33. Müller F, Schimmel M. Revised Success Criteria: A Vision to Meet Frailty and Dependency in Implant Patients. The international journal of oral & maxillofacial implants. 2016;31(1):15.

34. Friedrichsen M, Dirksen D, Runte C. In vitro measurement of the retention force of two stud attachment systems during cyclic load. Journal of Prosthodontics. 2024;33(2):164-170.

Table 3-1. Compression (Mean ± SD). Distinct uppercase letters represent significant differences in retention force (N) between time intervals within each attachment (Bonferroni test, $p<0.05$).

Attachment	Time (n cycles)					
	0 (Baseline)	5k	25k	75k	150k	300k
Locator	89.4 (±22.4)^{A}	80.4 (±28.7)^{AB}	80.9 (±21.8)^{AC}	88.4 (±17.2)^{A}	64.8 (±12.8)^{BC}	62.9 (±11.2)^{B}
Novaloc	18.5 (±4.9) ^{A}	17.7 (±4.4) ^{A}	14.7 (±3.5)^{A}	15.6 (±3.8)^{A}	15.3 (±3.5)^{A}	15.5 (±3.1)^{A}

Table 3-2. Insertion-removal (Mean ± SD). Distinct uppercase letters represent significant differences in retention force (N) between time intervals within each attachment (Bonferroni test, $p<0.05$).

Attachment	Time (n cycles)				
	0 (Baseline)	23	270	540	1080
Locator	111.4 (±20.4)^{A}	95.3 (±16.0)^{B}	83.5 (±6.6)^{B}	71.5 (±5.7)^{C}	42.1 (±10.6)^{D}
Novaloc	12.9 (±2.4)^{B}	10.7 (±1.2) ^{B}	11.2 (±1.7)^{B}	13.2 (±3.2)^{B}	16.8 (±3.3)^{A}

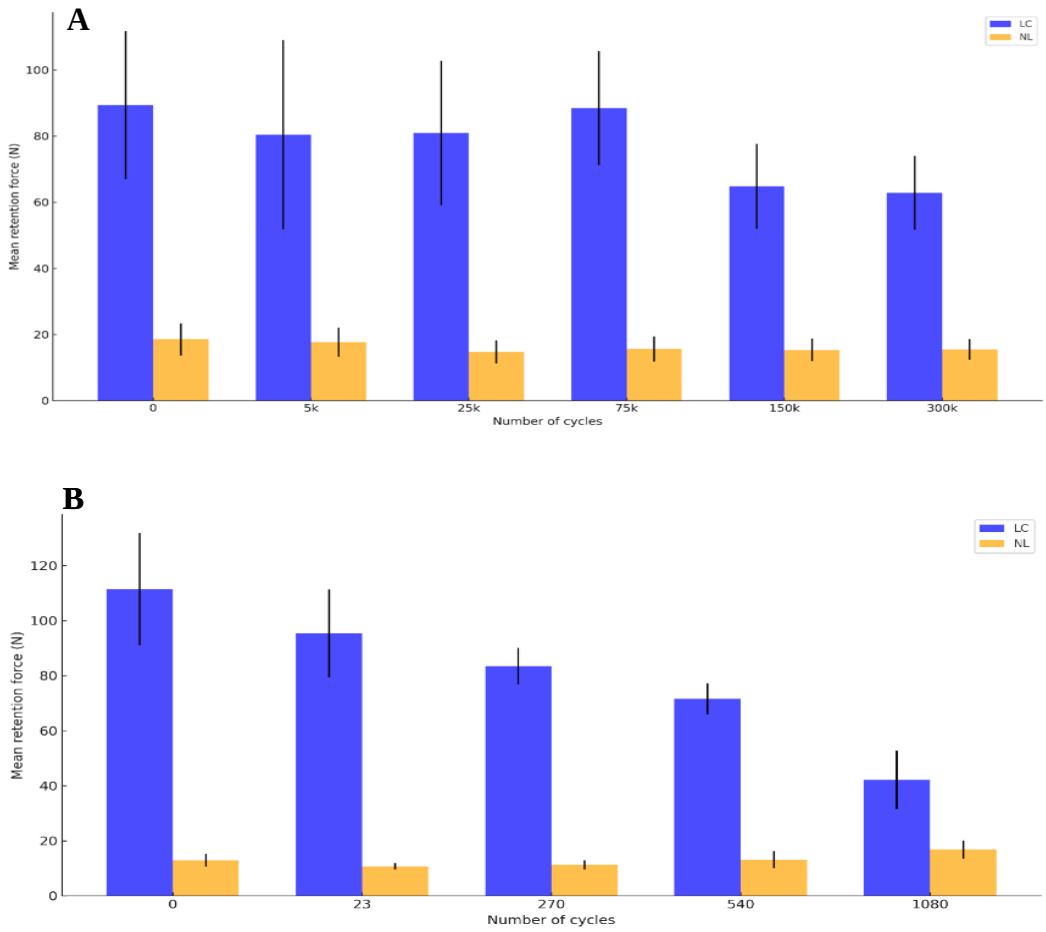

Figure 3-1. Retention forces (Mean±SD) of Novaloc (NL) Vs Locator (LC) attachments following: (A) compression cycles, and (B) insertion-removal cycles. A significant drop in retentive force over the cycling period was observed for Locator wheras Novaloc stayed relatively stable.

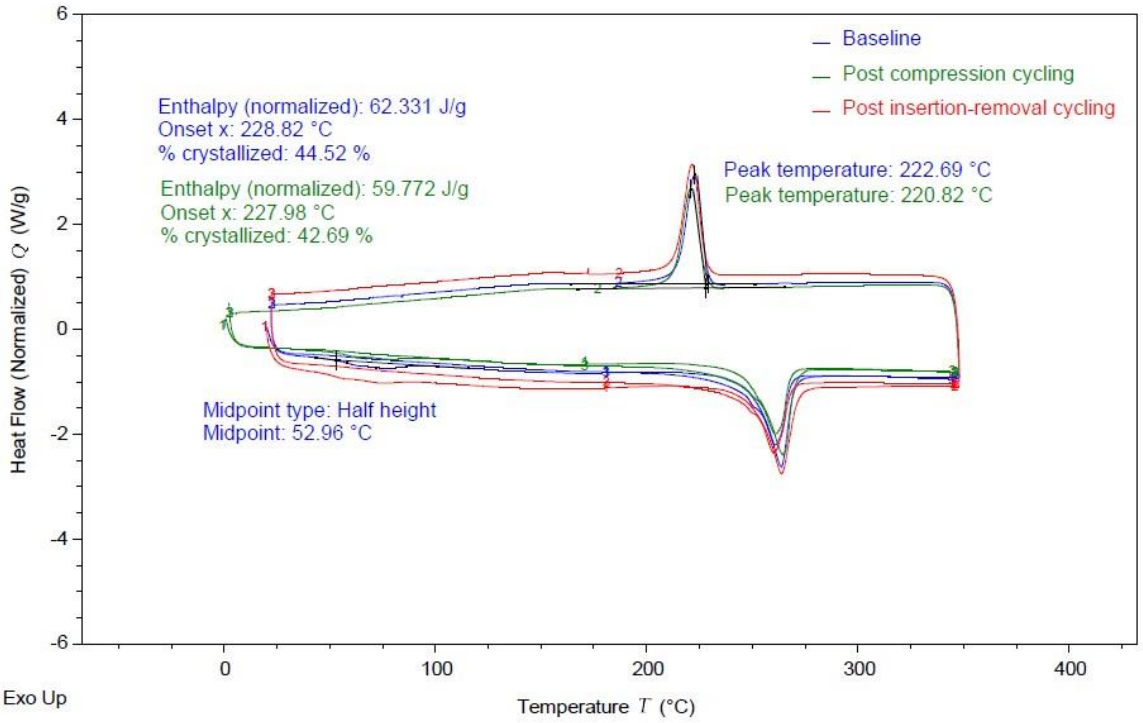

Figure 3-2. DSC analysis plot for Locator inserts: i. Baseline (Blue), ii. Post-compressive cycling (Green), and iii. Post-insertion and removal (Red). Degradation of Locator inserts was initiated at lower temperature post compression cycling.

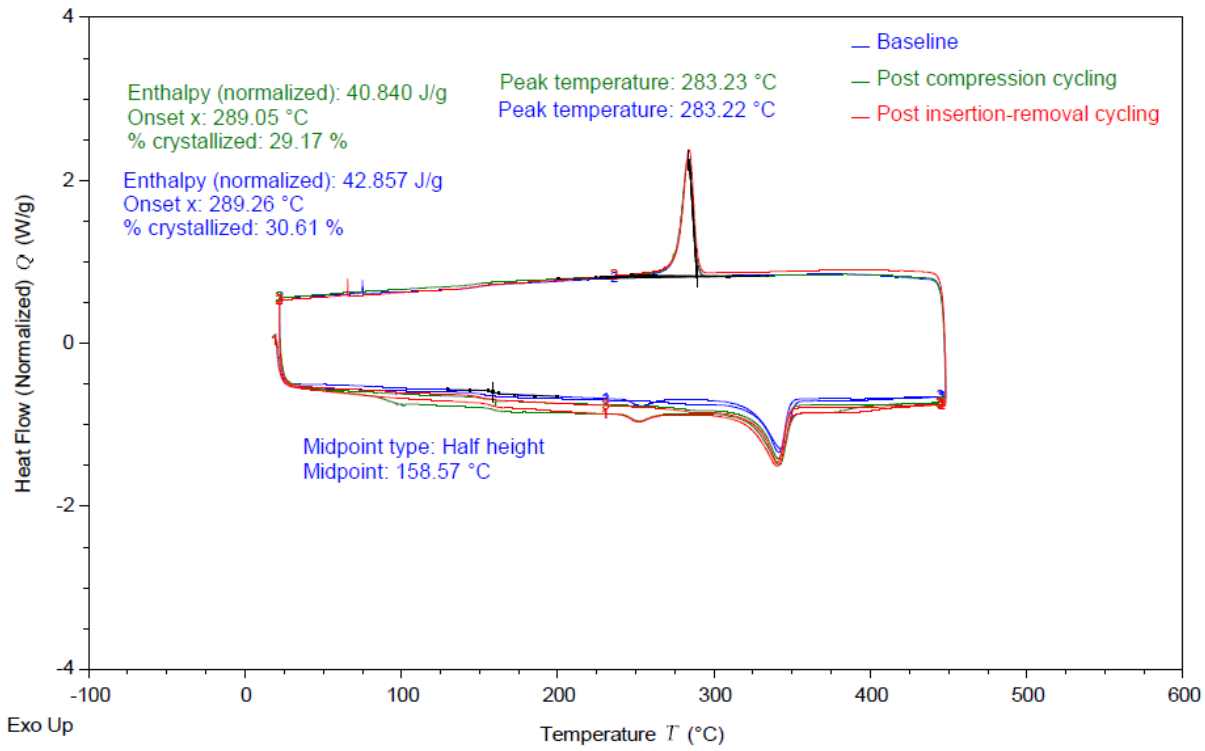

Figure 3-3. DSC analysis plot for Novaloc inserts: i. Baseline (Blue), ii. Post-compressive cycling (Green), and iii. Post-insertion and removal (Red). Novaloc seems to maintain its thermal characteristics post cycling.

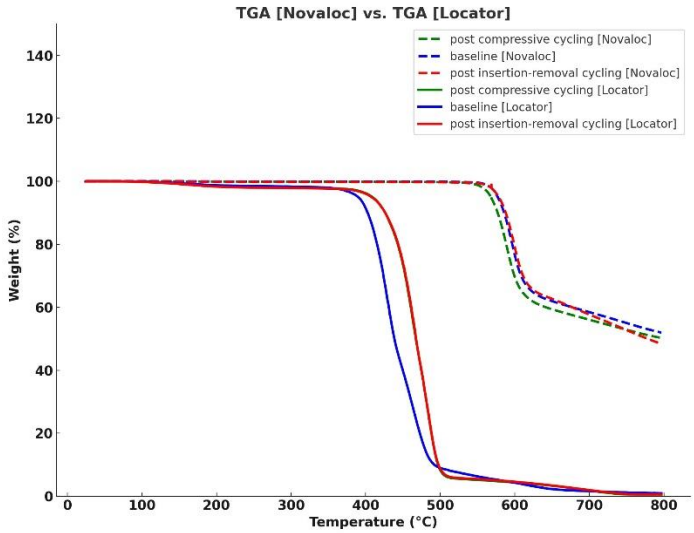

Figure 3-4. TGA plot for Locator and Novaloc inserts at: i. Baseline, ii. Post-compressive cycling, and iii. Post-insertion and removal. Novaloc seems to be more thermally stable compared to Locator.

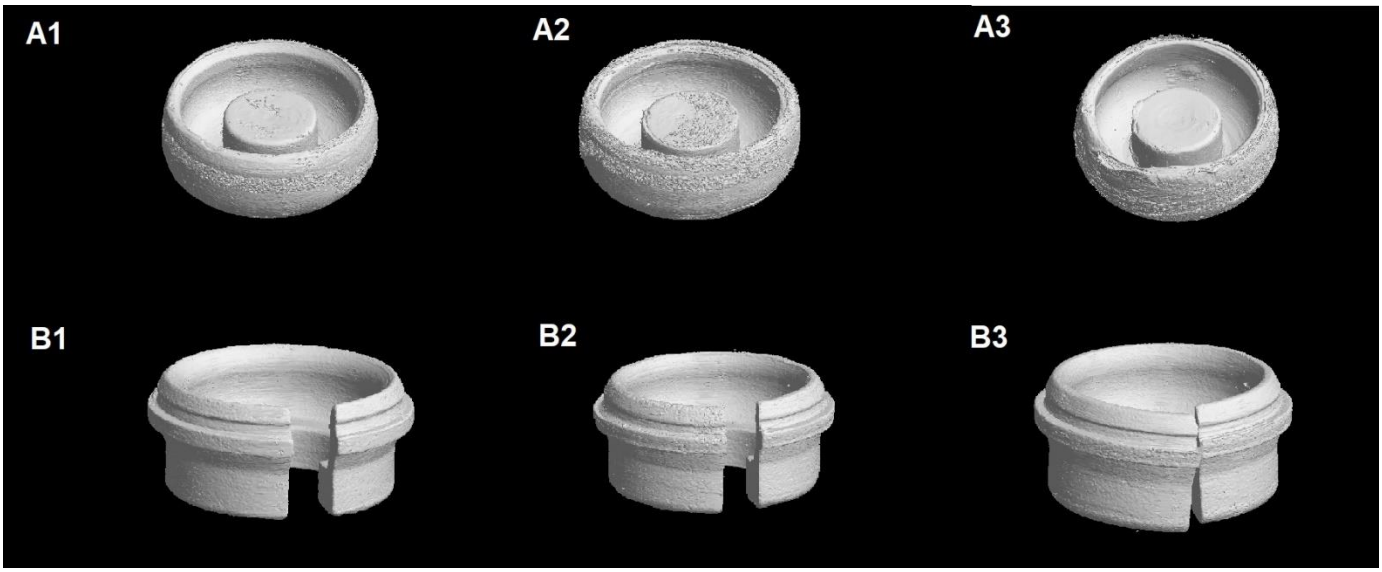

Figure 3-5- Locator (A) and Novaloc (B) attachments at baseline (1), post-compression cycling, and post-insertion and removal cycles (3).

4. Chapter 4: Manuscript II- Patient-reported outcomes and clinical performance of CAD/CAM removable dentures: A scoping review

This chapter covers our scoping review manuscript, in which we explored the existing literature on CAD/CAM technology for removable dental prostheses, focusing on their clinical performance and PROMs. This summary aimed to aid decision-making and guide future research and technical advancements in the field by evaluating both patient and clinician perspectives on the use of CAD/CAM in fabricating complete and removable partial dentures. It also helped us narrow down our research question into a focused one for our meta-analysis to be discussed in chapter 5. This review also helped with finding the gaps in knowledge, which built the grounds for our clinical trial protocol to be discussed in chapter 7. The manuscript has been published in the International Journal of Prosthodontics.

Title: Patient-reported outcomes and clinical performance of CAD/CAM removable dentures: A scoping review

Running title: A scoping review on CAD/CAM removable dentures

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CONFLICT OF INTEREST: The authors declare no conflict of interest.

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Title: Patient-reported outcomes and clinical performance of CAD/CAM removable dentures: A scoping review

ABSTRACT

Purpose: This scoping review mapped the literature on CAD/CAM removable complete and partial dentures regarding patient and clinician-reported outcomes.

Materials and Methods: We performed an electronic search of the Cochrane Central Register of controlled trials (CENTRAL), MEDLINE (Ovid), EMBASE, SCOPUS, and Web of Science databases (last update: March 2023). All clinical trials or observational studies investigating CAD/CAM removable dentures (conventional or implant-retained) were included.

Results: The search yielded 4035 records and led to 58 included studies. Results suggest that CAD/CAM complete and partial dentures, when compared to the conventional ones, can save time and resources while being rated either non-inferior or superior by patients and clinicians in most studies. However, consensus on which workflow offers fewer adjustments and post-operative sessions is still pending.

Conclusion: The literature suggests that CAD/CAM complete and partial dentures can combine substantial time and cost savings with patient and clinician experiences at least comparable to the conventional prostheses. Given the low evidence level of existing studies, future well-designed randomized trials with large sample size are required to confirm those advantages.

Keywords: Removable denture, CAD/CAM, Patient-reported outcomes, Clinical outcome

1. INTRODUCTION

Edentulism is still a widespread condition in the 21st century, mostly amongst seniors. The absolute number of edentulous patients still remains high (1) due to population growth and increased life expectancy (2), even if incidence rates tend to decline in some developed nations (3). In general, the treatment of completely or partially edentulous patients involves the provision of removable complete dentures (CDs) and partial dentures (RPDs), either conventional or implant-retained (4, 5).

Even if traditional denture fabrication methods have been well-established over the past century (6), recent advances have provided oral health professionals with computer-aided design and manufacturing (CAD/CAM) alternatives. Those CAD/CAM technologies include the use of software algorithms and data processing to render virtual denture parts, as done with crowns and bridges, plus several manufacturing techniques (7). Given the promising results of CAD/CAM methods in various fields of dentistry (8), their increasing popularity in CD and RPD fabrication is a natural outcome (9-13).

Common digital workflows for fabricating removable dentures combine (i) data acquisition (e.g., using intraoral or desktop optical scanners), (ii) CAD software work, and (iii) one or more CAM techniques. Digital procedures will produce denture parts, including CD bases and teeth, RPD frameworks and overdenture bars, either directly or indirectly.

In general, digital denture fabrication employs two main CAM methods: the additive (AM) and the subtractive manufacturing (SM) (14). AM comprises techniques which use digital images to create objects in a layer-by-layer fashion (15). AM techniques, also named rapid prototyping (RP) or 3D printing, were first used in dentistry in 1999 to reproduce images from tomograms (16). Different AM techniques include stereolithography (SLA), digital light projection (DLP), fused

deposition modeling (FDM), polyjet/multijet, and selective laser melting (SLM) (17). On the other hand, the subtractive methods (such as computerized numerical control [CNC] machining or milling) encompass techniques in which digital images are used to fabricate objects by physically subtracting material to reach a custom shape (15).

The aim of integrating digital technology into dental procedures is not only to benefit the clinician, but also to offer superior treatment options for the patient. Previous *in vitro* studies have reported improved fit/greater denture base adaptation (18-21), acceptable intaglio surface trueness (22), improved surface and mechanical properties (23), and comparable biocompatibility (24) for additive and subtractive CAD/CAM removable dentures than traditionally fabricated dental prostheses. However, to be relevant, those advantages must also lead to clinical benefits. Ongoing health research is now underscoring patient-centered outcome measures as a core element for the evaluation of any healthcare intervention, including dental prostheses (25). For that matter, using patient-reported outcome measures (PROMs), such as patient satisfaction and oral health-related quality of life (OHRQoL), is fundamental in the investigation of the effectiveness of prosthodontic interventions (10, 26-29).

The novelty of CAD/CAM methods for the fabrication of removable dentures and wide array of usable digital procedures raises a challenge for oral healthcare providers. Summarizing studies on CAD/CAM CDs and RPDs in which both patient and clinician perspectives are measured is fundamental for decision-making and recommendations for future research and technical development. Therefore, the purpose of this scoping review is to map the existing literature on CAD/CAM removable dental prostheses in terms of their PROMs and clinical performance. To the authors' best knowledge, this paper is the first scoping review to comprehensively survey the literature on CAD/CAM complete and partial removable dentures.

2. METHODS

2.1. Review framework

The aim of scoping reviews is to map the existing literature on a specific topic, identifying main theories, as well as finding the gaps in the research field (30). The application of CAD/CAM technology in fabricating removable dental prosthesis is a novel topic in dental practice and clinical research, with a variety of potential technical applications. Hence, this study follows the "scoping review" methodological framework (31) to describe the current state of published research in CAD/CAM removable dentures and, thus, better understand knowledge gaps regarding the PROMs and clinical performance of that treatment modality.

The following research question steered this review: "What are the PROMs and clinical performance of milled and 3D-printed CAD/CAM partial or complete removable dentures?" Separate PICOS components of the question guided study selection and data collection:

a. *Population*: Patients who needed a removable denture for least one partially or completely edentulous jaw and/or at least one immediate CD or RPD, combined with implants or not.

b. *Intervention*: CD or RPD (conventional or implant-retained) including CAD/CAM technology in part of their fabrication workflow, e.g., design by software and milled/3D printed denture bases, frameworks and teeth. Interventions could combine other restorative approaches, e.g., crowns and bridges, if a denture is provided and used some type of CAD/CAM method in its fabrication.

c. *Comparison*: No prosthetic treatment for existing or future edentulous spaces, or removable dentures fabricated by traditional workflows. In studies comparing only CAD/CAM methods, any denture fabrication workflow used as a control.

d. *Outcomes*: (i) PROMs, including self-appraisal of esthetics, patient satisfaction (e.g., McGill Denture Satisfaction Questionnaire [MDSQ]), patient preferences, and oral-health related quality of life (e.g., OHIP-EDENT). (ii) Clinical performance, including appraisal of esthetics, function, retention and stability by clinicians, maintenance events (e.g., number of adjustment appointments), professional time, complications, and cost.

e. *Study design*: Clinical experimental (single-arm and controlled clinical trials) or observational studies, regardless of the timespan for outcome data collection.

2.2. Search strategy

The studies were retrieved in March 2023 by a medical librarian (MM) using a structured electronic search strategy. A list of keywords and Medical Subject Headings (MeSH) linked to our research question (including truncation, adjacency functions, and Boolean operators) were used to tailor the search strategy, adapted for the following databases: Cochrane Central Register of controlled trials (CENTRAL), MEDLINE (Ovid), EMBASE, SCOPUS, Web of Science database. The search was restricted to reports published from 01 January 2000 to 01 March 2023. The search strategy was comprised of two main concepts of CAD/CAM and removable dentures, as follows:

1. exp Denture, Complete/
2. exp Denture, Partial, Removable/
3. ((removable or complete or partial or conventional) adj3 (denture? or prosthes?s)).tw,kf.
4. exp Jaw, Edentulous/
5. edentulous.tw,kf.
6. or/1-5
7. "CAD/CAM".tw,kf.

8. exp Computer-Aided Design/

9. (computer-aid* or computer-assist* or computer-engineer*).tw,kf.

10. (3D-print or milled or rapid prototyp* or additive manufactur*).tw,kf.

11. digital*.tw,kf.

12. or/7-11

13. 6 and 12

14. limit 13 to yr="2000 -Current"

15. limit 14 to (arabic or english or french or persian or portuguese or spanish)

16. "in-vitro".ti.

17. 15 not 16

2.3. Study selection

To find the most relevant research pertaining to the research question, a set of inclusion criteria was defined before initiating the search process. Eligible studies complied with the aforementioned PICOS components. Specifically, for study design, we included clinical experimental (single-arm and controlled clinical trials, randomized or not), or observational studies, protocols, and case series on CAD/CAM removable dentures. Studies were excluded if they investigated partially or completely edentulous patients treated with fixed dental prostheses only, either implant- or tooth-supported. *In vitro* studies, other review articles, and case reports were also excluded.

Two authors (DJ, RS) independently screened the titles and abstracts of these remaining records based on the eligibility criteria. The remaining texts were read in full, and reviewed based on the

same criteria. A study selection flow diagram was prepared according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR; Figure 4-1; (32)).

2.4. Data Extraction and Analysis

After final selection of articles, the reviewers (DJ, RS) extracted and charted the data, including studies' first authors, titles, publication years, study designs, study objectives, sample sizes, digital workflows (CAD/CAM components used), type of study outcomes (including data collection tools), study timelines and key findings. To confirm reliability, a pilot review was performed initially on ten articles. Then, the two reviewers compared their findings in order to address potential discrepancies for the remaining articles. In case of any charting inconsistency, the conflicts were discussed with other research team members to reach a consensus. Using tabulation and descriptive analysis, the authors categorized and described the retrieved studies' findings.

The included studies evaluated varying CAD/CAM components in digital fabrication of removable dental prosthesis, based on which the studies were classified: complete denture/overdenture, overdenture bar, denture base, and RPD framework. Each category was further classified based on the outcomes assessed: i) PROMs, ii) Clinical performance. Since this is a scoping review, no quantitative data synthesis (e.g., meta-analysis) was sought; thus, results were assessed by a descriptive approach.

3. RESULTS AND DISCUSSION

The electronic search yielded 4035 records, with 2775 articles remaining after the elimination of duplicates. A total of 90 papers were retained for full text review, and 58 studies were selected for analysis (Figure 4-1). All included studies were published between 2012 and 2023.

The included studies evaluated varying CAD/CAM components in digital fabrication of removable dental prosthesis, as follows: whole CD or overdenture (n=32; 55.17%), overdenture retentive component (n=9; 15.51%), denture base (n=5; 8.62%), and RPD framework (n=12; 20.69%). AM (3D printing) workflows were evaluated in 32 (55.17%) and subtractive manufacturing (milling) was investigated in 33 (56.90%) studies. In terms of design, included studies were clinical trials (n=35; 60.34%), prospective observational (n=8; 13.79%), retrospective cohort (n=7; 12.06%), cross-sectional (n=5; 8.62%), and case series (n=3; 5.17%). The main parameters and the findings of the 58 studies are shown in Tables 4-1to 4-4.

3.1. Whole CDs and overdentures

3.1.1 RPOMs of CAD/CAM CD and overdenture (18 studies)

Of the 32 studies about digital whole CDs and overdentures, 18 evaluated PROMs (clinical trials: 10; prospective observational: 2; retrospective: 2; cross-sectional: 1; case series: 2; Table 4-1). Some (n=7) studies evaluated "closed" workflows for the fabrication of new CDs (i.e., the set of procedures and equipment purported by a specific company; (33-37). Conventional denture fabrication sequence and "open" CAD/CAM based alternatives used by included studies are demonstrated in Figure 4-2.

The study by Kattadiyil *et al*. (36) compared AvaDent ("closed") milled CDs to conventional dentures, both provided in a teaching clinic. Authors found greater overall patient satisfaction with the AvaDent technique, with significantly higher results for comfort and chewing ability. However, the denture types were no different regarding self-reported esthetics (P=0.763). Inokoshi *et al.* (2012) found no significant differences between the 3D-printed and conventional dentures in patient ratings of esthetics, predictability of final denture shape, stability, comfort of the

dentures, and overall satisfaction (38). At the time this study was conducted, only one rapid prototyping material was safe for use in the oral environment, which could have led to the inferior properties observed. The esthetics of 3D-printed teeth was raised as an issue by Kim *et al.* (39), who found that patients preferred the conventional, rather than 3D-printed, mandibular dentures regarding that aspect. The likely explanation is that the traditional artificial teeth use multi-layered colors, while 3D printed teeth are colored monochromatically. Recently, Ohara *et al*. (40) also reported that conventional CDs performed significantly better than 3D-printed dentures in terms of patient satisfaction. As suggested, the primary reason could be the greater susceptibility of 3D printing resin to discoloration. Other alluded reason is better phonetics with conventional dentures due to their thinner bases. The most recent studies on 3D-printed dentures reported no significant difference in patient satisfaction (mastication, esthetics, stability, comfort (41-43), and pronunciation (41))(42) between conventional and 3D-printed CDs.

Regardless of the type of digital workflow, most studies revealed that patient ratings for the digital dentures were significantly better than those at baseline (33-35, 37, 42, 44-49). Bidra *et al*. (33) reported significant improvements in patient VAS ratings of treatment time and sore spots from baseline to one year for digitally milled mandibular dentures and overdentures ($P<0.05$). This improvement in ratings of treatment time is possibly due to the adoption of a two-visit monolithic CAD/CAM denture "closed" protocol (AvaDent) in this clinical study over the three-visit digital denture protocol. Similarly, another two-visit protocol proposed by Deng *et al*. (47) also resulted in satisfied patient ratings with 3D printed dentures. Otake *et al.* (46) also showed that general patient satisfaction with the milled dentures was significantly higher than conventional dentures after the treatment ($P=0.002$).

In a study on overdentures, Elawady *et al.* (48) reported a significant improvement in the OHRQoL of patients rehabilitated with 3D-printed implant overdentures compared to the conventional ones. The highest (worst) scores for the conventional dentures were given to the domains of denture fit and feeling of soreness, reflecting that the reduced retention of conventional overdentures was the primary reason for the inferior patient satisfaction with these dentures. In another cross-over clinical trial comparing conventional and digitally milled overdentures, the authors found superior patient satisfaction and better OHRQoL with CAD/CAM milled IODs (49).

A cross-sectional study on AvaDent milled CD (34) reported that most participants (78.95%) were satisfied with esthetics and agreed that their new digital dentures were "better" than their previous prostheses in terms of cleaning, comfort, fit, stability, speech and chewing ability. A case series on two-visit CAD/CAM milled maxillary CDs (Baltic Denture System, "closed") also revealed that the patients were pleased with their digital dentures and described no functional difficulty in a 6-week follow-up (35). Yet, a recent cross-over RCT on the Baltic Denture System found no significant difference between the OHRQoL of patients treated with this system and those treated with the conventional dentures (50). Also, Cepic *et al*. (37) recently showed similar OHRQoL and patient satisfaction scores for digitally milled Vita Vionic dentures and conventional ones, attribiuting it to the same number of visits required for the fabrication of these dentures. Cristache *et al*.'s 18-month prospective clinical trial evaluated an "open" digital workflow, for which impressions/casts, record bases and mounting in the articulator were conventional (44). Wax rims and casts were scanned to generate a virtual tooth set-up and try-in (3D files sent to dentists and patients for approval), and monolithic 3D-printed dentures were fabricated with a pink veneering on the flange's facial surface. Significant improvement was shown in all criteria for satisfaction and OHRQoL of maxillary and mandibular 3D-printed denture wearers from baseline, explicated

by the favorable retention, stability, and adaptation of the dentures made using a hybrid nanocomposite and the AM protocol.

The only cross-over trial investigating PROMs between different digital workflows revealed no difference between milled and 3D-printed dentures regarding patient satisfaction and OHRQoL (51).

3.1.2. Clinical performance of CAD/CAM CD and overdenture (30 studies)

A total of 16 clinical trials, five retrospective observational, three prospective observational, four cross-sectional, and two case series have examined the clinical outcomes of the CAD/CAM complete dentures and overdentures, most of which (n=14) evaluated 'closed' workflows (Table 4-1).

In agreement with the PROMs, the digital complete dentures and overdentures achieved adequate and satisfactory performance from the clinicians' perspective (fit and adaptation, denture base contour, extension, retention, stability, maxillomandibular relation, occlusion, phonetics, esthetics, biting force, overall result and minor complications) (33, 36, 37, 41, 47, 48, 52-59). In addition, Chaturvedi *et al*. (60) showed that digital dentures retained adjusted occlusal schemes better than the conventional ones, with greater centralization of forces observed in 3D-printed dentures. Kim *et al*. (39) also evaluated an "open" digital workflow, in which casts/record bases were scanned, teeth were set-up virtually, and denture base and teeth were 3D-printed. They showed that pain and visible ulcerous lesions in both the maxilla and the mandible were significantly fewer with the digital dentures (36.15%) than the conventional ones (46.67%) (P=0.047). Furthermore, one study reported that the students greatly preferred the AvaDent digital milled denture (P=0.035) as an easier technique to implement in their practice than the conventional technique (P=0.007) (36).

Other studies have reported that clinicans' ratings of digital dentures were similar to the conventional ones in terms of operator friendliness or overall satisfaction (38), internal adaptation and masticatory force (43), quality of tooth arrangement, esthetics, lip support, occlusion, phonetics, accuracy of centric relation, appropriate OVD, and prognosis (36), as well as the frequency of relines and remakes (39, 61). Only in Kang *et al*. (43)'s study, the masticatory efficiency was found to be superior with the conventional CDs rather than 3D-printed ones.

Four studies compared the number of post-op visits following delivery of conventional and digital dentures. While Clark *et al*. (61) reported that AvaDent digital dentures required fewer adjustment sessions than conventional dentures, Kim *et al.* (39) and Ohara *et al*. (40) found no substantial differences regarding the number of post insertion adjustment visits between their "open" digital fabrication methods and the conventional methods. Drago *et al*. (62) also detected no significant difference between the AvaDent digital dentures and the conventional ones in terms of the number of post insertion visits ($P>0.05$).

Regarding clinical time and cost, the digital dentures were found to be substantially superior to conventional ones regarding overall cost savings and time spent (36, 38, 42, 46, 50, 61, 63-65). – For instance, according to Kattadiyil *et al*. (36), the average clinical time was 205 minutes more for conventional dentures compared to AvaDent ones ($P=.003$).

No pronounced differences seem to exist between different types of digital workflows regarding the clinical performance (51, 52). Only recently, a cross-over study reported superior adaptation for the maxillary dentures designed by the 3Shape software compared to those designed by the Exocad software (66).

Data on the costs and amount of time saved in digital workflows seem to be in favor of the AvaDent denture system. Arakawa *et al.* (67) showed that while the overall cost and time were similar for their tested workflows, laboratory costs were significantly higher for the Wieland system than the AvaDent digital method (67). Moreover, Srinivasan *et al*. (51) showed that the NextDent 3D-printed dentures required more maintenance visits, adjustment time and costs compared to the AvaDent milled dentures.

3.2. Overdenture retentive component

3.2.1. PROMs of overdentures with CAD/CAM milled retentive components (7 studies)

Four clinical trials, two prospective and one retrospective observational study, have been carried out using patient-centered outcomes of overdentures with CAD/CAM bars (Table 4-2).

Promising patient experiences have been reported with the CAD/CAM maxillary and mandibular milled bar overdentures. A study on maxillary and mandibular 4-implant overdentures supported by a CAD/CAM titanium bar reported a significant improvement in the OHIP scores at the one-year follow-up (68). Similarly, high satisfaction rates for functional, esthetics, and psychological outcomes were observed by Toia *et al*. on CAD/CAM milled bars after a two-year follow-up (69). In another study by Sharaf *et al.* patients treated with CAD/CAM milled polyether-ether-ketone (PEEK) overdentures reported significantly higher satisfaction scores after six and 12 months compared to individuals treated with conventional IMOs retained by metal housings and nylon retentive elements (70).

The non-inferiority of CAD/CAM bar retained implant overdentures with traditional bars has also been suggested by a number of studies. Altonbary and Emera (71) found that patients' preferences for appearance and satisfaction with the time spent for treatment, oral hygiene, and undergoing

this procedure again were significantly greater for the CAD/CAM zirconia milled bar than the cobalt chromium bar (3-mm-wide Hader bar) to retain mandibular two-implant overdentures. Moreover, patient satisfaction with discomfort in surgery, speech, chewing performance, complications, and information prior to treatment was found to be similar between a CAD/CAM zirconia milled bar and a cobalt chromium bar retaining mandibular implant overdentures (71)**.** Srinavasan *et al*. showed that, despite faster improvements in mandibular 2-implant overdentures (IOD) with a CAD-CAM milled bar with long distal extensions, there were no significant differences in OHIP scores and denture satisfaction between CAD/CAM IODs and IODs on retentive anchors following a 1-year follow-up (72)**.** However, according to the authors, given the high patient satisfaction ratings with IODs on retentive anchors at baseline, a potential superiority of the CAD/CAM overdenture design over time might have been masked (72). Cordaro and colleagues (73) also reported similar patient satisfaction across all domains of a VAS questionnaire for CAD/CAM and non-CAD/CAM bar retaining overdentures. Lower satisfaction with cleaning was reported for the bar over the locator attachment. The observed difference could be attributed to the size and prominence of the bar attachement that hampers easy cleaning (73).

Comparing different CAD/CAM bar overdentures, one study reported greater patient satisfaction regarding stability, retention, esthetics, and speech with CAD/CAM milled PEEK housings over metal bars than with Co-Cr housings over metal bars retaining IMOs after one year follow-up (74). Yet, the researchers found no significant between-group differences regarding patient satisfaction compared to natural teeth, as well as ease of cleaning, comfort, chewing, occlusion, quality of bolus, absence of embarrassment, and handling (74). The patient reported outcomes were not measured at baseline; therefore, a comparison with baseline satisfaction was not possible for the tested overdentures.

3.2.2. Clinical performance of overdentures with CAD/CAM milled retentive components (9 studies)

To date, four clinical trials, as well as four prospective and one retrospective observational studies, have assessed the clinical performance of overdentures with CAD/CAM bars (Table 4-2). In line with PROMs, favorable clinician-related findings were observed for the overdentures with CAD/CAM milled bars. Superior assessments without implant loss (72), perfect passive adaptation and fit with a 1-year success rate of 80% (75), minor complications (68, 69, 76), and professional satisfaction with hygienic maintenance, soft tissue conditions, and retention (70, 73) were reported for overdentures with CAD/CAM milled retentive components. One study compared different CAD/CAM housings over metal bars, and reported inferior patient experiences for Co-Cr housings than for milled PEEK housings, and also found poor clinical performance in terms of plaque score, marginal bone resorption, and incidence of wear for Co-Cr metal housings than for milled PEEK housings (74).

3.3. Denture bases

A subgroup of four pilot trials have compared CAD/CAM and conventional methods to fabricate denture bases only – as a baseplate, without future use in a real denture. These studies were included for a broader view of existing evidence (Table 4-3).

3.3.1. PROMs of denture bases (3 studies)

Three clinical trials have assessed the patient-centered outcomes of digitally fabricated denture bases, all of which reported positive patient experiences (77, 78). One study reported signficantly greater patient satisfaction for comfort, retention, masticatory efficiency, and efficiency of technique for the AvaDent denture base than the heat-polymerized acrylic resin denture base (77).

The other clinical study introduced a newly formed zirconia CD base which consists of a ceria-stabilized zirconia/alumina nano-composite CAD/CAM framework (78). The authors suggested improved patient satisfaction with comfort, stability, chewing ability, and general satisfaction for the CAD/CAM composite framework compared to baseline scores. No significant difference in patient satisfaction was reported between the composite base and the conventional one (78). Maniewicz *et al*. (79) also showed that patients rated all the conventional, 3D-printed (NextDent), and milled (AvaDent) bases favorably, regardless of the fabrication technique.

3.3.2. Clinical performance of denture bases (4 studies)

Four clinical trials investigated the retention and surface adaptation of digital denture bases, all of which revealed non-inferior retention and adaptation over their conventional counterparts (77, 80-82). Alhelal *et al*. (77) reported significantly greater retention for the AvaDent denture base than the heat-polymerized denture base. As part of the same study, the authors evaluated the effect of denture adhesive on the retention of digital and conventional dentures; they reported greater retention for AvaDent denture bases with adhesive than conventional ones with or without adhesive (80). However, the researchers did not report the order in which the dentures were inserted. Since the milled and heat-activated control denture bases with and without adhesive were seated for each individual in one clinical session, the order of denture insertions could have significantly impacted the study outcomes due to an effect of adhesive residues.

Three studies compared AM and SM digital workflows in denture base retention and stability. Yoon and colleagues (81) demonstrated clinically acceptable tissue surface adaptation for both digital denture bases. It was found that both digital light processing (DLP) and milled denture bases exhibited intimate adaptation on the lingual slope of the mandible compared with pack and press bases. Maniewicz *et al. (79)* showed that CAD/CAM denture bases (either milled (AvaDent)

or 3D-printed (NextDent) had similar fit and retention to that of the conventionally fabricated ones. In another study, however, milled denture bases showed superior adaptation and retention than the printed denture bases (82). Greater retention of milled denture bases was attributed to the the lack of polymerization shrinkage (82). Randomized clinical trials are needed to verify the proposed discrepancies between different digital workflows.

3.4. RPD framework

3.4.1. PROMs of an RPD framework (One study)

Almufleh *et al*. (83) showed that patient satisfaction with the ability to speak, ability to clean, comfort, masticatory efficiency, and oral condition, as well as general satisfaction were significantly greater with laser-sintered RPD frameworks than the conventional cast RPDs. The researchers also reported that, at the end of the study, the laser-sintered RPD was preferred by every participant who initiated the trial with the digital 3D-printed RPD.

3.4.2. Clinical performance of RPD framework (11 studies)

A total of 11 studies have been conducted on the clinical feasibility and performance of CAD/CAM 3D-printed RPDs (Table 4). In a study by Lee *et al*., the accuracy of a digital RPD made by casting a rapid prototyped pattern was evaluated. It was found that different components of digital RPDs had varying accuracies of fit, with better accuracy observed at the periphery than the center. No failed dentures were reported for up to two years after the participants received the RPDs. Hongqiang *et al*. (84) claimed that, while the gap between the rest and rest seat was signficantly greater in the 3D-printed RPD than the cast framework, the CAD/CAM framwork is acceptable for clinical application. In another study, Tregerman and collleagues (85) found significantly better fit for the 3D-printed RPD than the conventional one. Another study also proposed the feasibility

of manufacturing major connectors by digital impression and the 3D printing technique (86). Moreover, a recent study by Ali *et al*. (87) also suggested that the fabrication of an RPD framework with a selective laser sintering technique may be more time-efficient than the traditional casting workflow. Other studies have reported that the clinician ratings of fit accuracy and rest seat adaptation for 3D-printed RPDs were acceptable (88) and comparable to conventional RPDs (89). The findings of a 1-year follow-up of 3D-printed PEEK RPDs also reported no differences in edentulous residual ridge height between patients wearing the digital RPD and controls without an RPD (90). Only recently, a study by Pelletier *et al*. (91) showed inferior adaptation of the frameworks made with selective laser sintering compared to those fabricated through conventional casting.

The two clinical studies comparing various digital workflows for RPD fabrication claimed that the trueness of the intaglio surface was better for the milled RPD frameworks compared to the 3D-printed ones (92), and milled polyetherketoneketone (PEKK) had superior dislodging force compared to milled PEEK (93).

In summary, almost all of the studies on 3D-printed RPDs point towards a positive clinical outcome, yet they raised the need for additional clinical studies to establish clinical recommendations. The low levels of evidence in existing studies, especially with regards to the PROMs, is a major concern.

3.5. Strenghts and limitations

To our best knowledge, this scoping review is the most comprehensive one on clinically relevant data for digital removable dental prostheses. Thus, we were able to identify patient- and clinician-

reported outcomes for digital workflows adopted in the clinic and to determine the knowledge gaps in this area.

There are a number of limitations in this review that must be noted. Since the aim of this scoping review was a comprehensive maping of the literature, we did not conduct a quality appraisal of the included studies. Moreover, we used a descriptive startegy to synthesize data and compile findings narratively. A different strategy for data synthesis may have yielded further results. In addition, since there is limited data on RPDs' PROMs, the number of adjustments, and post-op visits in digital workflows, no strong conclusions could be reached in this regard. Despite these limitations, a systematic methodology steered our scoping review. In addition, the search was executed by an expert medical librarian, and data extraction was double-checked by two reviewers.

3.6. Recommendations for future research

Although a few studies have been carried out to compare the AM and SM techniques in the fabrication of removable dentures, there is a lack of well-designed RCTs on the subject. Given the identified knowledge gaps, we propose that further rigorous RCTs are needed to investigate whether additive or subtractive digital workflows differ in terms of PROMs, clinical performance, time and cost saving, as well as the number of post-op visits. In addition, to verify the clinical applicability of digitally fabricated RPDs, we recommend that future RCTs be carried out on those made using CAD/CAM technologies. With regards to patient experiences with digital dentures, there is a need for qualitative research on PROMs to further explain the quantitative findings of the sastisfaction and OHRQoL questionnaires.

4. CONCLUSION

The current literature is in support of CAD/CAM fabricated removable dental prosthesis due to substantial time and cost savings, as well as patient and clinician experiences of non-inferiority or superiority with the conventionally fabricated prostheses. A consensus on which workflow offers fewer post-operative treatment sessions is yet to be determined. No pronounced difference has been reported by the literature between the existing digital workflows in terms of patient and clinican-related outcomes. Further randomized clinical trials are recommended to substantiate these proposed findings.

CONFLICT OF INTEREST: The authors declare no conflict of interest.

FIGURE LEGENDS

Figure 4-1. The study selection flow diagram according to the PRISMA-ScR.

Figure 4-2. Typical conventional denture fabrication sequence and "open" CAD/CAM based alternatives used by included studies.

Figure 4-3. PROMs studied in each type of prosthesis.

5. REFERENCES

1. Cardoso M, Balducci I, Telles Dde M, Lourenco EJ, Nogueira Junior L. Edentulism in Brazil: trends, projections and expectations until 2040. Ciencia & saude coletiva. 2016;21(4):1239-46.

2. Felton DA. Complete edentulism and comorbid diseases: an update. Journal of Prosthodontics. 2016;25(1):5-20.

3. Müller F, Naharro M, Carlsson GE. What are the prevalence and incidence of tooth loss in the adult and elderly population in Europe? Clinical oral implants research. 2007;18:2-14.

4. Zitzmann NU, Hagmann E, Weiger R. What is the prevalence of various types of prosthetic dental restorations in Europe? Clinical oral implants research. 2007;18:20-33.

5. Carlsson G, Omar R. The future of complete dentures in oral rehabilitation. A critical review. J Oral Rehabil. 2010;37(2):143-56.

6. Jacob RF. The traditional therapeutic paradigm: complete denture therapy. The Journal of prosthetic dentistry. 1998;79(1):6-13.

7. Dankwort CW, Weidlich R, Guenther B, Blaurock JE. Engineers' CAx education—it's not only CAD. Comput Aided Des. 2004;36(14):1439-50.

8. Miyazaki T, Hotta Y, Kunii J, Kuriyama S, Tamaki Y. A review of dental CAD/CAM: current status and future perspectives from 20 years of experience. Dental materials journal. 2009;28(1):44-56.

9. Busch M, Kordass B. Concept and development of a computerized positioning of prosthetic teeth for complete dentures. International journal of computerized dentistry. 2006;9(2):113-20.

10. Almufleh B, Emami E, Alageel O, de Melo F, Seng F, Caron E, et al. Patient satisfaction with laser-sintered removable partial dentures: a crossover pilot clinical trial. The Journal of prosthetic dentistry. 2018;119(4):560-7.e1.

11. Arafa KA. Assessment of the fit of removable partial denture fabricated by computer-aided designing/computer aided manufacturing technology. Saudi medical journal. 2018;39(1):17-22.

12. Maeda Y, Minoura M, Tsutsumi S, Okada M, Nokubi T. A CAD/CAM system for removable denture. Part I: Fabrication of complete dentures. international Journal of Prosthodontics. 1994;7(1):17-21.

13. Sun Y, Lü P, Wang Y. Study on CAD&RP for removable complete denture. Computer methods and programs in biomedicine. 2009;93(3):266-72.

14. Schweigera J, Stumbaumb J, Edelhoffc D, Güthd J. Systematics and concepts for the digital production of complete dentures: risks and opportunities Systematik und Konzepte zur digitalen Herstellung von Totalprothesen–Chancen und Risiken. International journal of computerized dentistry. 2018;21(1):41-56.

15. Bidra AS, Taylor TD, Agar JR. Computer-aided technology for fabricating complete dentures: systematic review of historical background, current status, and future perspectives. The Journal of prosthetic dentistry. 2013;109(6):361-6.

16. Dawood A, Marti BM, Sauret-Jackson V, Darwood A. 3D printing in dentistry. British dental journal. 2015;219(11):521-9.

17. Azari A, Nikzad S. The evolution of rapid prototyping in dentistry: a review. Rapid Prototyping Journal. 2009;15(3):216-225.

18. Ye H, Li X, Wang G, Kang J, Liu Y, Sun Y, et al. A Novel Computer-Aided Design/Computer-Assisted Manufacture Method for One-Piece Removable Partial Denture and Evaluation of Fit. International Journal of Prosthodontics. 2018;31(2):149-151.

19. Steinmassl O, Dumfahrt H, Grunert I, Steinmassl P-A. CAD/CAM produces dentures with improved fit. Clinical oral investigations. 2018;22(8):2829-35.

20. Goodacre BJ, Goodacre CJ, Baba NZ, Kattadiyil MT. Comparison of denture base adaptation between CAD-CAM and conventional fabrication techniques. The Journal of prosthetic dentistry. 2016;116(2):249-56.

21. Masri G, Mortada R, Ounsi H, Alharbi N, Boulos P, Salameh Z. Adaptation of complete denture base fabricated by conventional, milling, and 3-d printing techniques: an in vitro study. J Contemp Dent Pract. 2020;21(4):367-71.

22. Srinivasan M, Cantin Y, Mehl A, Gjengedal H, Müller F, Schimmel M. CAD/CAM milled removable complete dentures: an in vitro evaluation of trueness. Clinical oral investigations. 2017;21(6):2007-19.

23. Al-Dwairi ZN, Tahboub KY, Baba NZ, Goodacre CJ, Özcan M. A comparison of the surface properties of CAD/CAM and conventional polymethylmethacrylate (PMMA). J Prosthodont. 2019;28(4):452-7.

24. Srinivasan M, Gjengedal H, Cattani-Lorente M, Moussa M, Durual S, Schimmel M, et al. CAD/CAM milled complete removable dental prostheses: An in vitro evaluation of biocompatibility, mechanical properties, and surface roughness. Dent Mater J. 2018:2017-207.

25. Apelian N, Vergnes J-N, Bedos C. Humanizing clinical dentistry through a person-centred model. International Journal of Whole Person Care. 2014;1(2).

26. de Souza RF, Ahmadi M, Ribeiro AB, Emami E. Focusing on outcomes and methods in removable prosthodontics trials: a systematic review. Clinical oral implants research. 2014;25(10):1137-41.

27. Kodama N, Singh B, Cerutti-Kopplin D, Feine J, Emami E. Efficacy of mandibular 2-implant overdenture: an updated meta-analysis on patient-based outcomes. JDR Clinical & Translational Research. 2016;1(1):20-30.

28. Michaud P-L, de Grandmont P, Feine JS, Emami E. Measuring patient-based outcomes: is treatment satisfaction associated with oral health-related quality of life? Journal of dentistry. 2012;40(8):624-31.

29. Almufleh B, Emami E, Alesawy A, Rodan R, Morris M, Umebayashi M, et al. Patient-Reported Outcomes of Metal and Acrylic Resin Removable Partial Dentures: A Systematic Review and Meta-Analysis. Journal of Prosthodontics. 2020;29(5):378-86.

30. Peters M, Godfrey C, McInerney P, Soares C, Khalil H, Parker D. The Joanna Briggs Institute reviewers' manual 2015: methodology for JBI scoping reviews. 2015.

31. Arksey H, O'Malley L. Scoping studies: towards a methodological framework. International journal of social research methodology. 2005;8(1):19-32.

32. Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation. Annals of internal medicine. 2018;169(7):467-73.

33. Bidra AS, Farrell K, Burnham D, Dhingra A, Taylor TD, Kuo C-L. Prospective cohort pilot study of 2-visit CAD/CAM monolithic complete dentures and implant-retained overdentures: Clinical and patient-centered outcomes. J Prosthet Dent. 2016;115(5):578-86.e1.

34. Saponaro PC, Yilmaz B, Johnston W, Heshmati RH, McGlumphy EA. Evaluation of patient experience and satisfaction with CAD-CAM-fabricated complete dentures: A retrospective survey study. J Prosthet Dent. 2016;116(4):524-8.

35. John AV, Abraham G, Alias A. Two-visit CAD/CAM milled dentures in the rehabilitation of edentulous arches: A case series. J Indian Prosthodont Soc. 2019;19(1):88-92.

36. Kattadiyil MT, Jekki R, Goodacre CJ, Baba NZ. Comparison of treatment outcomes in digital and conventional complete removable dental prosthesis fabrications in a predoctoral setting. J Prosthet Dent. 2015;114(6):818-25.

37. Zupancic Cepic L, Gruber R, Eder J, Vaskovich T, Schmid-Schwap M, Kundi M. Digital versus Conventional Dentures: A Prospective, Randomized Cross-Over Study on Clinical Efficiency and Patient Satisfaction. Journal of Clinical Medicine. 2023;12(2):434.

38. Inokoshi M, Kanazawa M, Minakuchi S. Evaluation of a complete denture trial method applying rapid prototyping. Dent Mater J. 2012;31(1):40-6.

39. Kim TH, JungHuh B, Lee J, Bae EB, Park CJ. Retrospective Comparison of Postinsertion Maintenances Between Conventional and 3D Printed Complete Dentures Fabricated In A Predoctoral Clinic. J Prosthodont. 2021; 30(S2):158-162.

40. Ohara K, Isshiki Y, Hoshi N, Ohno A, Kawanishi N, Nagashima S, et al. Patient satisfaction with conventional dentures vs. digital dentures fabricated using 3D-printing: A randomized crossover trial. J Prosthodont Res. 2022;;66(4):623-629.

41. Deng K, Wang Y, Zhou Y, Sun Y. Comparison of treatment outcomes and time efficiency between a digital complete denture and conventional complete denture: A pilot study. Journal of the American Dental Association. 2023;154(1):32-42.

42. Liu YX, Yu SJ, Huang XY, Lin FF, Zhu GX. Primary Exploration of the Clinical Application of 3D-Printed Complete Dentures. International Journal of Prosthodontics. 2022;35(6):809-14.

43. Kang YJ, Oh KC, Kim GY, Moon HS. Comparative evaluation of digitally fabricated complete dentures versus conventional complete dentures: A randomized, single-blinded, cross-over clinical trial. Journal of Prosthetic Dentistry. 2022; S0022-3913(22)00339-0.

44. Cristache CM, Totu EE, Iorgulescu G, Pantazi A, Dorobantu D, Nechifor AC, et al. Eighteen Months Follow-Up with Patient-Centered Outcomes Assessment of Complete Dentures Manufactured Using a Hybrid Nanocomposite and Additive CAD/CAM Protocol. J Clin Med. 2020;9(2):324.

45. Brignardello-Petersen R. Most patients prefer computer-aided design/computer-aided manufacturing-fabricated complete dentures to their old dentures. J Am Dent Assoc. 2017;148(4):e28.

46. Otake R, Kanazawa M, Iwaki M, Soeda Y, Hada T, Katheng A, et al. Patient-reported outcome and cost-effectiveness analysis of milled and conventionally fabricated complete dentures in a university clinic: A retrospective study. J Prosthet Dent. 2024;131(2):227-232..

47. Deng K, Chen H, Wang Y, Zhou Y, Sun Y. Evaluation of functional suitable digital complete denture system based on 3D printing technology. J Adv Prosthodont.13(6):361-72.

48. Elawady DM, Ibrahim WI, Osman RB. Clinical evaluation of implant overdentures fabricated using 3D-printing technology versus conventional fabrication techniques: a randomized clinical trial. Int J Comput Dent.24(4):375-84.

49. Gomaa AM, Mostafa AZH, El-Shaheed NH. Patient Satisfaction and Oral Health-Related Quality of Life for Four Implant-Assisted Mandibular Overdentures Fabricated with CAD/CAM Milled Poly Methyl Methacrylate, CAD/CAM Milled Poly Ether Ether Keton, or Conventional Poly Methyl Methacrylate. A Cross-Over Clinical Trial. Journal of oral rehabilitation. 2023; 50(7):566-579.

50. Peroz S, Peroz I, Beuer F, Sterzenbach G, von Stein-Lausnitz M. Digital versus conventional complete dentures: A randomized, controlled, blinded study. J Prosthet Dent. 2022;128(5):956-963.

51. Srinivasan M, Kalberer N, Fankhauser N, Naharro M, Maniewicz S, Muller F. CAD-CAM complete removable dental prostheses: A double-blind, randomized, crossover clinical trial evaluating milled and 3D-printed dentures. J Dent. 2021:115:103842.

52. Schwindling FS, Stober T. A comparison of two digital techniques for the fabrication of complete removable dental prostheses: A pilot clinical study. J Prosthet Dent. 2016;116(5):756-63.

53. Cristache CM, Totu EE, Grosu AR, Ene O, Beuran IA, Burlibasa M. Nanocomposite for rapid prototyped complete denture eighteen months follow-up on clinical performance. Rev Chim. 2019;70(2):387-92.

54. Schlenz MA, Schmidt A, Wostmann B, Rehmann P. Clinical performance of computer-engineered complete dentures: a retrospective pilot study. Quintessence Int. 2019;50(9):706-11.

55. Saponaro PC, Yilmaz B, Heshmati RH, McGlumphy EA. Clinical performance of CAD-CAM-fabricated complete dentures: A cross-sectional study. J Prosthet Dent. 2016;116(3):431-5.

56. Hassan B, Greven M, Wismeijer D. Integrating 3D facial scanning in a digital workflow to CAD/CAM design and fabricate complete dentures for immediate total mouth rehabilitation. J Adv Prosthodont. 2017;9(5):381-6.

57. Emera RMK, Shady M, Alnajih MA. Comparison of retention and denture base adaptation between conventional and 3D-printed complete dentures. J. 2022;16(3):179-85.

58. El-Shaheed NH, Lamfon HA, Salama RI, Faramawy AMG, Mostafa AZH. Tissue Surface Adaptation and Clinical Performance of CAD-CAM Milled versus Conventional Implant-Assisted Mandibular Overdenture. International Journal of Dentistry. 2022;2022:8220233.

59. Nasr Mostafa TM, Elgarba BM, Alam-Eldein AM. Evaluation of Retention and Attachment Wear of CAD/CAM Versus Conventional Implant-Assisted Overdenture Frameworks. Int J Periodontics Restorative Dent. 2023;43(1):e43-e51.

60. Chaturvedi S, Addas MK, Alqahtani NM, Al Ahmari NM, Alfarsi MA. Clinical analysis of CAD-CAM milled and printed complete dentures using computerized occlusal force analyser. Technol Health Care. 2021;29(4):797-811.

61. Clark WA, Brazile B, Matthews D, Solares J, De Kok IJ. A Comparison of Conventionally Versus Digitally Fabricated Denture Outcomes in a University Dental Clinic. J Prosthodont. 2021;30(1):47-50.

62. Drago C, Borgert AJ. Comparison of nonscheduled, postinsertion adjustment visits for complete dentures fabricated with conventional and CAD-CAM protocols: A clinical study. J Prosthet Dent. 2019;122(5):459-66.

63. Srinivasan M, Schimmel M, Naharro M, O' Neill C, McKenna G, Müller F. CAD/CAM milled removable complete dentures: time and cost estimation study. J Dent. 2019;80:75-9.

64. Smith PB, Perry J, Elza W. Economic and Clinical Impact of Digitally Produced Dentures. J Prosthodont. 2021;30(S2):108-112.

65. Lo Russo L, Zhurakivska K, Guida L, Chochlidakis K, Troiano G, Ercoli C. Comparative cost-analysis for removable complete dentures fabricated with conventional, partial, and complete digital workflows. Journal of Prosthetic Dentistry. 2024;131(4):689-696.

66. Abd El Galil EG, Mohamed SL, Rizk FN, Sabet ME. Evaluation of two computer-aided design software on the adaptation of digitally constructed maxillary complete denture. J Indian Prosthodont Soc.21(4):383-90.

67. Arakawa I, Al-Haj Husain N, Srinivasan M, Maniewicz S, Abou-Ayash S, Schimmel M. Clinical outcomes and costs of conventional and digital complete dentures in a university clinic: A retrospective study. J Prosthet Dent. 2022;128(3):390-395.

68. Pozzi A, Tallarico M, Moy PK. Four-implant overdenture fully supported by a CAD-CAM titanium bar: A single-cohort prospective 1-year preliminary study. J Prosthet Dent. 2016;116(4):516-23.

69. Toia M, Wennerberg A, Torrisi P, Farina V, Corra E, Cecchinato D. Patient satisfaction and clinical outcomes in implant-supported overdentures retained by milled bars: Two-year follow-up. J Oral Rehabil. 2019;46(7):624-33.

70. Sharaf MY, Eskander A, Afify M. Novel PEEK Retentive Elements versus Conventional Retentive Elements in Mandibular Overdentures: A Randomized Controlled Trial. International Journal of Dentistry. 2022;2022:6947756.

71. Altonbary GY, Emera RMK. Patient satisfaction and masticatory performance of zirconia bar compared to cobalt chromium bar retaining mandibular implant overdenture: Across-over study. J Oral Rehabil. 2021; 48(7):827-835.72. Srinivasan M, Schimmel M, Buser R, Maniewicz S, Herrmann FR, Muller F. Mandibular two-implant overdentures with CAD-CAM milled bars with distal extensions or retentive anchors: A randomized controlled trial. Clin Oral Implants Res. 2020;31(12):1207-22.

73. Cordaro L, di Torresanto VM, Petricevic N, Jornet PR, Torsello F. Single unit attachments improve peri-implant soft tissue conditions in mandibular overdentures supported by four implants. Clin Oral Implants Res. 2013;24(5):536-42.

74. Abdraboh AE, Elsyad MA, Mourad SI, Alameldeen HE. Milled Bar with PEEK and Metal Housings for Inclined Implants Supporting Mandibular Overdentures: 1-Year Clinical, Prosthetic, and Patient-Based Outcomes. Int J Oral Maxillofac Implants. 2020;35(5):982-9.

75. Mangano F, Mangano C, Margiani B, Admakin O. Combining Intraoral and Face Scans for the Design and Fabrication of Computer-Assisted Design/Computer-Assisted Manufacturing (CAD/CAM) Polyether-Ether-Ketone (PEEK) Implant-Supported Bars for Maxillary Overdentures. Scanning. 2019;2019:4274715.

76. Zuercher AN, Molinero-Mourelle P, Schimmel M, Katsoulis J. Zirconia bars for mandibular implant overdentures: A 1-year clinical and radiographic pilot study. Int J Oral Implantol (New Malden). 2022;15(3):253-63.

77. AlHelal A, AlRumaih HS, Kattadiyil MT, Baba NZ, Goodacre CJ. Comparison of retention between maxillary milled and conventional denture bases: A clinical study. J Prosthet Dent. 2017;117(2):233-8.

78. Nishiyama H, Tanaka S, Nemoto R, Miura H, Baba K. Zirconia-Reinforced Framework for Maxillary Complete Dentures. Int J Prosthodont. 2018;31(2):114-6.

79. Maniewicz S, Imamura Y, El Osta N, Srinivasan M, Muller F, Chebib N. Fit and retention of complete denture bases: Part I - Conventional versus CAD-CAM methods: A clinical controlled crossover study. Journal of Prosthetic Dentistry. 2024;131(4):611-617.

80. AlRumaih HS, AlHelal A, Baba NZ, Goodacre CJ, Al-Qahtani A, Kattadiyil MT. Effects of denture adhesive on the retention of milled and heat-activated maxillary denture bases: A clinical study. J Prosthet Dent. 2018;120(3):361-6.

81. Yoon S-N, Oh KC, Lee SJ, Han J-S, Yoon H-I. Tissue surface adaptation of CAD-CAM maxillary and mandibular complete denture bases manufactured by digital light processing: A clinical study. J Prosthet Dent. 2020;124(6):682-9.

82. Faty MA, Sabet ME, Thabet YG. A comparison of denture base retention and adaptation between CAD-CAM and conventional fabrication techniques. Int J Prosthodont. 2023;36(4):469-478.

83. Almufleh B, Emami E, Alageel O, de Melo F, Seng F, Caron E, et al. Patient satisfaction with laser-sintered removable partial dentures: A crossover pilot clinical trial. J Prosthet Dent. 2018;119(4):560-7.e1.

84. Hongqiang Y, Jing N, Man L, Li N, Jian Y, Yuchun S, et al. Preliminary Clinical Application of Removable Partial Denture Frameworks Fabricated Using Computer-Aided Design and Rapid Prototyping Techniques. Int J Prosthodont. 2017;30(4):348-53.

85. Tregerman I, Renne W, Kelly A, Wilson D. Evaluation of removable partial denture frameworks fabricated using 3 different techniques. J Prosthet Dent. 2019;122(4):390-5.

86. Gan N, Ruan Y, Sun J, Xiong Y, Jiao T. Comparison of adaptation between the major connectors fabricated from intraoral digital impressions and extraoral digital impressions. Sci Rep. 2018;8(1):1-9.

87. Ali Z, Wood D, Elmougy A, Kelleher P, Martin N. Laboratory evaluation of production efficiency for removable partial denture frameworks using in-house casting versus outsourced additive manufacturing techniques. Int J Prosthodont. 2023;36(3):338-342.

88. Chia VAP, See Toh YL, Quek HC, Pokharkar Y, Yap AU, Yu N. Comparative clinical evaluation of removable partial denture frameworks fabricated traditionally or with selective laser melting: A randomized controlled trial. J Prosthet Dent. 2024;131(1):42-49. .

89. Conceicao PR, Franco M, Alves N, Portugal J, Neves CB. Fit accuracy of removable partial denture metal frameworks produced by CAD-CAM - a clinical study. Rev Port Estomatol Med Dent Cir Maxilofac. 2021;62:194-200.

90. Lo Russo L, Chochlidakis K, Caradonna G, Molinelli F, Guida L, Ercoli C. Removable Partial Dentures with Polyetheretherketone Framework: The Influence on Residual Ridge Stability. J Prosthodont.2022:31(4):333-40.

91. Pelletier S, Pelletier A, Al Dika G. Adaptation of removable partial denture rest seats in prostheses made with selective laser sintering or casting techniques: A randomized clinical trial. Journal of Prosthetic Dentistry. 2022; S0022-3913(22)00327-4.

92. Lo Russo L, Guida L, Zhurakivska K, Troiano G, Chochlidakis K, Ercoli C. Intaglio surface trueness of milled and 3D-printed digital maxillary and mandibular dentures: A clinical study. J Prosthet Dent. 2023;129(1):131-139.

93. Refai OM, Nawar NH, Lebshtien IT. Assessment of Retention of CAD-CAM Milled PEKK vs PEEK Double Crown-retained Removable Partial Dentures: A Randomized Clinical Trial. J Contemp Dental Pract. 2021;22(11):1250-6.

94. Chebib N, Imamura Y, El Osta N, Srinivasan M, Muller F, Maniewicz S. Fit and retention of complete denture bases: Part II - conventional impressions versus digital scans: A clinical controlled crossover study. Journal of Prosthetic Dentistry. 2024;131(4):618-625.

95. Lee J-W, Park J-M, Park E-J, Heo S-J, Koak J-Y, Kim S-K. Accuracy of a digital removable partial denture fabricated by casting a rapid prototyped pattern: A clinical study. J Prosthet Dent. 2017;118(4):468-74.

Table 4-1- Included studies on CD and overdenture.

Study design	Study (year)	Study objectives	Study sample	Type of Intervention (Study groups)	Type of outcome assessed	Data collection tools	Data collection timeline	Key findings
Prospective observational clinical study	Kattadiyil et al. (2015) (36)	"to compare clinical treatment outcomes, patient satisfaction, and dental student preferences for digitally and conventionally processed CRDP in a predoctoral setting"	15 completely edentulous patients	All Patients received: G1: Maxillary and mandibular conventional complete denture (n=15) G2: Milled maxillary and mandibular digital (AvaDent*) complete denture (n=15)	a. Faculty satisfaction (denture base contour, teeth arrangement, fit, retention, extension, stability, esthetics, lip support, and prognosis, centric relationship, occlusion, occlusal vertical dimension (OVD), phonetics, and overall result) b. Patient rating and preference c. Predoctoral dental student satisfaction	a. A 5-point Likert rating scale from 0 to 4 b. A 5-point Likert rating scale from 0 to 4 c. Student questionnaire	After fabrication and immediately after placement	-Faculty satisfaction regarding the denture base contour, fit, extension, stability, retention, and overall result: G2>G1 (P<0.05). -Faculty satisfaction regarding quality of tooth arrangement, esthetics, lip support, occlusion, phonetics, accuracy of centric relation, appropriate OVD, and prognosis: G1=G2 (P>0.05). - Patient satisfaction regarding comfort, chewing efficiency, prosthesis selected, and efficiency of technique, and overall patient satisfaction: G2>G1 (P<0.05) -Patient preference regarding appearance (esthetics): G1=G2 (P=0.763). -Student preference (as being easier to perform & the technique they would use in their practice: G2>G1 (P=.007, P-0.035, respectively) -The average clinical time was 205 minutes longer for G1 than for G2 (P=.003).
	Bidra et al. (2016) (33)	"to evaluate the clinical and patient-centered outcomes for CAD/CAM monolithic dentures fabricated in 2 visits "	20 participants with an existing set of maxillary complete dentures opposing either mandibular complete dentures or implant-retained overdentures that required replacement	Monolithic milled dentures with CAD/CAM technology (Global Dental Science) replacing: G1: Implant-retained mandibular overdentures (n=9) G2: Conventional mandibular complete dentures (n=5)	a. Patient-reported outcomes (Tightness,Absence of rocking,Bulkiness, cosmetics, lip projection,ability to chew and speak, denture finish, absence of food and sore spots, overall satisfaction, treatment tim) b. Clinical performance	a. 100-mm VAS instrument (12 items) b. Clinical outcomes were evaluated independently by 2 experienced prosthodontists	At baseline and at 1-year follow-up.	-Of 20 participants, 3 were lost to follow-up, and 3 were unsatisfied with the digital dentures, withdrew from the study, and were considered treatment failures. -Patient-reported outcome: each of the 12 studied outcomes was favorable at the 1-year recall for both G1 and G2. -Absence of denture sore spots and treatment time to make the dentures: significant improvements in patient ratings from baseline to 1 year for both G1 and G2 (P<0.05) -Minor complications related to loss of retention, excessive wear of teeth and the need for additional visits were observed in 5 participants. - No other adverse clinical outcomes related to the CAD/CAM dentures were observed in both G1 and G2.
	Srinivasan et al. (2019) (63)	"to compare the clinical time spent and the costs incurred whilst constructing complete dentures (CDs) using a two-visit digital-denture protocol with the conventional complete denture protocol, in a university setting"	-	G1: Maxillary conventional CD (n=18) G2: Maxillary digital (AvaDent*) CD (n=18) G3: Mandibular conventional CD (n=12) G4: Mandibular digital (Avadent*) CD (n=12)	Overall time spent and costs (clinical, materials, and laboratory)	Estimated hourly labor cost formula	After sixth and final clinical visit	-Conventional complete denture protocol required longer clinical time than digital complete dentures -The materials costs were higher for the digital complete dentures -The overall costs, were significantly higher for the conventional complete denture protocol than for the digital denture
Retrospective observational clinical study	Otake et al. (2022) (46)	"to evaluate general patient satisfaction with complete dentures fabricated through the custom disk method"	44 edentulous patients (mean age=75.6±8.4)	G1: Milled Custom disk (digital) dentures (n=20) G2: Conventional dentures (n=24) (Digital workflow: Scanned and designed by the 3shape software‡ trial denture printed with Form3**, definitive denture milled with custom disk method)	a. General patient satisfaction b. Cost-effectiveness	a. VAS b. Incremental cost-effectiveness ratio	Patient satisfaction was evaluated before and after denture fabrication	-General patient satisfaction: G1>G2 (P=.002) -The median labor costs: G2>G1 (P<0.001) -The incremental cost-effectiveness ratio was −251.4.
	Schlenz et al. (2019) (54)	"to analyze the clinical performance of computer-engineered complete dentures (CECDs) in edentulous patients regarding survival and maintenance"	10 edentulous patients	Maxillary and mandibular Digital Denture (Ivoclar Vivadent), 4-visit protocol $^{\delta}$ (n=10)	a. Number of appointments required for treatment b. Number of interventions during the initial (<= 4 weeks after insertion) and functional periods (> 4 weeks after insertion) c. Survival	Data obtained from Department of Prosthodontics, Justus Liebig University, Giessen, Germany, between September 2015 and October 2016.		-All CECDs survived the observation period of 2.54 ± 0.48 years. - More than 4 appointments were required for treatment (mean ± standard deviation, 4.6 ± 0.7), mainly for esthetic concerns. - An average of 1.7 ± 0.05 appointments during the initial period and 2.07 ± 0.32 during the functional period were noted as a consequence of functional concerns. -During both periods, the major reason for intervention was removal of pressure spots. -Relining was required in 40% of the CECDs - Fracture of the denture base occurred in two CECDs.
	Smith et al. (2020) (64)	"to evaluate the cost savings, if any, of fabricating complete dentures digitally versus traditionally through an outside lab"	30 random denture patients in the university clinic	Milled complete denture, Ivoclar 4-visit protocol $^{\delta}$ (n=30)	Cost savings in terms of material cost and chair time cost	The electronic health		-Using 3D printing for the preliminary steps resulted in substantial cost savings. -A significant cost savings was achieved, both in terms of material cost and in chair time cost, -Fewer visits to complete the denture

								fabrication steps - Fewer post-insertion visits
	Arakawa et al. (2021) (67)	"to compare the treatment duration, financial costs, and postdelivery adjustments of CAD-CAM and conventional removable complete dentures"	32 edentulous participants	G1: CAD-CAM milled maxillary and mandibular CDs: DDS-AV (AvaDent *) (n=11) or DD-IV (Wieland ᵠ) (n=5) G2: Conventional maxillary and mandibular removable complete dentures (n=16)	a. Total treatment period (days) b. Adjustments including removal of areas of excessive pressure, relining, or repairs. c. Costs of the dental treatment and the laboratory fees	-	The total treatment period was recorded at 3 different time points (T0: preliminary alginate impression; T1: denture delivery; T2: last scheduled post-delivery adjustment).	-The treatment duration: G1=G2 (T0-T1 (P=.889); T1-T2 (P=.675); T2-T3 (P=.978)) - The number adjustments for areas of excessive pressure, relines, or repairs: G1=G2 (P=.757, P=1.000, P=1.000, respectively) - Laboratory costs: G1<G2 (P<0.001) - Clinical fees G1=G2 (P=0.596) - The number of clinical visits: G1=G2, DDS-AV=DD-IV (P=.945, P=0.848, respectively)
	Kim et al. (2021) (39)	"to analyze the clinical performance of 3D printed complete dentures in edentulous patients compared with conventional complete dentures regarding post insertion visits and patient reported outcomes"	edentulous patients treated with complete dentures between the years of 2015 to 2018.	G1:420 (maxilla 270, mandible 150) heat-polymerized conventional complete dentures G2:217 (maxilla 130, mandible 86) 3D printed (Dentca§) complete dentures (PCD) using Zenith SLA 3D printer ᐞ	a. Number of remake b. Number of post insertion adjustments c. type and number of repairs d. Patient reported complications	Data were extracted via the electronic patient charts		-The number of post insertion adjustments and frequency of reline: G1=G2 (P>0.05) -In both groups, the two post-insertion internal adjustments of the denture base was the most common. -Pain and visible ulcer lesion in both maxilla and mandible: G1>G2 (P<0.05) -Discomfort in mandible: G1>G2 (P=0.026) -Esthetic in mandible: G1>G2 (P=0.047)
	Lo Russo et al. (2022) (65)	"to compare the clinical and laboratory costs of removable complete dentures fabricated with a conventional (workflow C), a partial digital (workflow M), and a complete digital (workflow D) workflow"	Clinical and laboratory costs from 10 private Italian dental laboratories and clinics (number of employees: 2 to 6)	G1: Conventional workflow (C) G2: Partial Digital workflow (M) G3: Complete Digital workflow (D)	Clinical and laboratory manufacturing time needed to complete each workflow (opportunity cost); costs for materials, labor, packaging, and shipping; and capital and fixed costs for software and hardware, including maintenance fees	A standardized data collection form	-	- From a clinical standpoint, G1 and G2 were almost identical. -G3, which included intraoral scanning, required 1 fewer appointment, saved 0.6 hours of chairside time and 14 USD for materials compared to G2.
	Clarke et al. (2021) (61)	"to evaluate if there is a difference in number of visits (including fabrication and postoperative) and remake rate when comparing conventionally fabricated and digitally fabricated complete dentures by dental students in a predoctoral student dental clinic"	314 patients receiving maxillary and/or mandibular complete dentures between 2017 and 2019 at the UNC Adams School of Dentistry predoctoral student clinic.	G1: conventional dentures (n=242) G2: digital dentures (AvaDent *) (n=39)	The number of patient appointments from preliminary impressions to denture placement, the number of postoperative visits, any complications noted, and any need for remakes	Data were extracted via the electronic health record		-6 or more visits from preliminary impression to placement: 50% of G1 , 5% of G2 ($p < 0.05$). -Postoperative visits: G1 had an average of 2-3, whereas G2 required 1-2 ($p < 0.05$). -The number of dentures requiring remake: G1=G2 ($p = 0.1904$).
Cross-sectional observational study	Saponaro et al. (2016) (55)	"to evaluate clinician experience with digital CD fabrication attempted in a 2-visit protocol"	48 edentulous individuals	90 digitally fabricated CD (AvaDent*) prostheses were inserted: G1: maxillary complete dentures (n=47) G2: mandibular complete dentures (n=34) G3: implant-supported mandibular overdentures (n=9)	a. The number of appointments needed to insert digital CDs adjustments b. The number of post-insertion c. Complications	Participant's clinical charts	-	-The mean number of appointments needed to insert CAD-CAM-fabricated CD prostheses: 2.39 -The number of post-insertion appointments was 2.08 -Two thirds of all participants had no complications; the remaining one-third presented with 1 or more complications
	Saponaro et al. (2016) (34)	"to assess patient preferences and satisfaction when treated with digitally fabricated CDs, by using a questionnaire"	50 edentulous patients	94 digitally fabricated CD (AvaDent *) prostheses were inserted: G1: maxillary complete dentures (n=49) G2: mandibular complete dentures (n=35) G3: implant-supported mandibular overdentures (n=10)	Patient satisfaction (comparison with previous dentures, ability to chew, speak, and clean, esthetics, fitness and stability, meeting expectations, comfort, overall satisfaction, recommendation to others)	A 10-item questionnaire		-78.95% were pleased with the esthetics; 78.57% agreed that their new digital CDs were "better" than their previous set of CDs -73.68% agreed they were satisfied with their new CDs; - 68.75% agreed that their new CDs were easy to clean; - 68.42% agreed that they considered their CDs comfortable" and that they would recommend digital CDs to others; -57.89% agreed that their speech and chewing abilities had improved with the use of digital CDs; and 52.63% agreed that their CDs fit well and stayed in place during function
	Brignardello-Petersen (2017) (45)	"to obtain information about patient experiences and satisfaction after receiving CAD/CAM-fabricated CDs"	19 patients who had received their CDs an average of 20 months before	CAD/CAM-fabricated (AvaDent˚) complete dentures (n=19)	Patient experiences and satisfaction	Survey	Average of 20 months after receiving CD	-Most patients (78.6%) who had already worn CDs reported that the new CAD/CAM CDs were better than their old ones. -Most patients were pleased with the esthetics of their new CDs (79.0%) and told that these CDs were easy to clean (68.8%) and comfortable (68.4%), improved their speech and chewing abilities (57.9%), and fit well (52.6%).
	Chaturved et al. (2021) (60)	"To compare the occlusal force parameters in complete dentures (CDs) fabricated by milling, 3-D printing and conventional techniques	5 completely edentulous patients	A total of 45 CDs for 5 patients: G1: Conventional CDs (CCD) (n=9) G2: 3Shape Milled CDs (MCD) (n=9)‡	Occlusal force analysis	Computerized occlusal analysis system (T-Scan III)	At the time of denture insertion	- CCD with MO had the maximum force difference on right and left side (37.48 ±1.03 N) - 3-DPCD with LO had the maximum occlusal-bite force % (95.40 ±1.30 N). - The chances of centre of force out of ellipse (centralization of forces) was 3.36 and 2.15

		having 3 commonly used occlusal schemes"		G3: Formlabs** 3D printed CDs (3-DP CD) (n=9) The CDs were further divided into 3 subgroups according to the occlusion scheme: - bilateral balanced (BBO) -Lingualized (LO) -Mono plane (MP)				times more in CCD and MCD compared to 3-DP CD,
Randomized crossover clinical trial	Cepic et al. (2023) (37)	"To compare clinical and patient-related outcomes of digital dentures prepared with the Vita Vionic System and conventional dentures produced from heat-polymerized polymethylmethacrylate resin."	10 edentulous patients	G1: Digital milled dentures followed by Conventional (n=5) G2: Conventional dentures followed by digital (n=5) (Digital workflow: Vita Vionic Solutions; Vita Zahnfabrik, Bad Säckingen, Germany))	a. Clinical parameters describing the quality of dentures: stability under pressure, retention, border extension, finish quality (polish), aesthetics, phonetics, static and dynamic occlusion, and vertical dimension	a. A 3-grade scale (poor = 0, fair = 1, good = 2)	Two-week follow up after denture delivery	- While upper and lower stability was greater in digital dentures (p = 0.03 and p = 0.10, respectively), denture polish was superior in conventional dentures (p = 0.03). -OHRQoL was slightly higher with conventional compared to digital Dentures - Superior clinical efficiency of digital compared to conventional dentures, and comparable patient satisfaction between the denture types
					b. OHRQoL	b. OHIP-20		
					c. Patient satisfaction with denture related factors (ease of cleaning, general satisfaction with the denture, ability to speak, comfort, aesthetics, stability, and the ability to chew seven index food, and general satisfaction with their oral health)	c.VAS		
	Gomaa et al. (2023) (49)	"To compare the difference between CAD/CAM-milled poly methyl methacrylate (PMMA), poly ether ether ketone (PEEK) and conventional mandibular implant-assisted overdentures regarding patient satisfaction and OHRQoL"	18 completely edentulous patients	18 patients each received three mandibular implant-assisted overdentures with three different denture base materials opposing a maxillary single denture in a random manner: G1: CAD/CAM-milled PMMA G2: CAD/CAM-milled PEEK G3: conventional PMMA	a. Patient satisfaction	a.VAS	After 6 months of each overdenture use	- There were statistically significant higher patient satisfaction scores for CAD/CAM-milled PMMA and PEEK compared to conventional PMMA base except for speech, aesthetic and smell. -Regarding OHRQoL.statistically significant lower problem scores were revealed for CAD/CAM-milled PMMA and PEEK than conventional PMMA base except psychological discomfort, psychological disability and social disability.
					b. OHRQoL	b. OHIP-EDENT-19		
	Deng et al. (2023) (41)	"To compare the treatment outcomes and time efficiency between digital and conventional complete denture restorations"	10 edentulous patients	Each patient received two dentures in a random manner: G1: Conventional first followed by digital G2: Digital First followed by conventional (Digital workflow: functionally suitable digital complete denture [FSD])	a. Clinical and laboratory operation times. Material and labor cost	a. Recording the time and costs	Clinician rating at the time of denture delivery. Patient assessment following 1 week of denture wear.	-The patient and clinician satisfaction ratings with FSDs were higher than those of conventional dentures but the difference was not significant (P<0.05). -The clinical and laboratory times of the FSD groups were less than the conventional group, saving 28 minutes and 64.3 minutes in the clinic and laboratory, respectively.
					b. Clinician satisfaction (denture retention, stability, occlusal stability, and margin extension)	b. Score between 0 and 10		
					c. Patient satisfaction (denture retention, stability, mastication, comfort, and esthetics)	c. Score between 0 and 10		
	Kang et al. (2022) (43)	"To evaluate the clinical performance and patient satisfaction associated with digitally versus conventionally fabricated CDs"	8 participants requiring CDs	Each patient received 2 sets of CDs in a random order: G1: Conventional denture G2: Digitally 3D printed denture {Digital workflow: NextDent}	a. Internal adaptation	a. Replica technique	24 to 48 hours (ninth visit) and 1 month (tenth visit) after placement	-Internal adaptation and masticatory force: G1=G2 (P>0.05) -Masticatory efficiency (P=0.009) and patient satisfaction with pronunciation (P=0.006): G1>G2 -Overall Patient satisfaction: G1=G2
					b. Masticatory efficiency (mixing ability index (MAI)) and masticatory force	b. 2-colored wax cube & an occlusal force–measuring system		
					c. Patient Satisfaction	c. A 12-item patient satisfaction questionnaire (VAS)		
	Emera et al. (2022) (57)	"to compare the retention and denture base adaptation of 3D-printed complete dentures fabricated using dimethacrylate-based resins with a photoinitiator versus conventional complete dentures"	10 completely edentulous patients	Each patient received 2 sets of CDs in a random order: G1: Conventional denture G2: Digitally 3D printed denture	a. Denture base adaptation	a. Matching software	At the time of complete denture insertion (T0), after three months (T3) and six months (T6) of denture use.	-Retention and denture base adaptation: G1=G2 (P>0.05).
					b. Denture retention	b. Digital force meter		
	El-Shaheed et al (2022)	" To evaluate the surface adaptation and maximal biting force of CAD-CAM milled mandibular	10 completely edentulous patients	Each patient received in a random order: G1: milled CAD/CAM MOD G2: CC MOD	a. Tissue surface adaptation	a. Surface matching software	-After MOD construction	-Tissue surface adaptation and maximum biting force: G1>G2 (P=0.0001)

	(58)	overdenture (CAD-CAM MOD) compared to conventional compression mold mandibular overdenture (CC MOD)"			b. Maximum biting force	b. A force transducer occlusal force meter		
	Ohara et al. (2022) (40)	"to evaluate patient satisfaction with conventional dentures (CDs) and digital dentures (DDs) fabricated using 3D printing."	20 edentulous patients	G1: Digital dentures followed by Conventional (n=6) G2: Conventional dentures followed by digital (n=9) (Digital workflow: 3D printed dima denture base try-in; Kulzer Japan, Co., Ltd., Tokyo, Japan)	a. Patient satisfaction (chewing efficiency, pain, stability, retention, comfort, esthetics, ease of cleaning, phonetics, and general satisfaction)	a. VAS	-	- Patient satisfaction in regards to phonetics, ease of cleaning, stability, comfort, and general satisfaction: CD>DD (P<0.05) - Social disability and the number of clinic visits: CD>DD (P<0.05) -The number of visits needed for denture fabrication, including the number of remakes: CD>DD (P<0.05) - No significant differences in the number of adjustment visits and the time needed for denture fabrication and adjustment between CDs and DDs
					b. Quality of life (QOL)	b. OHIP-EDENT-J		
					c. Number of visits, time required for definitive denture fabrication, number of adjustment appointments, and time required for denture stabilization after denture delivery	c. Stopwatch		
	Peroz et al. (2021) (50)	"to evaluate the impact of the digital versus conventional production of complete dentures on oral health-related quality of life (OHRQoL) measures"	16 edentulous patients	16 participants received 2 sets of new complete dentures produced with: G1: Milled Baltic Denture System digital workflow*** (2 visits) G2: Conventional workflow (5 visits)	a. OHRQoL	a. Oral Health Impact Profile, German version (OHIP-G49)	Baseline, 14 days, and 3 months after insertion of each denture	- The median and the sum scores of the OHIP-G49 dimensions: G1=G2 (P>.05) --Digital dentures were manufactured within 4 hours, while conventional dentures took 10.5 hours.
					b. The time needed for the fabrication process.	b. The estimated working time provided by the dentist and the technician		
	Srinivasan et al. (2021) (51)	"to compare the differences between milled and 3D-printed complete removable dental prostheses"	15 edentulous patients	15 patients received 2 sets of dentures: G1: AvaDent Milled denture G2: NextDent ßß 3D-printed denture	a. Patient's denture satisfaction (PDS)	a. 5-point Likert questionnaire	a,b,e,f,g were assessed at 1- and 6-weeks post insertion of each denture	- PDS, OHIP, FC, CDQE, CE, and MBF: G1=G2 - Maintenance visits, adjustment time: G2>G1 (p = 0.0003) - Adjustment costs: G2>G1 (p = 0.021). - Patients were willing-to-pay an average of 606.67 Swiss Francs more than the actual cost for the milled CRDPs.
					b. Oral-health related quality of life)	b. OHIP-EDENT		
					c. Willingness-to-pay analysis	c. An open-ended contingency valuation (CV) method of questioning		
					d. Final choice (FC) of CRDPs	-		
					e. Clinician's denture quality evaluation (CDQE)	e. A dichotomous scale (0 to 7)		
					f. Chewing efficiency (CE)	f. Validated two-color mixing test		
					g. Maximum-voluntary-bite-force (MBF)	g. Digital force gauge		
					h. Prosthodontic maintenance needs	h. Noted by the clinician		
Non randomized crossover clinical trial	Abd El Galil (2021) (66)	"to evaluate the adaptation of maxillary complete denture designed by two different open computer-aided design software programs (3Shape and Exocad)"	20 completely edentulous patients	40 3D printed complete dentures designed using two different software programs: G1: 20 maxillary and mandibular dentures designed by 3Shape‡ G2: 20 maxillary and mandibular dentures designed by Exocad software.ɤ	Denture adaptation	Geomagic software	-	- While both software produced acceptable maxillary complete dentures, dentures designed by G1 (3Shape) had better adaptation than those designed by G2 (Exocad): G1>G2
Non-randomized controlled clinical trial	Drago & Borgert (2019) (62)	"to identify differences in the number of unscheduled postinsertion-adjustment visits of patients with complete dentures fabricated by injection molding (IM) versus dentures fabricated by computer-aided design and computer-aided manufacturing"	106 participants with previously worn complete dentures	G1: Complete dentures fabricated using an IM system (n=33) G2: Complete CAD/CAM milled (AvaDent˜) dentures (n=73)	The number of unscheduled visits	Evaluated by the clinician	Followed up for 1 year after the insertion of new complete dentures.	-The number of unscheduled visits: G1=G2 (P=0.940) -Participant returns for unscheduled adjustments were not associated with the method of denture fabrication -Return visits for unscheduled adjustments were significantly associated with patients with single dentures and patients who returned for scheduled postinsertion visits -G2 took longer to achieve satisfactory levels of comfort with their dentures compared to G1 -G2 took longer to return for unscheduled visits compared to G1
Randomized controlled clinical trial	Nasr Mostafa et al. (2023) (59)	" To evaluate retention and attachment wear of CAD/CAM versus conventional implant-assisted overdenture frameworks"	16 completely edentulous men	Patients were divided into 2 groups: G1: conventional metal-reinforced framework with prefabricated metal housing	Retention and wear of attachments	-	At 3 months (prostheses loading), 6 months, and 12 months after implant placement	Attachment housing integrated within a CAD/CAM implant overdenture can be a better substitute to the manufacturer's metal housing, since it reduces retention loss and attachment wear over time

				G2: CAD/CAM metal-reinforced framework with custom metal housing				
	Liu et al. (2022) (42)	"To explore the applications of 3D scanning and 3D printing techniques in the restorative treatment of edentulous patients"	30 edentulous patients	Patients were randomly divided into two groups: G1: traditional complete denture (n=15) G2: 3D-printed complete denture (n=15)	a. Patient satisfaction b. Number of visits	a. VAS b. recorded by the team	Immediately and 1, 3, and 6 months after denture delivery	-The ability to speak, ability to chew, and comfort in both G1 & G2 gradually improved at the first three time points. - VAS scores increased to a satisfactory level after 3 months. - The esthetics and stability of both groups were scored high after the initial delivery. -The VAS scores regarding esthetics, ability to speak, ability to chew, stability, and comfort: G1=G2 (P > .05) at any time point. -The number of visits in G2 was significantly decreased in comparison to G1
	Elawady et al. (2022) (48)	"To evaluate the oral health-related quality of life (OHRQoL) of patients rehabilitated with conventional or 3D-printed implant overdentures."	28 completely edentulous participants	Patient were randomly allocated to 2 groups (n=14): G1: Conventionally manufactured PMMA maxillary complete dentures (CDs) and mandibular implant overdentures (Control) G2: Digital light processing (DLP)-printed PMMA maxillary CDs and mandibular implant overdentures. (Digital workflow: -Scanned and designed with 3shape‡ -Printed with RapidShape D30††)	a. OHRQoL b. Denture retention	a. OHIPEDENT19 b. Digital force gauge device	3.6. and 12 months	-The OHRQoL values were significantly higher (less improvement) in G1 at 6 months (P = 0.02) and 12 months (P = 0.04). -At all the follow-up periods, the mean retention values were higher for G2 (P = 0.001).
	Inokoshi et al. (2012) (38)	"to compare a new trial method for complete dentures using rapid prototyping (RP) with the conventional method"	10 edentulous patients	All Patients received: G1: Maxillary and mandibular conventional complete dentures (n=10). G2: Maxillary and mandibular complete dentures using rapid prototyping (EDEN250 RP machine ζ) (n=10).	a. Prosthodontist satisfaction b. Patients satisfaction	a. VAS (esthetics; stability; operator friendliness for verifying jaw relation records; chair time; and overall satisfaction) b. VAS (esthetics; predictability of final denture shape; stability; comfort of the dentures; and overall satisfaction)	Immediately in trial insertion	-Prosthodontist's ratings (esthetics and stability): G1>G2 (P<0.05) - Prosthodontist's ratings (chair time): G1>G2 (P<0.05) -Prosthodontic rating (operator friendliness or overall satisfaction): G1= G2 (P>0.05) -Patient rating (esthetics, predictability of final denture shape, stability, comfort of the dentures or overall satisfaction.): G1=G2 (P>0.05)
Pilot controlled clinical trial	Schwindling and Stober (2016) (52)	"to compare the clinical feasibility, complications during fabrication, and quality of 2 types of digitally designed complete dentures"	5 participants	All participants received: G1: complete maxillary and mandibular digital denture by milling (Wieland Dental Digital Denture system ♀) from polymethyl methacrylate blanks (n=5) G2: complete maxillary and mandibular digital denture by injection molding. (n=5)	Clinical outcome including fit, retention, esthetics, phonetics, maxillomandibular relation, and occlusion	6-point scales ranging from poor (grade 6) to excellent (grade 1)	Throughout the fabrication process and during the final clinical session	-All functional aspects: G1=G2 -Fit: both types received predominantly excellent grades -Esthetics were rated "very good" after the necessary corrections. -No major complication. -Only a few minor complications occurred during the fabrication process, predominantly esthetic issues.
Single-arm clinical trial	Cristache et al. (2019) (53)	"to evidence the improved behavior of modified PMMA-TiO2 nanocomposite material used to obtain 3D printed complete dentures and to describe a protocol for long-term rapid prototyping complete denture manufacturing using our nanocomposite material, and the evaluation of the clinical performance and complications after eighteen months of continuous wearing "	35 fully edentulous patients received a total of 45 complete dentures	G1: Maxillary complete dentures (n=31) G2: Mandibular complete dentures (n=14) (Digital workflow: -Designed with 3Shape software ‡. - 3D printed using Digital Light Projection Manufacturing †)	a. Clinical evaluations of retention and stability b. The total number of post insertion adjustment visits (unscheduled), and any reported complications	a. By two experienced prosthodontists using the modified Kapur index (MKI) b. Single examiner	Follow-up at 1 week, 6 month, 12 month, 18 month	-Retention and stability for both G1 and G2: significant improvement post insertion (p<0.05) which maintained at 18 months follow-up with little or no changes -The MKI post insertion: between 5 and 9 for G1 meaning good and very good retention and stability, and between 3 and 5 for G2 -An average of 3.06 denture adjustments were needed after insertion -No major functional complications have been observed after 18 months of continuous wearing.
	Cristache et al (2020) (44)	"to assess the eighteen month follow-up patient-centered outcomes of a simple and predictable protocol for 3D-printed functional complete dentures manufactured using an improved (PMMA)-nanoTiO2"	A total of 35 fully edentulous patients received a total of 45 complete dentures	G1: Maxillary complete dentures (n=31) -G2: Mandibular complete dentures (n=14) (Digital workflow: Scanned using Medit T500 digital scanner ⊕ - Designed with EXOCAD ∝ - Tooth shape and positioning with Planmeca Romexis Smile Design software β -3D-printed with DLP technology)	a. Patient-Centered Outcomes (general satisfaction, satisfaction with aesthetic, speech, masticatory efficiency, hygiene, and comfort) b. OHRQoL	a. VAS b. OHIP-EDENT	Before denture insertion, 1 week, 12 month, and 18-month follow up	- OHIPEDENT scores: Significant reductions for G1,G2 at the 1 week and 12 and 18 month follow-ups (p < 0.05) -Patient satisfaction: significant improvements in all criteria for both groups compared to baseline -OHRQoL: significant improvements in all participants
Case Series	Deng et al. (2021) (47)	"To improve the clinical effects of complete denture use and simplify its clinical application"	40 edentulous patients	A 3D printed complete denture restoration workflow (Functional Suitable Digital Complete Denture System, FSD) fabricated by:	a. The number of visit until denture delivery, and return visit after denture delivery b. Accuracy of impression	a. Evaluated by the investigator b. Geomagic software	1 week after denture insertion	-The amount of 3D deviation between the impression made through diagnostic dentures and the final dentures was 0.165 ± 0.033 mm in the maxilla and 0.139 ± 0.031 mm in the mandible.

			G1: A prosthodontic chief physician (n=20) G2: A postgraduate student (n=20)	c. Patient-reported outcomes (retention, stability, masticatory efficiency, comfort, and esthetics)	c. VAS		-VAS ratings were between 8.5-9.6 in G1, and 7.7-9.5 in G2. -FSD can reduce two visits.
				d. Clinician-reported outcome (tissue surface adaptation, retention, stability, and border extension)	d. VAS		
John et al. (2019) (35)	"to describe the rehabilitation of completely edentulous arches using the Baltic Denture System (Merz Dental GmbH®) in just two patient visits"	15 edentulous older adults	CAD-CAM maxillary complete denture using the Baltic Denture System*** (n=15) (Digital workflow: - Scanned the impression using s D2000 extraoral scanner θ -Virtual design by WorkNC® CAM software ψ - Milled using imes-icore® 5-axis milling machine ɬ)	Patient satisfaction	-	The patients were recalled after a week and then after 6 weeks for evaluation	Patients were visibly satisfied with the new dentures and did not face any problem in function
Hassan et al. (2017) (56)	"to integrate extra-oral facial scanning information with CAD/CAM complete dentures to immediately rehabilitate terminal dentition "	10 patients with terminal dentition scheduled for total extraction and immediate denture placement	CAD/CAM (AvaDent*) milled immediate complete denture (n=10) (Digital workflow: -The casts were scanned using iSeries DWOS ϰ -3 facial scans were obtained from each patient using the in-office 3D facial scanner Pritimirror þ -Milled using M7 CNC 5-axis industrial milling machine q)	Clinical fit, occlusion/articulation, and esthetics	Evaluated by the clinician	3 months post insertion follow-up	-All dentures exhibited satisfactory retention, stability, and aesthetic outcomes with no notable technical or biological complications. -All provisional prostheses remained three months in function with no notable technical complications. - Clinical fit, occlusion/articulation, and esthetics were satisfactory.

*AvaDent, Global Dental, Science, Scottsdale, AZ, USA; ‡ 3D Shape, Copenhagen, Denmark; † EnvisonTEC Perfactory® 3D printer, GmbH, Gladbeck, Germany; ɸ Medit Corp., Seoul, Korea; ɣ Exocad GmbH, Darmstadt, Germany; β Panmeca Oy, Helsinki, Finland; δ Ivoclar Vivadent, Liechtenstein; ψWieland Digital Denture, Ivoclar Vivadent; £ DOF USA Inc., Fullerton, CA; § Dentca design software, Torrance, CA, USA ; Δ Zenith, Dentis Co, LTD., La Palma, CA; α TRIOS 3; 3Shape, Inc, Copenhagen, Denmark; ε CATIA V5R19, Dassault Systemes, VélizyVillacoublay, France; and FreeForm, SensAble Technologies, Woburn, MA, USA; ζ EDEN250, Objet Geometries, Rehovot, Israel; θ D2000, 3Shape®, Denmark; ψ WorkNC®, Vero India Software PvtLtd; ɬ imes-icore® Gmbh, Germany; ϰ iSeries DWOS; Dental Wings, Montreal, Canada; þ Pritidenta GmbH, LeinfeldenEchterdingen, Germany; q M7 CNC; Darton AG General, Mühltal,, Germany; **Formlabs Inc., Somerville, MA, USA); †† Rapid Shape, Heimsheim, Germany; ***Baltic Denture System, Merz, Dental GmbH, Germany; δδ NextDent B.V., Soesterberg, Netherlands.

-Reports highlighted in the same color, pertain to a similar study.

Table 4-2. Included studies on overdenture with CAD/CAM bar or retentive component.

Study design	First author (year)	Study objectives	Study sample	Type of Intervention (Study groups)	Type of outcome assessed	Data collection tools	Data collection timeline	Key findings
Non-randomized controlled clinical trial	Abdraboh et al. (2020) (74)	"to evaluate clinical, prosthetic, and patient-based outcomes of a milled bar with polyether ether ketone (PEEK) and metal housings for inclined implants supporting mandibular overdentures"	36 edentulous patients	G1: Mandibular overdentures attached to the bars with PEEK female housing (n=18) G2: Mandibular milled bar overdentures with conventional metal housings (n=18) (Digital workflow: -The cast was scanned using CAD/ CAM (Ceramill Map400, Amann Girrbach) - the milled bar was designed using the software (exocad) -The bar was printed by prototyping)	a. Clinical parameters (Plaque Index, Gingival Index, pocket depth, and bone loss)	a. Measurements by two examiners after instruction and calibration.	a. Clinical parameters at baseline, 6 months, and 12 months. b,c. Patient satisfaction and prosthetic complications at 12 months.	- Plaque score and marginal bone resorption: G2>G1 (P<0.05). - Patient satisfaction with retention, stability, speech, and esthetics: G1>G2 (P < .048). - Incidence of female housing wear, plastic clip wear, and plastic clip fracture/renewal: G2>G1) (P = .017, < .001, and P=.049 respectively). -Other clinical, prosthetic, and patient-based outcomes: G1=G2
					b. Prosthetic complications	b. Measurements by two examiners after instruction and calibration.		
					c. Patient satisfaction	c. VAS		
Randomized controlled clinical trial	Srinivasan et al. (2020) (72)	"to demonstrate the non-inferiority of mandibular 2-implant overdentures (IODs) on a CAD-CAM milled bar with long distal extensions (MBDE) against IODs on retentive anchors (RA)"	40 edentulous participants	G1: Mandibular 2-IOD on retentive anchors (n=20) G2: Mandibular 2-IOD on a CAD-CAM MBDE (n=20) (Digital workflow: - The scanned data were imported into a software (Cares®, Institut Straumann AG, Basel, Switzerland) to design the CAD-CAM milled bars)	a. Implant survival rate (ISR)	a. Clinical evaluation using success criteria published by Buser et al.	Baseline , 2 weeks, 6 months, and at 1 year after the intervention	-There was no implant loss in either of the groups (ISR = 100%). - PI-MBL changes: G1=G2 (P>0.05) -VoH, MBF, OHIP-EDENT, and the DS: G1=G2 (P>0.05) -SA: Better in G2 (p = .022)
					b. Chewing efficiency	b. Quantitative variance of hue (VoH) and subjective (SA) assessments		
					c. Peri-implant marginal bone levels (PI-MBL)	c. Rule of three with an image processing and analysis freeware		
					d. Maximum bite force (MBF)	d. Occlusal Force-Meter GM 10		
					e. Patient-reported outcomes	e. OHIP-EDENT & denture satisfaction index (DSI)		
	Sharaf et al (2022) (70)	"To compare retention and patient satisfaction of implant-supported mandibular overdentures (IMOD) retained by conventional nylon clip and metal housings for ball attachments against CAD/CAM PEEK clip and housings"	22 edentulous patients	G1: IMOD retained by conventional metal housings and nylon retentive elements G2: IMOD retained by CAD/CAM PEEK retentive elements and housings.	a. Retention	a. Force meter	At overdenture insertion and 3, 6, and 12 months	-The CAD/CAM PEEK group showed significantly increased retention force at the time of insertion and after 3, 6, and 12 months (P<0.05). -The conventional group had a significantly higher overall satisfaction (P < 0.05) at the time of insertion. -PEEK showed significantly higher satisfaction after 6 and 12 months.
					b. Patient satisfaction	b. a 7-point VAS		
Cross-over clinical trial	Altonbary & Emera (2021) (71)	"comparison of patient satisfaction and masticatory performance for patients rehabilitated with mandibular two implant overdentures retained with two different bar attachments; zirconia bar and cobalt chromium bar"	20 completely edentulous patients	All patients received: G1: mandibular implant overdenture retained with CAD/CAM zirconia bar on two implants in the canine region (n=20) G2: mandibular overdenture retained with conventional casted cobalt-chromium metal bar (n=20) (Digital workflow: -Casts were scanned by laboratory scanner (D800 3Shape) -Design by Wieland software (3shape Dental system) - Zirconia bar was milled from semi-sintered zirconia blanks (Zenostar MO 2, Wieland dental, Ivoclar Vivadent) by the milling machine (Zenotic select hybrid)	a. Patient satisfaction	a. Survey questionnaire (PSQ-18)	After 3month of overdenture insertion	-Patient satisfaction with chewing performance, speech, discomfort in surgery, doctor, complications, information prior to treatment: G1=G2 (P>0.05) -Patient's preference due to appearance, patient's satisfaction with the time spent for treatment, oral hygiene, undergoing this procedure again: G1>G2 (P<0.05)
					b. Masticatory performance	b. Two-color mixing ability test		
Prospective observational study	Mangano et al. (2015) (75)	"to present a digital method that combines intraoral and face scanning for the computer-assisted design/computer-assisted manufacturing (CAD/CAM) fabrication of implant-supported bars for maxillary overdentures"	15 patients presented to a private dental clinic with a removable complete denture in the maxilla, seeking rehabilitation with implants	Maxillary overdenture supported by a CAD/CAM polyether-ether-ketone (PEEK) implant-supported bar (n=15) (Digital workflow: -Pre-existing denture scanned with a structured light IOS (CS 3600®, Carestream Dental, Atlanta, Georgia, USA). -All files deriving from Meshmixer® were imported into a prosthetic CAD (Dentalcad®, Exocad, Darmstadt, Germany) -The STL file of the bar was printed in 3D with 3500PD®)	a. Passive fit/adaptation of the bar	a. Checked clinically, before and after screwing the replica (and the final bar) on the implants.	1 year follow-up	-12 bars out of 15 (80%) had a perfect passive adaptation and fit. – A 1-year success rate of 80% for the implant-supported overdenture. - The combination of intraoral and face scans allowed to successfully restore fully edentulous patients with maxillary overdentures supported by 4 implants and a CAD/CAM PEEK bar.
					b. The 1-year implant survival	b. Clinical and radiographic assessment		
					c. The success rates of the implant-supported overdentures	c. The absence of any biologic and prosthetic complications		

	Pozzii et al. (2016) (68)	"to evaluate the clinical performance of a 4-implant overdenture fully supported by a computer-aided designed and computer-aided manufactured (CAD-CAM) titanium bar"	18 edentulous participants rehabilitated with a 4-implant overdenture in 1 of the 2 jaws.	4-implant overdenture fully supported by a CAD/CAM milled titanium bar (NobelProcera Innovation Center; Nobel Biocare)	a. Implant and prosthetic survival and success rates, any biologic and technical complications, periimplant marginal bone loss, bleeding on probing, and the plaque index.	a. Clinical and radiographic evaluation	Follow-up visits were scheduled at 1 and 6 months after prostheses delivery and then annually	-The OHIP summary scores demonstrated a significant improvement in oral health-related quality of life. -At the 1-year follow-up, no implants and/or prosthesis had failed, No biologic or technical complications occurred.
					b. Patient satisfaction with function and esthetics	b. Scale with ratings from 1-10		
					c. Oral health-related quality of life.	c. OHIP		
	Toia et al. (2019) (69)	"to evaluate the patient satisfaction and the clinical outcomes of edentulous arches rehabilitated with overdentures retained by CAD-CAM milled titanium bars"	40 edentulous patients	overdentures ("2in-1" Atlantis® Suprastructure Dentsply Sirona Implants, Mölndal, Sweden) retained by CAD-CAM milled titanium bars.	a. Patient satisfaction	a.(OHIP-14) questionnaire	a. At the pre- and post-treatment visits, up to two years after prosthesis delivery b. Before the final prostheses' delivery c. Radiographic and clinical examinations were performed at baseline and after 2 years of function.	-Pre- and post-treatment OHIP-14 score: High satisfaction for aesthetics, functional and psychological outcomes (P < 0.0001) - The prosthodontists were very satisfied about the delivery and the versatility of the two milled bars (a mean score of 3.4 ± 4) -All complication were considered minor and successfully addressed by the treating clinicians.
					b. Prosthodontist satisfaction	b. Designed questionnaire		
					c. clinical evaluation, Implant and prostheses complications.	c. Radiographic & clinical examinations		
	Zuercher et al (2022) (76)	"To investigate the clinical performance of CAD/CAM Zirconia bars with distal extensions for mandibular implant overdentures"	15 edentulous patients	Each patient received 2 interforaminal implants and a mandibular implant OD supported by a CAD/CAM zirconia bar with distal extensions	a. Biological factors (implant survival and peri-implant conditions)	a. Radiographs and Dimaxis Pro software	At 1 year follow-up	-After 1 year, all 15 zirconia bars with their prostheses and implants were successful with no prosthodontic maintenance required and no biological complications. -1 patient developed moderate mucosal hyperplasia around the bar.
					b. Prosthodontic maintenance (i.e. bar fracture, screw loosening)	b. Prosthodontist assessment		
Retrospective observational study	Cordaro et al. (2013) (73)	"to evaluate the clinical performance as well as patients' and clinicians' satisfaction on two different prosthodontic retention systems for implant-overdentures in the mandible"	A total of 39 patients were selected who were using a mandibular removable prosthesis at presentation, but their desire was to improve its stability. Only patients receiving four implants were considered for the present study	G1: Mandibular implant-overdenture with Locator (R) attachment (n=19) G2: mandibular implant-overdenture with cad-cam StructSURE® bar (BIOMET 3i, Palm Springs, FL, USA). (n=20)	a. Clinical parameters such as Peri-implant Probing Depth (PPD), Plaque Index (PI), and Bleeding on Probing (BOP) perceptions regarding the outcome	a. Professional evaluation by 3 dentists who were not involved in the treatment	every 6 month with at least 12 months of follow-up since overdenture delivery	-PPD, PI, and BOP: G1>G2 (P<0.001). -Ease of cleaning : G1>G2 (P=0.0183) - Other VAS items: G1=G2 (P>0.05) -Professional satisfaction with hygienic maintenance, soft tissue conditions, retention: G1>G2 (P<0.05).
					b. Patients' and clinicians'	b. VAS		

Table 4-3. Included studies on denture bases.

Study design	First author	Study objectives	Study sample	Type of Intervention (Study groups)	Type of outcome assessed	Data collection tools	Data collection timeline	Key findings
Cross-over clinical trial	Maniewicz et al (2022) Part-I (79)	"to evaluate the peak retention force and fit of CAD/CAM manufactured (3D-printed and milled) maxillary complete denture bases and conventional heat-polymerized bases (control)"	19 patients with edentulous maxilla	Denture bases made for each patient: G1: conventional impression and conventional PMMA base (CB) G2: conventional impression and printed base (PB1) {NextDent; Vertex-Dental BV)} G3: conventional impression and milled base (MB1) {(AvaDent Denture Base Puck; Global Dental Science Europe BV)} G4: Intraoral scan and printed base (PB2) G5: Intraoral scan and milled base (MB2)	a. Retention b. Patients' rating of taste, smell, fit sensation of the base, pain on insertion and removal, and the smoothness of the bases c. fit	a. A digital traction dynamometer b. VAS c. Comparison software program (Geomagic Control X 2020; 3D systems)	At 3rd and 4th appointment	-There was no significant difference in peak retention between MB1, PB1, and CB bases in the post dam and right tuberosity. -Compared with the definitive cast, the fit of the conventional base was closer than the printed and milled bases (P<0.001)
	Chebib et al. (2022) Part II (94)	« to determine the retention of complete denture bases fabricated from digital intraoral scans versus conventional impressions by using border molding and posterior palatal seal compression »	19 patients with edentulous maxilla	Denture bases made for each patient: G1: conventional impression and conventional PMMA base (CB) G2: conventional impression and printed base (PB1) {NextDent; Vertex-Dental BV)} G3: conventional impression and milled base (MB1) {(AvaDent Denture Base Puck; Global Dental Science Europe BV)} G4: Intraoral scan and printed base (PB2) G5: Intraoral scan and milled base (MB2)	a. Retention b. Trueness	A digital traction dynamometer b. Scanning	After 2 weeks of immersion in artificial saliva	- The retention of 3D printed bases and milled bases made from conventional impressions was significantly higher than those printed and milled from the intraoral scans (P<.05). - Comparison of the 3D distances between the intraoral scan and the definitive cast showed a deviation of 0.45 ±0.11 mm.
	AlHelal et al. (2017) (77)	"to compare the retention values of conventional heat-polymerized denture bases with those of digitally milled maxillary denture bases"	20 individuals with completely edentulous maxillary arches	Patients received both: G1: Maxillary CAD/CAM milled denture base (AvaDent®) (n=20) G2: Maxillary heat-polymerized acrylic resin denture base resin (n=20)	a. Denture retention b. Patient satisfaction	a. Custom-designed testing device b. A patient questionnaire	a. 3 times at 10-minute intervals b. After wearing both dentures, each denture for a week.	-Retention: G1>G2 (P<.001) -Patient satisfaction in terms of comfort, retention, masticatory efficiency, prostheses selection, and efficiency of technique: G1>G2 (P<0.05)
Controlled clinical trial	AlRumaih et al. (2018) (80)	"to evaluate the effectiveness of denture adhesive on the retention of milled and heat-activated denture bases"	20 participants with complete maxillary edentulism	Patients alternatively received: G1: Maxillary CAD-CAM milled denture (AvaDent®) bases with adhesive (n=20) G2: Maxillary CAD-CAM milled denture (AvaDent®) bases without adhesive (n=20) G3:Maxillary heat-activated acrylic resin denture bases with adhesive (n=20) G4:Maxillary heat-activated acrylic resin denture bases without adhesive (n=20)	Denture retention	Custom-designed testing device	3 times at 10-minute intervals	-Retention: G1> (G2,G3,G4) (P<.001) -Retention: G3=G4 (P<0.05) -The use of adhesive significantly decreased the retention of the milled bases
Non-randomized clinical trial	Nishiyama et al. (2018) (78)	"to introduce a newly developed zirconia complete denture (ZrD) that incorporates a ceria-stabilized zirconia/alumina nano-composite framework fabricated with computer-aided design/computer-aided manufacture"	29 edentulous patients	G1: Maxillary zirconia complete denture (n=10) (Dental System D-810, 3shape); Framework is milled from nano-zirconia blanks by machining center (CORiTEC 250i, Panasonic Healthcare, Japan) G2: Maxillary conventional complete denture (n=19)	Patient satisfaction	McGill Denture Satisfaction Instrument	Before and 12 months after prosthesis placement.	-All aspects of patient satisfaction in G1 improved at the 12-month follow-up, with statistically significant changes in general satisfaction, comfort, stability, chewing ability (P<0.05) -Patient satisfaction: G1=G2 (P>0.05)
Randomized clinical trial	Yoon et al. (2020) (81)	"to assess the tissue surface adaptation of complete denture bases generated by the DLP technique and to compare the adaptation with that of denture bases manufactured by 5-axis milling (MIL) and pack-and-press (PAP) method"	9 participants	Using a CAD software program (3Shape Dental Designer; 3Shape A/S), the complete dentures were prepared by 3 different denture bases: G1: 5-axis milling (MIL) G2: pack-and-press (PAP) G3:digital light processing (DLP)	a. Absolute tissue surface adaptation (ATA) b. Relative tissue surface adaptation (RTA)	Clinical evaluation using the thickness of indicator (Fit Checker II; GC Corp) under a stereomicroscope	after prosthesis delivery	Absolute Tissue surface adaptation: G1=G2=G3 (P>0.05) -RTA values for mandibular arch: G3=G1 (P>0.05) -G3 was likely to exhibit intimate adaptation in the stress-bearing areas of the maxillary arch while G1 was likely to display loose adaptation to the tissue. -Both G3 and G1 denture bases were likely to show either intimate adaptation or mild impingement on the lingual slope of mandible.

Controlled clinical trial	Faty et al. (2021) (82)	"to assess the retention and adaptation of milled and printed denture bases and to compare them to conventional ones"	A total of 24 completely edentulous patients	All participants received: G1: conventional denture bases (n=24) G2: denture bases milled from prepolymerized blocks of PMMA (n-24) G3: denture bases fabricated by a 3D printing (n=24) (Digital workflow: The 3Shape scanner (D850, 3Shape, Copenhagen, Denmark) and software (3shape dental designer, 3Shape A/S, Copenhagen, Denmark) were used to scan the casts and design the denture bases. .The 3D printing machine (MOGASSAM Dent2 3D Printer, Mogassam, Egypt) was used to fabricate the printed denture bases.	a. Retention b. Adaptation of the denture bases with their corresponding master casts	a. A digital force gauge b. Geomagic Control X 64 software	The measurement procedures were repeated 5 times at 5 minutes intervals for each	-Retention: G2>G3>G1 (with the difference being significant only for G2 and G1, P<0.05). -Gap areas: G3>G1>G2 (P<0.05) -Pressure areas: G3>G1>G2 (with the difference being significant only between G3 and G2 (p=0.004)

*Reports highlighted in the same color, pertain to a similar study.

Table 4-4. Included studies on RPD framework.

Study design	First author	Study objectives	Study sample	Type of Intervention (Study groups)	Type of outcome assessed	Data collection tools	Data collection timeline	Key findings
Randomized controlled clinical trial	Pelletier et al. (2022) (91)	" to compare the adaptation of RPD framework rests made with conventional casting or computer-aided design and computer-aided manufacturing (CAD-CAM) with selective laser sintering (SLS) at the clinical evaluation and 1 year after the delivery of the prostheses.	18 participants presenting with maxillary and/or mandibular partial edentulism	G1: RPD framework made with CAD/CAM SLS (n=9) G2: RPD framework made with conventional lost-wax casting (n=9)	Adaptation of the RPD at the rest seat area	SEM	-At the metal framework evaluation and 1 year follow-up	- One year after the delivery of the RPD, the adaptation of the frameworks made with conventional casting was still significantly better
	Refai et al. (2022) (93)	"To assess and compare the dislodging force of double crown-retained removable partial dentures (RPDs) made from polyetherketoneketone (PEKK) and polyetheretherketone (PEEK) at insertion (baseline) and one year after clinical functional use"	18 patients with maxillary symmetrical Kennedy class I	Patients were randomly assigned to 2 groups: G1: Double crown-retained RPDs made from Milled PEKK G2: Double crown-retained RPDs made from Milled PEEK	The dislodging force	A digital force gauge	At baseline and 1 year after clinical use	-At baseline; dislodging force: G1=G2 -After 1 year; dislodging force: G1>G2
	Gan et al. (2018) (86)	"to compare the adaptation between the major connectors of removable partial dentures derived from intraoral digital impressions and extraoral digital impressions."	24 volunteers	All participants received: G1: Maxillary major connectors designed on intraoral digital impressions and 3D printed (n=24) G2: Maxillary major connectors designed on extraoral digital impressions and 3D printed (n=24) (Digital workflow: -Design by (Dental System, 3Shape's 3rd generation Removable Partial Design, 3 Shape, Copenhagen, Denmark). -Printed by 3D printing machine (Objet Eden 260VS Dental Advantage, Stratasys, U.S.A.))	Adaptation	Light body silicone impression and a.stereomicroscope (SteREO Discovery.V12 stereo microscope, Carl Zeiss, Germany)		-Both the adaptation of the two kinds of digital impressions were clinically acceptable. -Adaptation at midline palatine suture: G1>G2 ($p = 0.003$) -Adaptation at two sides of palatal vault: G2>G1 ($p < 0.001$) -In both groups, the highest accuracy in adaptation was revealed at the anterior margin of the major connectors. -It is feasible to manufacture the major connectors by digital impression and 3D printing technique
	Hongqiang et al. (2017) (84)	"to explore the application of computer-aided design and rapid prototyping (CAD/RP) for removable partial denture (RPD) frameworks and evaluate the fitness of the technique for clinical application"	A total of 15 cases of RPD prostheses	All participants received: G1: RPD frameworks, prepared by CAD/RP (n=15) (Scan and Design by 3Shape Dental System) G2: RPD frameworks, prepared by investment casting (n=15)	Clinical fitness	Qualitatively, visual inspection and a pressing test were used by three prosthodontists who were not involved in the fabrication. Silicon impression was used for quantitative evaluation of the gaps.	When the frameworks were well seated after certain adjustments, clinical fitness evaluations were initiated	-G1 may meet the clinical requirements with satisfactory retention and stability and no undesired rotation. - The average gap between the occlusal rest and the corresponding rest seat: G1>G2 ($P < .05$), but it was acceptable for clinical application.
Crossover double-blinded clinical trial	Chia et al. (2022) (88)	"to compare the performance of SLM-fabricated frameworks with that of those fabricated via traditional lost wax casting."	29 experienced denture wearers in need of only a single-arch prosthesis with at least 2 remaining posterior teeth for occlusal rests	Participants were randomly allocated to 2 groups and received: G1: Traditional followed by SLM RPD) (n=15) G2: sequence B (SLM followed by traditional RPD) (n=14) (Digital workflow: -Scanned and designed by 3shape - Printed with an SLM rapid prototyping system (M270; EOS))	a. The time taken for adjustments b. The clinical fit and stability of the adjusted frameworks c. The accuracy of the frameworks	a. Noted by the examiner b. Visual inspection and tactile examination by the blinded prosthodontists and by using digital microscope c. By measuring the space between the occlusal rest seat and the corresponding rest seat	-	- Frameworks fabricated by both SLM and traditional techniques had an acceptable fit. - The mean space between the occlusal rest and rest seat was comparable for SLM frameworks (273.7 ±44.5 mm) and traditional frameworks (242.2 ±44.5 mm). - The clinical fit adjustment time was statistically similar for SLM and conventional framework (P=.067).
	Almufleh et al. (2018) (83)	"to compare short-term satisfaction in patients wearing RPDs fabricated with conventional or CAD/CAM laser-sintering technology"	12 participants with partial edentulism	All Patients received: G1: Maxillary wear cast RPDs (n=12) G2: Maxillary CAD-CAM laser-sintered RPDs for alternate periods of 30 days. (n=12) (Digital workflow: -Scan by 3D scanner (3Series; Dental Wings) -Design by software (3Shape CAD Points; 3Shape) -Rapid prototyping machine (PM100 Dental & PM100T Dental; Phenix Systems))	a. Patient satisfaction b. Patient's preference in regard to the type of prosthesis	a. McGill Denture Satisfaction Instrument and VAS b. By asking patients	a. Patient satisfaction assessments at 1, 2, and 4 weeks. b. Preference at the final followup	-General satisfaction, ability to speak, ability to clean, comfort, ability to masticate, masticatory efficiency, and oral condition: G2 > G1 ($P<.05$) -Every participant who started with a lasersintered RPD (n=4) preferred it at the end of the study. -Among the participants who received the cast RPD first, 1 preferred the cast RPD, 3 found no difference between the 2 prostheses, and 1 preferred the laser-sintered RPD

Controlled clinical trial	Conceição et al. (2021) (89)	"To assess the effect of a CAD-CAM protocol fabrication on the clinical fit accuracy of removable partial denture metal frameworks to abutment teeth"	15 patients with partial edentulism with 20 dental arch rehabilitations	All participants received cobalt-chromium frameworks produced through two protocols: G1: CAD-CAM (n=20) G2: Conventional lost-wax casting technique (n=20) (Digital workflow: -Scanned by scanner (S600 Arti, Zirkonzahn GmbH, Italy) -Designed by The Partial Planner software (Zirkonzahn GmbH, Italy) - Produced by the direct metal laser sintering (DMLS) technique (Sineldent®, Spain)	Clinical fit accuracy	Silicone mold of that gap and micro-computed tomography	-	- Clinical fit accuracy: G1=G2 (P>0.05)
	Russo et al. (2021) (92)	"to compare the trueness of the intaglio surface of milled and 3D-printed removable complete digital dentures"	14 participants with a total of 20 edentulous arches	10 maxillary and 10 mandibular denture bases were fabricated with: G1: Milling workflow (n=20) {Scanned with 3shape, designed with hyperDENT; FOLLOW-ME! Technology Group, and milled in a 5-axis milling machine (DWX-51D; Roland DG Corp)} G2: 3D-printing (n=20) {Scanned with 3shape and printed with NextDent 5100; NextDent B.V.}	Deviation measurements of intaglio surface (total surface and regions of interest)	Geomagic WRAP	-	- Global trueness of the entire intaglio surface: G1>G2 for the whole data set (P<.001) and for maxillary (P=.032) or mandibular (P=.049) denture base subgroups. - Maxillary (P<.11) and mandibular (P=.2) dentures showed no significant difference in trueness within each fabrication technology. - For G1, no significant difference in trueness was found among the 11 regions of interest for the maxillary dentures (P=.085) and the 13 regions of interest for the mandibular dentures (P=.211). - G2 showed significant variations in trueness among the same zones of interest, both in maxillary (P<.001) and mandibular (P=.004) dentures.
	Tregerman et al. (2019) (85)	"to determine the quality of RPD frameworks fabricated using 3 different fabrication methods: analog, combined analog-digital, and digital."	9 participants	All participants received: G1: RPD framework manufactured by analog method (n=9) G2: RPD framework manufactured by combined analog-digital (n=9) G3: RPD framework manufactured by digital.(n=9) (Design by 3Shape CAD)	Clinical fit	Clinical evaluation by 3 prosthodontists and 2 general dentists using a yes/no survey with 7 framework-related parameters		Clinical fit: -G3 > G1 (P<.001). -G3>G2 (P<0.001) -Intraoral scanning was also significantly better than G2 (P<.001). -G1 > G2 (P=.008).
Cross-sectional clinical study	Lee et al. (2017) (95)	"to analyze the accuracy of digital RPDs by using the replica technique. "	10 participants who had a treatment plan, including the restoration of oral function with an RPD	Maxillary/mandibular digital RPD (Digital workflow: -The cast was scanned using a laboratory scanner (Activity 101; Smartoptics). -Designed by the CAD software (FreeForm; Sensable). -3D printed using a rapid prototyping machine (ProJet DP 3000; 3D Systems))	Internal fit of different components	Silicone registration material, stereomicroscope and image program	At the first recall after the delivery appointment	Significant differences were found in the internal discrepancy of the various framework components (P<.05). No differences were observed among different Kennedy classifications (P>.05). The internal discrepancy of the major connector was significantly greater than that of the rest, clasp, and minor connector. The internal discrepancy of the edentulous area was significantly greater than that of the clasp and minor connector. The internal discrepancy of the rest was significantly greater than that of the minor connector (P<.05) The discrepancy under the periphery of the rest was determined to be smaller than that of the center, especially for the cingulum rest (P<.01)
Observational prospective study	Ali et al. (2021) (87)	"To compare the production efficiency of selective laser sintering (SLS) to traditional casting (CAST) for the fabrication of metal prosthodontic frameworks in a prospective pilot evaluation"	50 patients requiring fabrication of RPDs for the replacement of missing teeth	50 RPD frameworks made using either: G1: SLS (n = 25) G2: CAST (n = 25)	The mean time for production and time saving per year for the most efficient workflow.	Number of frameworks made in the production laboratory per year was calculated using historic activity data	-	The SLS workflow resulted in a mean time saving of 118.9 minutes per framework.
Retrospective case-control study	Russo et al. (2021) (90)	"To provide, in a clinical case-control study, 1-year data on edentulous residual ridge dimensional changes for patients wearing removable partial dentures (RPD) with Polyetheretherketone (PEEK) framework, fabricated with a digital work-flow, and a control group of untreated patients"	16 participants	G1: Partially edentulous patients treated with PEEK RPD (n=10) G2: Untreated partially edentulous patients (controls) (n=6) (Digital workflow: -Scanned with 3shape, and 3D printed with Prusa i3 MK3S; Prusa Research)	Residual ridge dimensional changes	Intraoral scans and metrology software	At baseline and after a median period of 1 year	-Vertical height and 3D changes of residual ridges: G1=G2 (P>0.05)

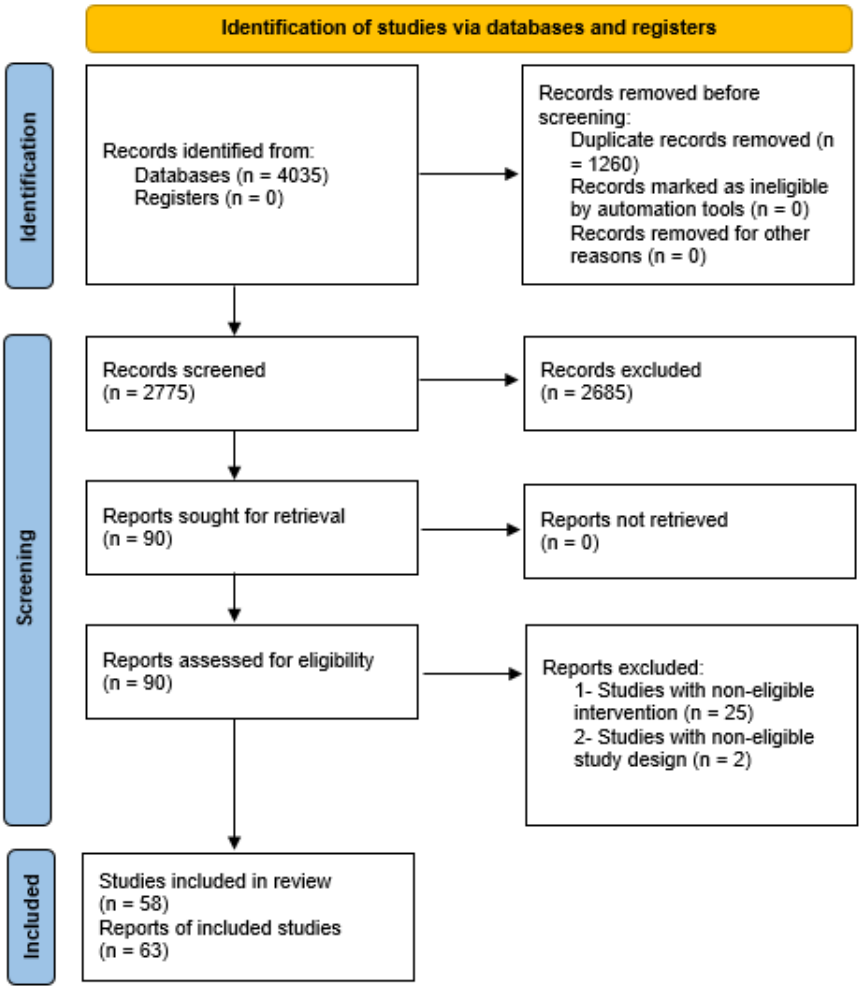

Figure 4-1. PRISMA flowchart.

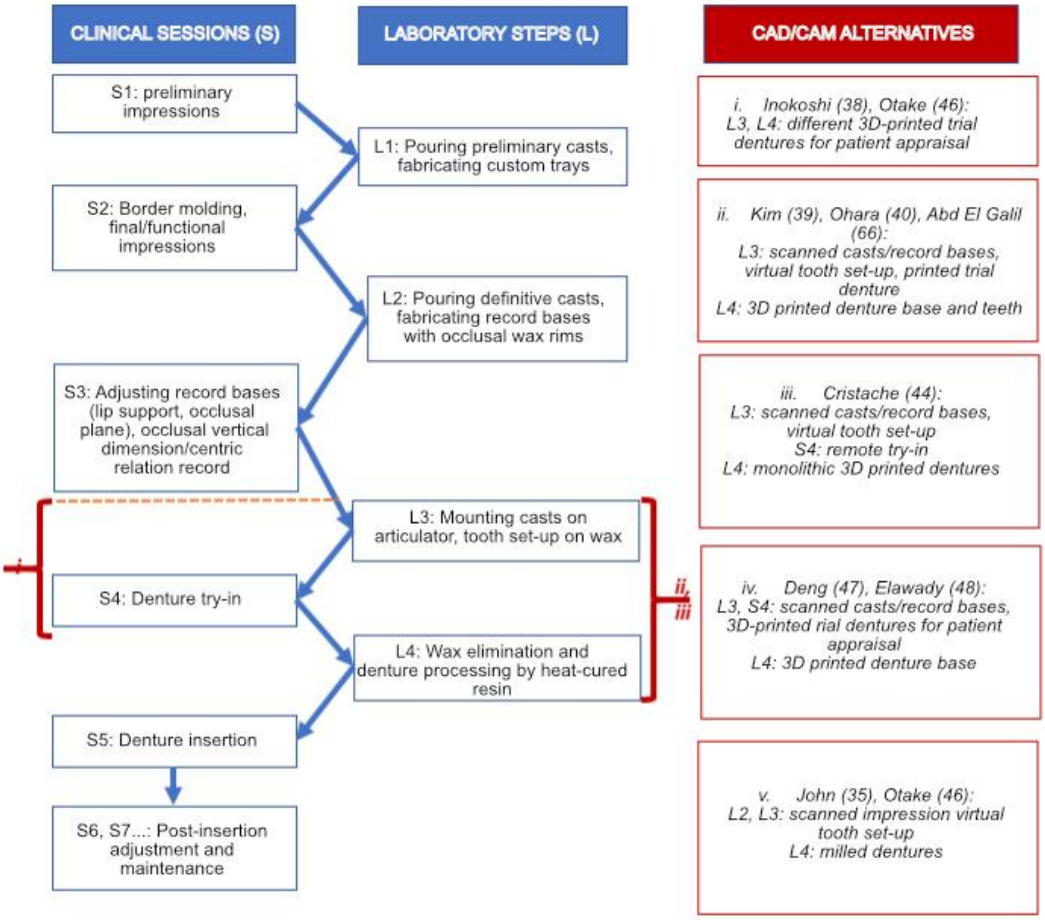

Figure 2. Typical conventional denture fabrication sequence and "open" CAD/CAM based alternatives used by included studies.

Figure 4-2. Open CAD/CAM technical workflow reported by included studies.

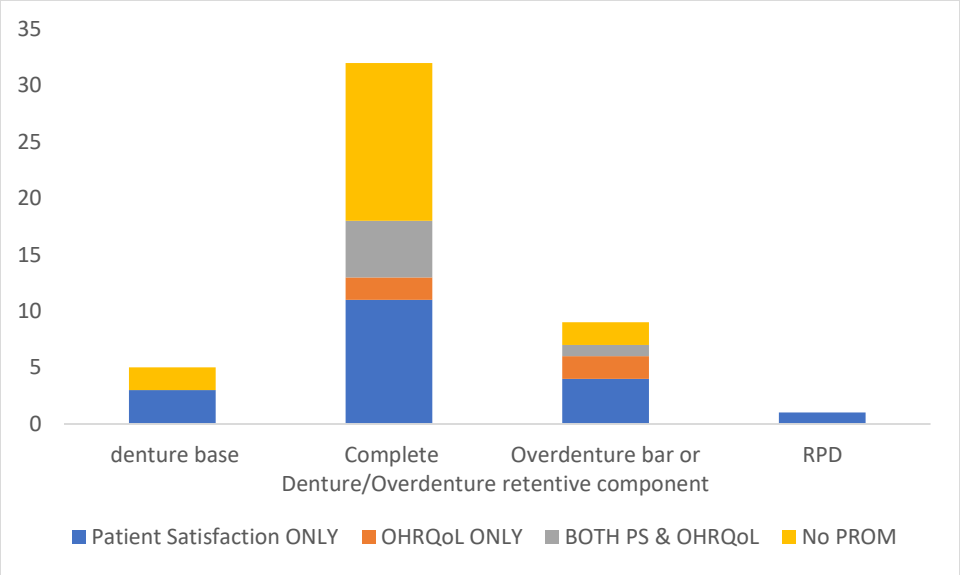

Figure 4-3. PROMs studies in each type of prosthesis.

5. Chapter 5: Manuscript III- CAD/CAM vs traditional complete dentures: a systematic review and meta-analysis of patient and clinician-reported outcomes, and costs

Through the comprehensive search of databases described in chapter 4, we found 11 studies on CAD/CAM complete dentures with similar outcomes of interest, the results of which could be pooled together and analyzed statistically. Therefore, we carried on a systematic review and meta-analysis to investigate the efficacy of the proposed interventions, and appraise the literature in a systematic methodology fashion. This chapter presents our meta-analysis paper which is under revision in the Journal of Oral Rehabilitation.

Title: CAD/CAM vs traditional complete dentures: a systematic review and meta-analysis of patient and clinician-reported outcomes, and costs

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Author Contributions:

DJ: conception and design, acquisition of data, analysis and interpretation of data, drafting the manuscript

PB: conception and design, analysis and interpretation of data

RS: conception and design, supervision, critical revision

Data availability statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

ABSTRACT

Statement of Problem. Computer-aided design and manufacturing (CAD/CAM) have been increasingly used to enhance the patient and clinician experiences with removable complete dentures (CDs). Yet, evidence from systematic reviews is lacking to validate the clinical significance of these digital prostheses.

Purpose. The purpose of this systematic review was to compare CAD/CAM CDs with the traditional ones in terms of patient and clinician-reported outcomes, post-insertion adjustment visits, and costs.

Material and Methods. An electronic search of four databases [Medline (Ovid), Embase, Scopus, and Cochrane CENTRAL; last update: May 2022] was performed to retrieve clinical studies comparing CAD/CAM and traditional CDs. Two independent reviewers screened the articles, extracted data (methods and outcomes) and assessed risk of bias of the included studies. The following outcomes underwent meta-analysis (random-effects model): overall patient and clinician satisfaction, oral health-related quality of life (OHRQoL), number of post-insertion adjustment visits, as well as laboratory and total costs.

Results. This review included 11 studies. Meta-analysis revealed that CAD/CAM CDs are comparable to the traditional CDs in terms of overall patient satisfaction and OHRQoL. Clinician-reported data depended on the manufacturing technique: whereas milled CDs performed better than traditional CDs in terms of clinician satisfaction and number of adjustments, 3D printed and traditional CDs were similar. Fabrication of CAD/CAM CDs required significantly less laboratory and overall costs than the traditional CDs.

Conclusions. There is some evidence showing that CAD/CAM CDs are at least comparable to traditional CDs. Further well-designed randomized clinical trials are needed to evaluate the performance of specific CAD/CAM approaches for manufacturing CDs, however.

Keywords. CAD/CAM, digital technology, complete denture, patient reported outcome measures, clinical performance

INTRODUCTION

The growth of the elderly population worldwide also increases the relevance of oral health issues associated with this community (1). Edentulism, or complete loss of all natural teeth, is one of the most important of those issues among the elderly (2). Besides leading to major disability, edentulism correlates with an earlier mortality (3). For decades, common oral rehabilitation modalities for the completely edentulous patients have included removable complete dentures (CDs). CDs are still widely used to rehabilitate edentulous patients and can restore the stomatognathic function and comfort (4).

Recent technology advances have led to the incorporation of computer-aided design and manufacturing (CAD/CAM) into the fabrication of CDs. Common CAD/CAM workflows for CDs include data collection (e.g., via intraoral scanners), CAD (e.g. design by a software), and CAM, which consists of two main methods: the additive (AM) and the subtractive (SM) manufacturing (5).

Previous primary studies and meta-analyses on the *in vitro* properties of digital CDs point toward favorable outcomes (6-10). However, to be translated into practice, those *in vitro* outcomes must also lead to clinically relevant advantages. One of the main goals of introducing computer-assisted technologies into CD fabrication is to benefit the patients and improve their access to oral healthcare (11-12). Thus, there is need to compare CAD/CAM CDs with the traditional ones with

respect to the clinically relevant outcomes. For this matter, our group first carried out a scoping review to map the existing literature on digital removable dentures and find knowledge gaps in the area. That review found controversial data on patient and clinician-related outcomes in the clinical studies comparing digital and traditional CDs (13).

Therefore, this systematic review aimed to compare the CAD/CAM and traditionally manufactured CDs in terms of overall patient and clinician satisfaction, number of post-insertion adjustments, and the laboratory/overall costs. The PICO-focused research question for this systematic review was: "Among completely edentulous patients, how different are CAD-CAM removable CDs from traditional CDs with respect to patient reported-outcomes, clinician satisfaction, number of post-insertion adjustments, and costs?" The null hypothesis was that no difference would be found in the overall patient and clinician satisfaction, patients' oral health-related quality of life (OHRQoL), number of post-insertion adjustments, and the laboratory/overall costs among patients rehabilitated with CAD/CAM CDs compared to those treated with traditional CDs.

MATERIAL AND METHODS

This quantitative systematic review with meta-analysis included clinical studies comparing CAD/CAM and traditional CDs. It was reported according to the 2020 updated PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) recommendations (14).

Eligibility criteria and search strategy

A set of eligibility criteria was defined before initiating the screening process. The eligibility criteria for the aspects of population, intervention, comparison, outcomes, and study design (PICOS) are depicted in Table 5-1. All (single-arm/controlled/cross-over) clinical trials or observational studies, comparing traditional dentures and CAD/CAM CDs in terms of patient- and

clinician-reported outcomes, number of adjustments, and costs were considered. Studies were excluded if they investigated partially edentulous patients, completely edentulous patients treated with fixed dental prostheses, or completely edentulous patients treated with implant-retained prosthesis. *In vitro* studies, other review articles, and case reports were also excluded.

A medical librarian (MM) carried out a systematic electronic literature search of Cochrane Central Register of controlled trials (CENTRAL), MEDLINE (Ovid), EMBASE, and SCOPUS databases. The search strategies consisted of two core concepts of CAD/CAM and removable dentures. A list of keywords and Medical Subject Headings (MeSH) along with truncation, adjacency functions, and Boolean operators were used to run the search strategy and were adapted according to each database (Table 5-2). The search was restricted to reports published from 01 January 2000 to 30 May 2022. Studies were filtered to include English, Arabic, French, Persian, Portuguese, or Spanish languages, considering the linguistic competency of the research team.

Two authors independently screened the titles and abstracts of the retrieved records according to the eligibility criteria. Any conflict between the reviewers was discussed and resolved by agreement. The full texts of the remaining relevant studies were retained for further review based on the same criteria. A study selection flow diagram was prepared according to PRISMA (Figure 5-1).

Assessment of methodological quality and risk of bias

The quality of included studies in this systematic review and meta-analysis was assessed by two independent reviewers (DJ and PB) based on a checklist created from the modified Jadad scale for reporting randomized controlled clinical trials (RCTs) and the Newcastle-Ottawa scale for assessing the quality of non-randomized studies in meta-analyses (15-16). We graded each element of the quality checklist as: high risk, low risk, or unclear risk. If the item was not applicable to the

study, the risk was marked as unclear. Discussions were held among all authors to solve any disagreements.

Data extraction and outcomes

For each study, the following data were extracted: authors, year, study design, sample size, population characteristics, study groups, type of digital workflow enlisting the manufacturer name, intervention characteristics, outcomes of interest (general patient satisfaction, OHRQoL, general clinician satisfaction, number of post-insertion adjustment visits, laboratory and total costs), data collection tool, and the follow-up period.

Statistical analysis and synthesis of results

The meta analyses were performed using the Review Manager software version 5.0 (17). Only clinical studies comparing traditional vs CAD/CAM dentures and reporting the same outcome of interest were included in the meta-analysis. Studies were pooled with mean differences and corresponding 95% confidence intervals (CIs) for continuous outcomes (DerSimonian and Laird method) (18).

To standardize the measurements in a scale-free measure, the effect sizes (ES) were calculated as standard mean differences (SMD) using Hedge's d. The magnitude of an ES has been described as small if it is 0.3, medium if it is 0.5, and large if it is 1.0 (19). In cases where medians and lower/upper range data were presented, the values were converted to means and Standard Deviations (SD) using the formula described by Hozo *et al*. (20). For the studies in which the results were reported as interquartile ranges, an approximation of the SD was calculated using the formula: $(q3 - q1)/1.35$ (21). For the data presented in boxplots, the webplotdigitizer platform was used to extract the data. Data obtained from Likert-type scales were transformed into visual analogue scales (VAS). Data extracted from the Oral Health Impact Profile (OHIP-49)

questionnaire were converted to the 20 item OHIP-EDENT scale (Min 0 to Max 80) (22). For the cost analysis, all data were transformed to US dollars.

Meta-analyses were performed using a random-effects model and an inverse variance weighting scheme (23). Given the small sample size (<30) of the included studies, and because of the different intervention effects in each study due to high heterogeneity, we used the random-effects model to account for inter-study variation (24).

The Cochran Q test, Higgins I^2 statistic, H^2 and τ^2 were used to handle heterogeneity between the studies (25). An α error of $P<0.20$ and I^2 of at 50% or more were considered as substantial heterogeneity. No further subgroup analysis or meta-regression was possible due to the limited number of studies and the insufficient power of the analysis. Sources of heterogeneity were, therefore, discussed descriptively (26,27). Moreover, the small number of included trials (<10) precluded the use of funnel plot analysis to rule out the publication bias (24). The fail-safe number was calculated instead to assess the potential retrieval and publication bias. This value estimates the number of missing studies that are required to turn the combined effect size of the included and missing studies insignificant (28).

RESULTS

Study characteristics

In total, 3126 articles were identified from the initial search strategies. After duplicate removal, 2271 abstracts remained for title and abstract screening. Eighteen studies were retained for full text review. Finally, 11 clinical studies were identified as suitable for inclusion in a series of meta-analyses (Figure 5-1). A total of 7 studies were excluded after full text screening due to: i) ineligible comparison group (29-33), and ii) having outcomes which were of no interest in this systematic review (34-35).

Of the included studies, three were cross-over RCTs (36-38), three were retrospective observational (39-41), two were prospective (42,43), one was cross-sectional (44), one was a non-randomized controlled clinical trial (45), and one was a parallel-arm RCT (46). The characteristics of these studies are described in Table 5-3. All studies were in English. The earliest study was published in 2012 (46), and the latest in 2022 (37,39).

The included clinical studies varied by study design, sample size, population characteristics, the type of CAD/CAM digital workflow used, the dentists providing the treatment, and the follow-up durations. Of the 11 included studies, five reported overall satisfaction ratings for CAD/CAM CDs and the traditional CDs (36,37,39,42,46), three assessed OHRQoL (36-38), three reported overall clinician satisfaction (36,42,46), four inspected the number of post-insertion adjustment visits between the dentures (37,41,44,45), and three compared the costs associated with the fabrication of these dentures (39,40,43).

Patient-reported outcomes

Patient satisfaction

Concerning the patient-reported outcome measures (PROMs), five clinical studies evaluated the patients' degree of satisfaction after they received rehabilitation treatment with CAD/CAM and traditional CDs (Table 5-3). Of these, two were cross-over RCTs (36,37), two were observational studies (39,42), and one was a parallel-arm RCT (46). The sample sizes in these studies ranged from n=10 to n=24 participants. All five studies were carried out at university dental clinics or hospitals. The inclusion criteria in all the included clinical studies were completely edentulous patients requiring a new set of maxillary and mandibular dentures. In three of the trials (36,39,46), the participants were already wearing traditional dentures before the initiation of the trial. Dentures were fabricated by prosthodontists (37,39,46) or pre-doctoral dental students (36,42). The digital

workflow adopted by these studies included 3D printing (36,37,46), AvaDent milling workflow (36,42), and a custom disk milling technique (39). Regarding the data collection and follow-up timeline, Kattadiyil *et al. (*42) reported that data collection took place after each denture was worn for one week whereas Srinivasan *et al. (*36) reported a six-week post-insertion follow-up data. No data on the length of follow-up was presented in the other three studies (37,39,46).

For all these clinical studies, the groups seemed comparable with respect to the primary outcomes. Three studies (37,39,46) calculated the overall satisfaction of these patients using a VAS with a numerical scale ranged from 0, meaning not satisfied at all, to 100, meaning total satisfaction. Two studies used a 5-point Likert rating scale from 0 to 4 (36,42) with the highest score corresponding to a high level of satisfaction. Data obtained from Likert-type scales were transformed into a 100-mm VAS and expressed in percentage for statistical analysis.

The patient satisfaction data from these five studies are summarized in Figure 5-2. Although the mean effect size was more inclined towards the traditional CDs when comparing traditional vs 3D printed CDs (ES: -0.88; 95% CI, -2.58 to 0.82; I^2=91%), and more towards the CAD/CAM CDs when comparing traditional vs milled CDs (ES: 0.62; 95% CI, 0.95 to 1.89; I^2=0%), their pooling showed no statistically significant difference in the mean overall patient satisfaction between CAD/CAM and traditional CDs (P=0.84). The pooled mean difference was -0.11 (95% CI, -1.15 to 0.93). The studies, which assessed this parameter, showed substantial heterogeneity (I^2 = 90%, τ^2 = 1.51, Q=52.02, P<0.001).

OHRQoL

The lack of evidence regarding this PROM was evident. We found three cross-over RCTs in which the OHRQoL was compared between the traditional and CAD/CAM CDs (36-38), one of which failed to report the overall quality of life scores. We estimated the sum score for that study by

adding all seven dimension scores (37). Of the three RCTs included in the meta-analysis, one evaluated the OHRQoL using the Oral Health Impact Profile, German version (OHIP-G49) (38), one (36) used the Oral Health Impact Profile for edentulous patients (OHIP-EDENT), and one used the Japanese version of OHIP-EDENT (OHIP-EDENT-J) (37). In all instruments, higher scores correspond to a lower quality of life. The studies also differed in regards to the data collection timeline. Peroz *et al. (*38) collected the data three months after the insertion of dentures, Srinivasan *et al. (*36) reported the 6-week post-insertion data and Ohara *et al.* (37) collected the data immediately after insertion. As shown in Figure 5-2, the results of pooled data revealed no significant difference between the CAD/CAM (milled or 3D printed) and traditional CDs in the overall assessment of the OHIP scores (pooled ES: 0.39; 95% CI, -0.28 to 1.05). There was high heterogeneity among studies evaluating the OHIP scores ($I^2 = 69\%$, $\tau^2 = 0.32$, $Chi^2=9.81$, P=0.02).

The study by Ohara *et al.* (37) showed that the social disability and the number of clinic visits were significantly lower in patients with 3D printed dentures. However, there were no significant differences between the CAD/CAM and the control groups in the other quality of life domains. The results of subgroup analysis across all three studies for the four clinically relevant OHIP dimensions proposed by John *et al*. (47) (physical pain, physical disability, psychological discomfort, and handicap) showed no significant difference between the CAD/CAM and conventional dentures (P>0.05).(See Appendix I)

Clinician-reported outcome

Clinician satisfaction

Three of the clinical studies assessing patient satisfaction also compared the overall clinician satisfaction ratings between CAD/CAM and traditional CDs (36,42,46). The clinician satisfaction assessment tool varied across the included studies. One study calculated the overall satisfaction of

clinicians using a 100-mm VAS (46), whereas the other studies used either a 5-point Likert rating scale from 0 to 4 (42) or a scale rating from 0 to 7 (36). The study by Inokoshi *et al. (*46) involved 20 certified prosthodontists ratings of 10 sets of CDs (rapid-prototyping vs traditional). Kattadiyil *et al. (*42) had two faculty prosthodontists grading 15 sets of CDs (AvaDent milled vs traditional). In the study by Srinivasan *et al.* (36), the 15 sets of CDs (traditional/milled/3DP) were assessed by a single experienced examiner with >10 years of clinical experience in removable prosthodontics.

The meta-analysis revealed that the overall clinician satisfaction with the milled CDs was significantly superior to the traditional CDs (ES: 1.42; 95% CI, 0.95 to 1.89; I^2=0%). The 3D printed CDs had the same clinician satisfaction ratings as the traditional CDs (ES: 0.56; 95% CI, -0.90 to 2.01; I^2=92%). In total, although slightly in favor of CAD/CAM, the pooled results showed no significant difference in the mean overall clinician satisfaction between the CAD/CAM and traditional CDs (P=0.07) (Fig. 5-2). The pooled ES was 0.98; 95% CI, -0.06 to 2.03. There was substantial heterogeneity between the studies assessing clinician satisfaction (I^2 = 93%, τ^2 = 1.03, Chi^2=45.15, P<0.001).

Number of post-insertion adjustment visits

Four studies have compared the traditional and CAD/CAM CDs in terms of the number of post-delivery adjustment visits. Of these, one was a cross-over RCT (37), one was a non-randomized controlled clinical trial (45), one was cross-sectional (44), and one was a retrospective observational study (41). The sample sizes in these studies varied from n=15 to n=420. Three studies were carried out at university dental clinics or hospitals (37,41,44), and one study was conducted in a private practice setting (45). The inclusion criteria of these studies were completely edentulous patients requiring a new set of maxillary and/or mandibular CDs. Dentures were made

by prosthodontists (37,45) or predoctoral dental students (41,44). The CAD/CAM workflow adopted by these studies included 3D printing (37,41), the AvaDent milling workflow (44), and an "open" milling workflow (45).

The meta-analysis showed that the milled CDs required significantly less post-insertion adjustment visits compared to the traditional CDs (ES= -0.68; 95% CI, -0.95 to -0.41; I^2=0%). The 3D printed CDs needed the same number of adjustments as the traditional CDs (ES= 0.06; 95% CI, -0.10 to 0.22; I^2=0%). In total, the results of the meta-analysis showed that CAD/CAM CDs are comparable with the traditional CDs regarding the number of post-insertion adjustments (P=0.21) (Fig. 5-2). The mean effect size was -0.31 (95% CI, -0.79 to 0.17).

Costs

A total of three studies including one prospective (43) and two retrospective (39,40) observational clinical studies have investigated the laboratory and total costs involved in fabricating CAD/CAM and traditional CDs. The sample size ranged from n=6 to n=24 in these studies. Dentures were fabricated by either certified prosthodontists (39,40), or dental students (43), all carried out in University clinics. The study by Srinivasan *et al. (*43) reported the costs in two different groups: i) maxillary CDs, ii): maxillary and mandibular CDs. All the included studies used the subtractive digital workflow (milling), which comprised of the AvaDent system (40,43) Wieland Digital Denture (40), or an "open" custom-disk milling method (39).

Laboratory costs

As shown in Figure 5-2, the laboratory costs were found significantly lower for CAD/CAM CDs compared to the traditional dentures (P<0.001). The mean effect size was -5.92 (95% CI, -9.58 to -2.26). Summary of the meta-analysis showed that the laboratory costs of CAD/CAM dentures

were 39.53% lower than the traditional CDs. Substantial heterogeneity was observed between the studies evaluating the laboratory costs (I^2 = 95 %, τ^2 = 12.66, Q=62.59, P<0.001).

Total costs

The total costs included the sum of clinical and laboratory costs. As illustrated in Figure 5-2, the total costs of fabricating a traditional denture was found significantly higher than the digital CDs (P=0.02). The mean effect size was -1.54 (95% CI, -2.84 to -0.23). The total fabrication costs of the CAD/CAM dentures were 22.44% lower than the traditional CDs. The studies showed substantial heterogeneity, as expected (I^2 = 87%, τ^2 = 1.46, Q=23.01, P<0.001).

Methodological quality

As shown in figure 5-3, risk of bias varied among the included studies. Since most of the studies were observational, they were mostly classified as having low methodological quality. In addition, the results of quality appraisal indicated lack of proper randomization in the included RCTs. Furthermore, lack of blinding was observed in most of the included clinical studies. Lack of appropriate follow-up data was identified across half of the studies. Statistical analyses were satisfactory in all included studies.

Although not a source of bias per se, we evaluated the sample size estimation of included studies. Proper sample size estimation was lacking from the trials. Results from studies on patient satisfaction with CDs suggest that n=26 per group are sufficient to detect a clinically meaningful difference in satisfaction (20mm of a 100-mm VAS), considering 80% power with a type I error of 0.05, and 20% of dropouts (48,49). Given this calculation, the sample size of only one of the clinical trials evaluating patient satisfaction could be considered large enough to detect clinically meaningful differences (39).

Publication bias

The fail-safe number was calculated as 1 for the overall patient satisfaction and OHRQoL, showing concerns about the influence of publication bias on the outcome. However, the fail-safe number for the overall clinician satisfaction, the number of adjustment visits, laboratory costs, and total costs were 16, 10, 186, and 67, respectively. Therefore, the risk for publication bias was considered low.

DISCUSSION

CAD/CAM CDs have been suggested as an alternative to the traditionally fabricated dentures, especially when time and access to care are of major concern. CAD/CAM techniques can save resources by reducing chairside time and enabling virtual/online appointments (11,12). However, before using them as replacement for the traditional CD fabrication methods, it is as important to verify if they provide the patients with a quality of care which is at least comparable to standard treatment. Therefore, this systematic review and meta-analysis compared the CAD/CAM and traditional CDs in terms of patient- and clinician-reported outcomes and to determine whether these CDs differ in terms of the number of post-insertion adjustments and the costs. The null hypotheses of no between-treatment difference was partially rejected. The meta-analyses revealed that the costs of CAD/CAM CDs were significantly lower than with traditional ones, whereas patient and clinician-reported outcomes generally yielded similar results.

Numerous factors affect the clinical performance of CDs and no single criteria can gauge that. While some studies rely on PROMs to assess the performance of a denture (37,39), others investigate clinical factors (e.g. fit/retention/esthetics) or the amount of adjustments/repairs/remakes required (45,50). Although previous meta-analyses have investigated the *in vitro* properties of the CAD/CAM dentures (6,7), the amount of evidence for the patient- and clinician-reported outcomes is still low. The only published meta-analysis targeting PROMs

compared the esthetics between CAD/CAM and traditional dentures in two studies (6). They reported that while traditional CDs were superior to 3D-printed in terms of patient satisfaction with esthetics in the study by Inokoshi *et al.* (46), there was no significant difference when milled and injection-molded CDs were compared in a study by Schwindling *et al.* (50). It is noteworthy to mention that the researchers carried out their meta-analysis based on the assumption that in the Schwindling study, the milled group is CAD/CAM and the control is non- CAD/CAM. However, the CAD/CAM technique was used in the fabrication of both tested groups in their study.

To our best knowledge, this meta-analysis is the first to provide a broad perspective of PROMs of patients wearing CAD/CAM CDs, i.e., with data for overall patient satisfaction and OHRQoL. Regarding both outcomes, results were comparable for CDs fabricated by CAD/CAM technology and those made by the traditional methods. Different CAD/CAM techniques had influence on patient satisfaction, however. Patient satisfaction was more inclined towards the traditional CDs when compared to 3D printed CDs, but better with milled CDs. The inferior satisfaction with 3D printed dentures in the studies by Inokoshi *et al.* (46) and Ohara *et al.* (37) could be attributed to the lower esthetics ratings. Fully 3D printed CDs may have inferior esthetics due to monochromatic artificial teeth (5), and higher susceptibility to discoloration.51 The inferior scores for CAD/CAM CDs observed in Otake *et al.* (39) could be explained by the differences in the characteristics of the tested groups. That was a retrospective study with a between-group pretreatment imbalance in satisfaction scores, and CDs fabricated in different moments for each group. In summary, our findings showed that irrespective of the CAD/CAM workflow, dentures made with this technology are non-inferior to the traditional ones in regards to the patient satisfaction and OHRQoL.

Data on the clinician-reported outcomes are also scarce. Our analysis showed that the clinicians' overall satisfaction with the milled CDs was significantly superior to the traditional CDs, and the 3D printed CDs had the same clinician satisfaction ratings as the traditional CDs. While the milling technique has now become well established in the clinical practice, the 3D printing technique, despite its inherent advantages, is still in the inception phase. *In vitro* studies have shown that milled dentures demonstrate physical properties equal to or superior than those of traditional CDs and 3D printed dentures (6,9,10). Moreover, better color stability of milled CDs could be a potential reason for the high clinician satisfaction ratings with the milled CDs (36,37). Nevertheless, from a clinical standpoint, both types of CAD/CAM CDs are judged of high quality by the clinicians and can be regarded as non-inferior to the traditional manufacturing technique.

In terms of the post-insertion adjustment visits, the results of this meta-analysis showed that the milled CDs required significantly less adjustment visits compared to the traditional CDs. On the other hand, the 3D printed CDs needed the same number of adjustments as the traditional CDs. Several factors determine the number of post-insertion adjustment visits required for a denture, one of which is the used technique and protocol. In addition, complexity of the jaw anatomy, patient compliance skills, and the clinician expertise also play a crucial role in determining the number of post-op visits (45). All these factors could have influenced the results of this meta-analysis, suggesting less post-insertion adjustment with milled CDs and similar clinical findings for the 3D printed CDs when compared to the traditional CDs.

Regarding the fabrication costs, our findings were in line with those of Srinivasan *et al.* (6) who also showed that manufacturing digital dentures required lower costs compared to the traditional dentures. Conventional methods of fabricating a denture require several manual steps and processes, most of which can be automated in the CAD/CAM workflows, resulting in less

material waste and higher time saving for the dental laboratory technician. This material and labor cost saving will ultimately lead to a reduction in the laboratory costs. The clinical costs could not be evaluated separately in this meta-analysis due to the inconsistency in reporting the costs attributed to the clinic. Yet, the analysis of total costs (including the sum of clinical and laboratory costs) was also in favor of the CAD/CAM techniques.

Some limitations should be considered when interpreting the results of these meta-analyses. Despite of the systematic search strategy, which yielded an extensive number of publications, few RCTs were included. While the fail-safe analyses ruled out any publication bias for the studies evaluating several outcomes (i.e., clinician satisfaction, number of adjustments, and costs), it disclosed a potential bias for trials investigating the PROMs. The latter finding suggests the possibility of missing reports due to negative findings. Furthermore, our findings can be limited by any errors in the quality of the included studies. The results of quality appraisal revealed a low methodological quality due to the observational nature of most of the included studies as well as a lack of appropriate randomization and blinding in the included RCTs.

Our meta-analysis revealed that, although the overall ES for patient satisfaction was comparable between the CAD/CAM and traditional workflows, the magnitude of effect substantially varied among the studies. Similar to any meta-analysis involving clinically heterogeneous trials (27), the inconsistency in our included studies was foreseeable. Yet, this substantial heterogeneity should not be disregarded. The clinical studies included in this meta-analysis differed in the study design, patient characteristics, the expertise of clinicians, the time of denture fabrication, data collection tools (VAS/Likert scale), the duration of follow-up, and the digital workflow implemented. Therefore, the present heterogeneity could be attributed to both the methodological heterogeneity, meaning the variability in study design and quality among the

included studies, as well as the biological heterogeneity, meaning the variability observed in participants and the interventions. For instance, the inclusion of participants who did not have previous dentures is expected to increase the patient satisfaction scores when compared to their existing oral condition, although it might increase the potential for selection bias in that population. No further subgroup analysis was possible to explore the heterogeneity due to the small number of studies in each arm (<3) and the low power of analysis. However, as mentioned, the difference in the patient characteristics (previous edentulism/socioeconomic status/gender), as well as the type of digital workflow (milling/3D printing) could be one of the explanatory factors for the detected heterogeneity. Moreover, the study size can be considered as the main source of heterogeneity in these series of meta-analyses as small studies tend to exaggerate the effect and most of the included studies were of small sample size. In the studies evaluating the fabrication costs, a substantial heterogeneity was expected due to the difference in the currency values pertaining to the country in which each research was conducted.

Caution should be taken in drawing conclusions from the summary results when the number of RCTs are limited. In such cases, the results could be used along the judgment and expertise of the clinicians for clinical decision-making, and the interpretations regarding the sources of heterogeneity could be reflected in future research as potential hypotheses (26). There is a need for well-designed RCTs with large sample size and adequate power as well as long-term performance evaluation of CAD/CAM CDs to be able to draw definitive conclusions and establish clinical practice guidelines.

CONCLUSIONS

The results of this systematic review and meta-analysis revealed that CAD/CAM CDs have significantly lower fabrication costs compared to the traditional dentures, with comparable patient

and clinician satisfaction ratings, OHRQoL, and number of adjustment visits. Thus, it can be concluded that CAD/CAM CDs are not inferior when compared to the traditional CDs and can be suggested as a promising treatment modality for the edentulous patients, given the lower costs associated with this treatment and the potential for better access to care for the elderly. It seems that patients are still concerned about the 3D printed CAD/CAM prosthesis when it comes to esthetics. There is need for further adequately powered well-designed RCTs to gauge the patient- and clinician-reported outcomes, and to verify the magnitude of effect for the assessed parameters.

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REFERENCES

1. Steele J, Treasure E, O'sullivan I, Morris J, Murray J. Adult dental health survey 2009: Transformations in British oral health 1968–2009. Br Dent J 2012;213:523—7.

2. World Health Organization. Working together for health: the World health report 2006: policy briefs. World Health Organization; 2006.

3. Holm-Pedersen P, Schultz-Larsen K, Christiansen N, Avlund K. Tooth loss and subsequent disability and mortality in old age. J Am Geriatr Soc 2008;56:429—35.

4. Carlsson G, Omar R. The future of complete dentures in oral rehabilitation. A critical review. J Oral Rehabil 2010;37:143—56.

5. Anadioti E, Musharbash L, Blatz MB, Papavasiliou G, Kamposiora P. 3D printed complete removable dental prostheses: A narrative review. BMC Oral Health 2020;20:1—9.

6. Srinivasan M, Kamnoedboon P, McKenna G, Angst L, Schimmel M, Özcan M, et al. CAD-CAM removable complete dentures: A systematic review and meta-analysis of trueness of fit, biocompatibility, mechanical properties, surface characteristics, color stability, time-cost analysis, clinical and patient-reported outcomes. J Dent 2021;113:103777.

7. de Oliveira Limírio JPJ, de Luna Gomes JM, Rezende MCRA, Lemos CAA, Rosa CDDRD, Pellizzer EP. Mechanical properties of polymethyl methacrylate as a denture base: Conventional versus CAD-CAM resin–A systematic review and meta-analysis of in vitro studies. J Prosthet Dent 2021.

8. Wang C, Shi Y-F, Xie P-J, Wu J-H. Accuracy of digital complete dentures: a systematic review of in vitro studies. J Prosthet Dent 2021;125:249—56.

9. Srinivasan M, Gjengedal H, Cattani-Lorente M, Moussa M, Durual S, Schimmel M, et al. CAD/CAM milled complete removable dental prostheses: An in vitro evaluation of biocompatibility, mechanical properties, and surface roughness. Dent Mater J 2018; 2017:207.

10. Kalberer N, Mehl A, Schimmel M, Müller F, Srinivasan M. CAD-CAM milled versus rapidly prototyped (3D-printed) complete dentures: an in vitro evaluation of trueness. J Prosthet Dent 2019;121:637—43.

11. Steinmassl P-A, Klaunzer F, Steinmassl O, Dumfahrt H, Grunert I. Evaluation of currently available CAD/CAM denture systems. Int J Prosthodont 2017;30:116—22.

12. Hassan B, Greven M, Wismeijer D. Integrating 3D facial scanning in a digital workflow to CAD/CAM design and fabricate complete dentures for immediate total mouth rehabilitation. J Adv Prosthodont 2017;9:381—6.

13. Jafarpour D, deSouza R, Morris M. Patient-Reported Outcomes and Clinical Performance of CAD/CAM Removable Dentures: a Scoping Review. 2022 AADOCR/CADR Annual Meeting: International Association for Dental Research; 2022.

14. Page M, Moher D, Bossuyt P, Boutron I, Hoffmann T, Mulrow C. PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. Br Med J 2021; 372:160.

15. Stephen H, Halpern M, Joanne D. Jadad scale for reporting randomized controlled trials. Oxford, UK: Blackwell Publishing Ltd; 2005.

16. Wells GA, Shea B, O'Connell D, Peterson J, Welch V, Losos M, et al. The Newcastle-Ottawa Scale (NOS) for assessing the quality of nonrandomised studies in meta-analyses. Oxford; 2000.

17. Cochrane T. Review Manager (RevMan) 5.3. Copenhagen: The Nordic Cochrane Centre. 2008;373.

18. DerSimonian R, Laird N. Meta-analysis in clinical trials. Control Clin Trials 1986;7:177—88.

19. Cohen J. Statistical power analysis for the behavioral sciences Lawrence Earlbaum Associates. 20th–. Lawrence Earlbaum Associates; 1988.

20. Hozo SP, Djulbegovic B, Hozo I. Estimating the mean and variance from the median, range, and the size of a sample. BMC Med Res Methodol 2005;5:1—10.

21. Greco T, Biondi-Zoccai G, Gemma M, Guérin C, Zangrillo A, Landoni G. How to impute study-specific standard deviations in meta-analyses of skewed continuous endpoints? World J Meta-Anal 2015;3:215—24.

22. Allen F, Locker D. A modified short version of the oral health impact profile for assessing health-related quality of life in edentulous adults. Int J prosthodont 2002;15:5.

23. Higgins JP, Thomas J, Chandler J, Cumpston M, Li T, Page MJ, et al. Cochrane handbook for systematic reviews of interventions: John Wiley & Sons; 2019.

24. Higgins JP, Green S, Scholten R. Maintaining reviews: updates, amendments and feedback. Cochrane handbook for systematic reviews of interventions. 2008:31.

25. Higgins JP, Thompson SG. Quantifying heterogeneity in a meta-analysis. Stat Med 2002;21:1539—58.

26. Thompson SG. Systematic Review: Why sources of heterogeneity in meta-analysis should be investigated. Br Med J 1994;309:1351—5.

27. Hardy RJ, Thompson SG. Detecting and describing heterogeneity in meta-analysis. Stat Med 1998;17:841—56.

28. Orwin RG. A fail-safe N for effect size in meta-analysis. J Educ Stat 1983;8:157—9.

29. Bidra AS, Farrell K, Burnham D, Dhingra A, Taylor TD, Kuo C-L. Prospective cohort pilot study of 2-visit CAD/CAM monolithic complete dentures and implant-retained overdentures: Clinical and patient-centered outcomes. J Prosthet Dent 2016;115:578—86.

30. Schlenz MA, Schmidt A, Wostmann B, Rehmann P. Clinical performance of computer-engineered complete dentures: a retrospective pilot study. Quintessence Int 2019;50:706—11.

31. Saponaro PC, Yilmaz B, Johnston W, Heshmati RH, McGlumphy EA. Evaluation of patient experience and satisfaction with CAD-CAM-fabricated complete dentures: A retrospective survey study. J Prosthet Dent 2016;116:524—8.

32. Elawady DM, Ibrahim WI, Osman RB. Clinical evaluation of implant overdentures fabricated using 3D-printing technology versus conventional fabrication techniques: a randomized clinical trial. Int J Comput Dent 2021;24:375—84.

33. Deng K, Chen H, Wang Y, Zhou Y, Sun Y. Evaluation of functional suitable digital complete denture system based on 3D printing technology. J Adv Prosthodont 2021;13:361—72.

34. Smith PB, Perry J, Elza W. Economic and Clinical Impact of Digitally Produced Dentures. J Prosthodont 2021;30:108—12.

35. Chaturvedi S, Addas MK, Alqahtani NM, Al Ahmari NM, Alfarsi MA. Clinical analysis of CAD-CAM milled and printed complete dentures using computerized occlusal force analyser. Technol Health Care 2021;29:797—811.

36. Srinivasan M, Kalberer N, Fankhauser N, Naharro M, Maniewicz S, Muller F. CAD-CAM complete removable dental prostheses: A double-blind, randomized, crossover clinical trial evaluating milled and 3D-printed dentures. J Dent 2021;115:103842.

37. Ohara K, Isshiki Y, Hoshi N, Ohno A, Kawanishi N, Nagashima S, et al. Patient satisfaction with conventional dentures vs. digital dentures fabricated using 3D-printing: A randomized crossover trial. J Prosthodont Res 2022; JPR_D_21_00048.

38. Peroz S, Peroz I, Beuer F, Sterzenbach G, von Stein-Lausnitz M. Digital versus conventional complete dentures: A randomized, controlled, blinded study. J Prosthet Dent 2021;8.

39. Otake R, Kanazawa M, Iwaki M, Soeda Y, Hada T, Katheng A, et al. Patient-reported outcome and cost-effectiveness analysis of milled and conventionally fabricated complete dentures in a university clinic: A retrospective study. J Prosthet Dent 2022;16.

40. Arakawa I, Al-Haj Husain N, Srinivasan M, Maniewicz S, Abou-Ayash S, Schimmel M. Clinical outcomes and costs of conventional and digital complete dentures in a university clinic: A retrospective study. J Prosthet Dent 2021;128:390—95.

41. Kim TH, JungHuh B, Lee J, Bae EB, Park CJ. Retrospective Comparison of Postinsertion Maintenances Between Conventional and 3D Printed Complete Dentures Fabricated In A Predoctoral Clinic. J Prosthodont 2021; 30:158—62.

42. Kattadiyil MT, Jekki R, Goodacre CJ, Baba NZ. Comparison of treatment outcomes in digital and conventional complete removable dental prosthesis fabrications in a predoctoral setting. J Prosthet Dent 2015;114:818—25.

43. Srinivasan M, Schimmel M, Naharro M, O' Neill C, McKenna G, Müller F. CAD/CAM milled removable complete dentures: time and cost estimation study. J Dent 2019;80:75—9.

44. Clark WA, Brazile B, Matthews D, Solares J, De Kok IJ. A Comparison of Conventionally Versus Digitally Fabricated Denture Outcomes in a University Dental Clinic. J Prosthodont 2021;30:47—50.

45. Drago C, Borgert AJ. Comparison of nonscheduled, postinsertion adjustment visits for complete dentures fabricated with conventional and CAD-CAM protocols: A clinical study. J Prosthet Dent 2019;122:459—66.

46. Inokoshi M, Kanazawa M, Minakuchi S. Evaluation of a complete denture trial method applying rapid prototyping. Dent Mater J 2012;31(1):40—6.

47. John MT, Omara M, Su N, List T, Sekulic S, Häggman-Henrikson B, et al. Recommendations for use and scoring of oral health impact profile versions. J Evid-Based Dent Pract 2022; 22:101619.

48. Ellis JS, Burawi G, Walls A, Thomason JM. Patient satisfaction with two designs of implant supported removable overdentures; ball attachment and magnets. Clin Oral Implants Res 2009;20:1293—8.

49. de Souza RF, Bedos C, Esfandiari S, Makhoul NM, Dagdeviren D, Abi Nader S, et al. Single-implant overdentures retained by the Novaloc attachment system: study protocol for a mixed-methods randomized cross-over trial. Trials 2018;19:1—11.

50. Schwindling FS, Stober T. A comparison of two digital techniques for the fabrication of complete removable dental prostheses: A pilot clinical study. J Prosthet Dent 2016;116:756—63.

51. Gruber S, Kamnoedboon P, Özcan M, Srinivasan M. CAD/CAM complete denture resins: an in vitro evaluation of color stability. J Prosthodont 2021;30:430—9.

TABLES

Table 5-1. Search strategy in Medline (Ovid), consisted of terms representing our population of interest, interventions, and comparators; search date: 30 May 2022.

1.	exp Denture, Complete/
2.	exp Denture, Partial, Removable/
3.	((removable or complete or partial or conventional) adj3 (denture? or prosthes?s)).tw,kf.
4.	exp Jaw, Edentulous/
5.	edentulous.tw,kf.
6.	or/1-5
7.	"CAD/CAM".tw,kf.
8.	exp Computer-Aided Design/
9.	(computer-aid* or computer-assist* or computer-engineer*).tw,kf.
10.	(3D-print or milled or rapid prototyp* or additive manufactur*).tw,kf.
11.	digital*.tw,kf.
12.	or/7-11
13.	6 and 12
14.	limit 13 to yr="2000 -Current"
15.	limit 14 to (arabic or english or french or persian or portuguese or spanish)
16.	"in-vitro".ti.
17.	15 not 16

Table 5-2. Eligibility criteria (PICOS) for the present systematic review.

Domain	Inclusion Criteria	Exclusion Criteria
Participants	Patients who needed a complete removable denture for least one completely edentulous jaw	- Partially edentulous patients - Patients in need of implant-retained CDs, RPDs, Fixed prosthesis
Intervention	CD made by CAD/CAM technology, e.g., design by software and milled/3D printed denture bases, frameworks and teeth	-
Comparison	CD made by conventional technique	-
Outcome	Overall patient satisfaction, OHRQoL, overall clinician satisfaction, number of post-insertion adjustment visits, laboratory and total costs	-
Study Design	Randomized/nonrandomized clinical trials, cross-over clinical trials, prospective/retrospective clinical trials, cross-sectional clinical studies	In-vitro studies, ex-vivo studies, animal studies, non-comparative studies, case reports, case series, narrative reviews, systematic reviews with or without meta-analysis, letters to the editors, short communications

Table 5-3. The characteristics of the included studies

Study design	Study (year)	Study objectives	Study sample	Type of Intervention (Study groups)	Type of outcome assessed	Data collection tools	Data collection timeline	Key findings
Prospective observational clinical study	Kattadiyil et al[42] (2015)	"to compare clinical treatment outcomes, patient satisfaction, and dental student preferences for digitally and conventionally processed CRDP in a predoctoral setting"	15 completely edentulous patients	All Patients received: G1: Maxillary and mandibular conventional complete denture (n=15) G2: Milled maxillary and mandibular digital (AvaDent) complete denture (n=15)	a. Faculty satisfaction (denture base contour, teeth arrangement, fit, retention, extension, stability, esthetics, lip support, and prognosis, centric relationship, occlusion, occlusal vertical dimension (OVD), phonetics, and overall result) b. Patient rating and preference c. Predoctoral dental student satisfaction b. Clinical performance	a. A 5-point Likert rating scale from 0 to 4 b. A 5-point Likert rating scale from 0 to 4 c. Student questionnaire b. Clinical outcomes were evaluated independently by 2 experienced prosthodontists	After fabrication and immediately after placement	-Faculty satisfaction regarding the denture base contour, fit, extension, stability, retention, and overall result: G2>G1 (P<0.05). -Faculty satisfaction regarding quality of tooth arrangement, esthetics, lip support, occlusion, phonetics, accuracy of centric relation, appropriate OVD, and prognosis: G1=G2 (P>0.05). - Patient satisfaction regarding comfort, chewing efficiency, prosthesis selected, and efficiency of technique, and overall patient satisfaction: G2>G1 (P<0.05) -Patient preference regarding appearance (esthetics): G1=G2 (P=0.763). -Student preference (as being easier to perform & the technique they would use in their practice: G2>G1 (P=.007, P-0.035, respectively) -The average clinical time was 205 minutes longer for G1 than for G2 (P=.003).
	Srinivasan et al[43] (2019)	"to compare the clinical time spent and the costs incurred whilst constructing complete dentures (CDs) using a two-visit digital-denture protocol with the conventional complete denture protocol, in a university setting"	-	G1: Maxillary conventional CD (n=18) G2: Maxillary digital (AvaDent) CD (n=18) G3: Mandibular conventional CD (n=12) G4: Mandibular digital (Avadent) CD (n=12)	Overall time spent and costs (clinical, materials, and laboratory)	Estimated hourly labor cost formula	After sixth and final clinical visit	-Conventional complete denture protocol required longer clinical time than digital complete dentures -The materials costs were higher for the digital complete dentures -The overall costs, were significantly higher for the conventional complete denture protocol than for the digital denture
Retrospective observational clinical study	Otake et al[39] (2022)	"to evaluate general patient satisfaction with complete dentures fabricated through the custom disk method"	44 edentulous patients (mean age=75.6±8.4)	G1: Custom disk (digital) dentures (n=20) G2: Conventional dentures (n=24) (Digital workflow: Scanned and designed by the 3shape software and printed with Form3)	a. General patient satisfaction b. Cost-effectiveness	a. VAS b. Incremental cost-effectiveness ratio	Patient satisfaction was evaluated before and after denture fabrication	-General patient satisfaction: G1>G2 (P=.002) -The median labor costs: G2>G1 (P<0.001) -The incremental cost-effectiveness ratio was −251.4.
	Arakawa et al[40] (2021)	"to compare the treatment duration, financial costs, and postdelivery adjustments of CAD-CAM and conventional removable complete dentures"	32 edentulous participants	G1: CAD-CAM milled maxillary and mandibular CDs: DDS-AV (AvaDent) (n=11) or DD-IV (Wieland) (n=5) G2: Conventional maxillary and mandibular removable complete dentures (n=16)	a. Total treatment period (days) b. Adjustments including removal of areas of excessive pressure, relining, or repairs. c. Costs of the dental treatment and the laboratory fees	-	The total treatment period was recorded at 3 different time points (T0: preliminary alginate impression; T1: denture delivery; T2: last scheduled post-delivery adjustment).	-The treatment duration: G1=G2 (T0-T1 (P=.889); T1-T2 (P=.675); T2-T3 (P=.978)) - The number adjustments for areas of excessive pressure, relines, or repairs: G1=G2 (P=.757, P=1.000, P=1.000, respectively) - Laboratory costs: G1<G2 (P<0.001) - Clinical fees G1=G2 (P=0.596) - The number of clinical visits: G1=G2, DDS-AV=DD-IV (P=.945, P=0.848, respectively)
	Kim et al[41] (2021)	"to analyze the clinical performance of 3D printed complete dentures in edentulous patients compared with conventional complete dentures regarding post insertion visits and patient reported outcomes"	edentulous patients treated with complete dentures between the years of 2015 to 2018.	G1:420 (maxilla 270, mandible 150) heat-polymerized conventional complete dentures G2:217 (maxilla 130, mandible 86) 3D printed (Dentca) complete dentures (PCD) using Zenith SLA 3D printer	a. Number of remake b. Number of post insertion adjustments c. type and number of repairs d. Patient reported complications	Data were extracted via the electronic patient charts		-The number of post insertion adjustments and frequency of reline: G1=G2 (P>0.05) -In both groups, the two post-insertion internal adjustments of the denture base was the most common. -Pain and visible ulcer lesion in both maxilla and mandible: G1>G2 (P<0.05) -Discomfort in mandible: G1>G2 (P=0.026) -Esthetic in mandible: G1>G2 (P=0.047)
Cross-sectional observational study	Clarke et al[44] (2021)	"to evaluate if there is a difference in number of visits (including fabrication and postoperative) and remake rate when comparing conventionally fabricated and digitally fabricated complete dentures by dental students in a	314 patients receiving maxillary and/or mandibular complete dentures between 2017 and 2019 at the UNC Adams School of Dentistry	G1: conventional dentures (n=242) G2: digital dentures (AvaDent) (n=39)	The number of patient appointments from preliminary impressions to denture placement, the number of postoperative visits, any complications noted, and any need for remakes	Data were extracted via the electronic health record		-6 or more visits from preliminary impression to placement: 50% of G1 , 5% of G2 ($p < 0.05$). -Postoperative visits: G1 had an average of 2-3, whereas G2 required 1-2 ($p < 0.05$). -The number of dentures requiring remake: G1=G2 ($p = 0.1904$).

		predoctoral student dental clinic"	predoctoral student clinic.					
	Ohara et al[37] (2022)	"to evaluate patient satisfaction with conventional dentures (CDs) and digital dentures (DDs) fabricated using 3D printing."	20 edentulous patients	G1: Digital dentures followed by Conventional (n=6) G2: Conventional dentures followed by digital (n=9) (Digital workflow: 3D printed Dima denture base try-in; Kulzer Japan, Co., Ltd., Tokyo, Japan)	a. Patient satisfaction (chewing efficiency, pain, stability, retention, comfort, esthetics, ease of cleaning, phonetics, and general satisfaction) b. Quality of life (QOL) c. number of visits, time required for definitive denture fabrication, number of adjustment appointments, and time required for denture stabilization after denture delivery	a. VAS b. OHIP-EDENT-J c. Stopwatch	-	- Patient satisfaction in regards to phonetics, ease of cleaning, stability, comfort, and general satisfaction: CD>DD (P<0.05) - Social disability and the number of clinic visits: CD>DD (P<0.05) -The number of visits needed for denture fabrication, including the number of remakes: CD>DD (P<0.05) - No significant differences in the number of adjustment visits and the time needed for denture fabrication and adjustment between CDs and DDs
Randomized crossover clinical trial	Peroz et al[38] (2021)	"to evaluate the impact of the digital versus conventional production of complete dentures on oral health-related quality of life (OHRQoL) measures"	16 edentulous patients	16 participants received 2 sets of new complete dentures produced with: G1: Baltic Denture System digital workflow (2 visits) G2: Conventional workflow (5 visits)	a. OHRQoL b. The time needed for the fabrication process.	a. Oral Health Impact Profile, German version (OHIP-G49) b. The estimated working time provided by the dentist and the technician	Baseline, 14 days, and 3 months after insertion of each denture	- The median and the sum scores of the OHIP-G49 dimensions: G1=G2 (P>.05) --Digital dentures were manufactured within 4 hours, while conventional dentures took 10.5 hours.
	Srinivasan et al[36] (2021)	"to compare the differences between milled and 3D-printed complete removable dental prostheses"	15 edentulous patients	15 patients received 2 sets of dentures: G1: AvaDent Milled denture G2: NextDent 3D-printed denture	a. Patient's denture satisfaction (PDS) b. Oral-health related quality of life) c. Willingness-to-pay analysis d. Final choice (FC) of CRDPs e. Clinician's denture quality evaluation (CDQE) f. Chewing efficiency (CE) g. Maximum-voluntary-bite-force (MBF) h. Prosthodontic maintenance needs	a. 5-point Likert questionnaire b. (OHIP-EDENT c. An open-ended contingency valuation (CV) method of questioning d.- e. A dichotomous scale (0 to 7) f. Validated two-color mixing test g. Digital force gauge h. Noted by the clinician	a,b,e,f,g were assessed at 1- and 6-weeks post insertion of each denture	- PDS, OHIP, FC, CDQE, CE, and MBF: G1=G2 - Maintenance visits, adjustment time: G2>G1 (p = 0.0003) - Adjustment costs: G2>G1 (p = 0.021). - Patients were willing-to-pay an average of 606.67 Swiss Francs more than the actual cost for the milled CRDPs.
Non-randomized controlled clinical trial	Drago & Borgert[45] (2019)	"to identify differences in the number of unscheduled postinsertion-adjustment visits of patients with complete dentures fabricated by injection molding (IM) versus dentures fabricated by computer-aided design and computer-aided manufacturing"	106 participants with previously worn complete dentures	G1: Complete dentures fabricated using an IM system (n=33) G2: Complete CAD/CAM milled (AvaDent) dentures (n=73)	The number of unscheduled visits	Evaluated by the clinician	Followed up for 1 year after the insertion of new complete dentures.	-The number of unscheduled visits: G1=G2 (P=0.940) -Participant returns for unscheduled adjustments were not associated with the method of denture fabrication - Return visits for unscheduled adjustments were significantly associated with patients with single dentures and patients who returned for scheduled postinsertion visits -G2 took longer to achieve satisfactory levels of comfort with their dentures compared to G1 -G2 took longer to return for unscheduled visits compared to G1
Randomized controlled RCT	Inokoshi et al[46] (2012)	"to compare a new trial method for complete dentures using rapid prototyping (RP) with the conventional method"	10 edentulous patients	All Patients received: G1: Maxillary and mandibular conventional complete dentures (n=10). G2: Maxillary and mandibular complete dentures using rapid prototyping (EDEN250 RP machine) (n=10).	a. Prosthodontist satisfaction b. Patients satisfaction	a. VAS (esthetics; stability; operator friendliness for verifying jaw relation records; chair time; and overall satisfaction) b. VAS (esthetics; predictability of final denture shape; stability; comfort of the dentures; and overall satisfaction)	Immediately in trial insertion	-Prosthodontist's ratings (esthetics and stability): G1>G2 (P<0.05) - Prosthodontist's ratings (chair time): G1>G2 (P<0.05) -Prosthodontic rating (operator friendliness or overall satisfaction): G1= G2 (P>0.05) -Patient rating (esthetics, predictability of final denture shape, stability, comfort of the dentures or overall satisfaction.): G1=G2 (P>0.05)

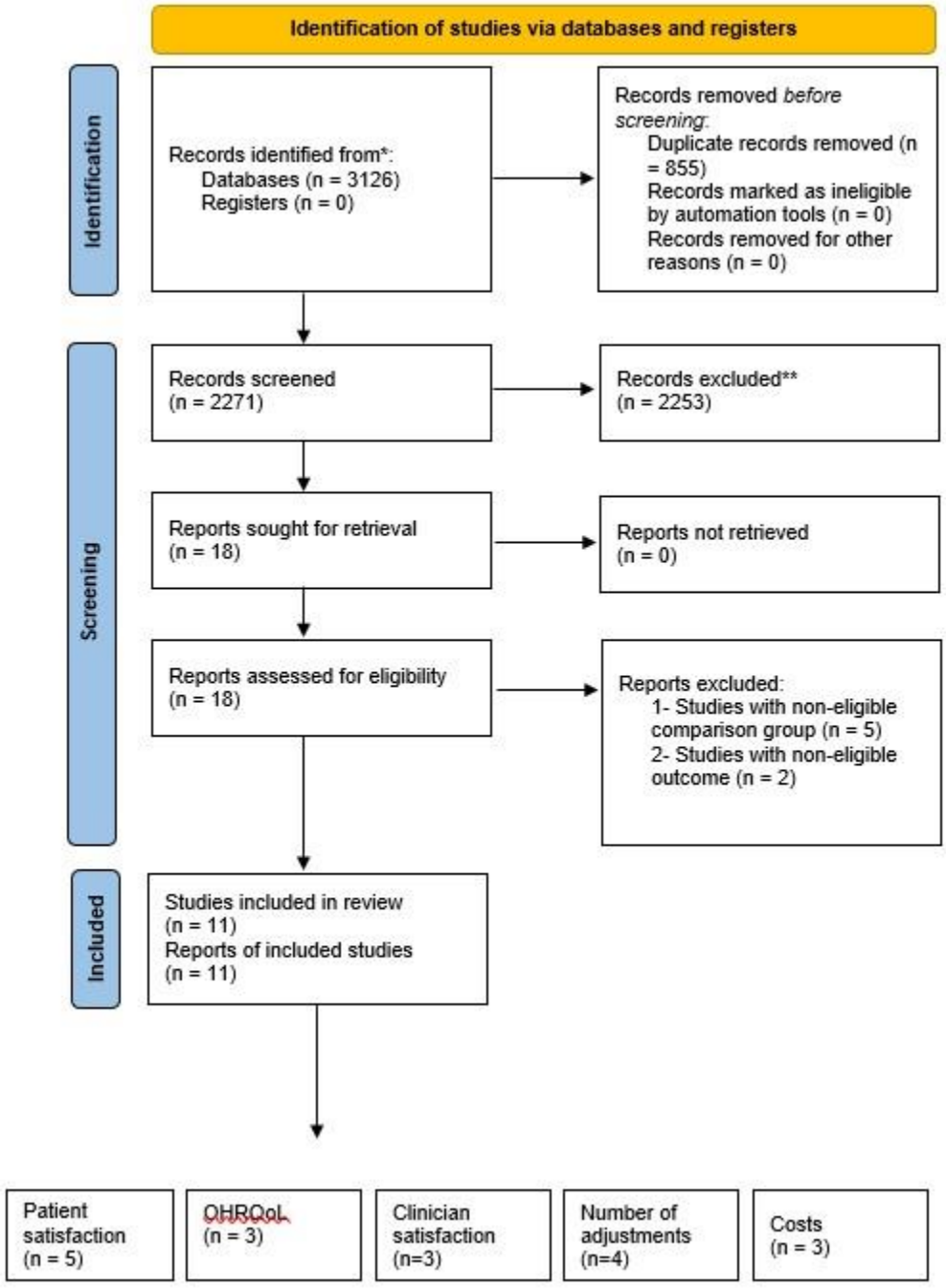

Figure 5-1. PRISMA flow diagram.

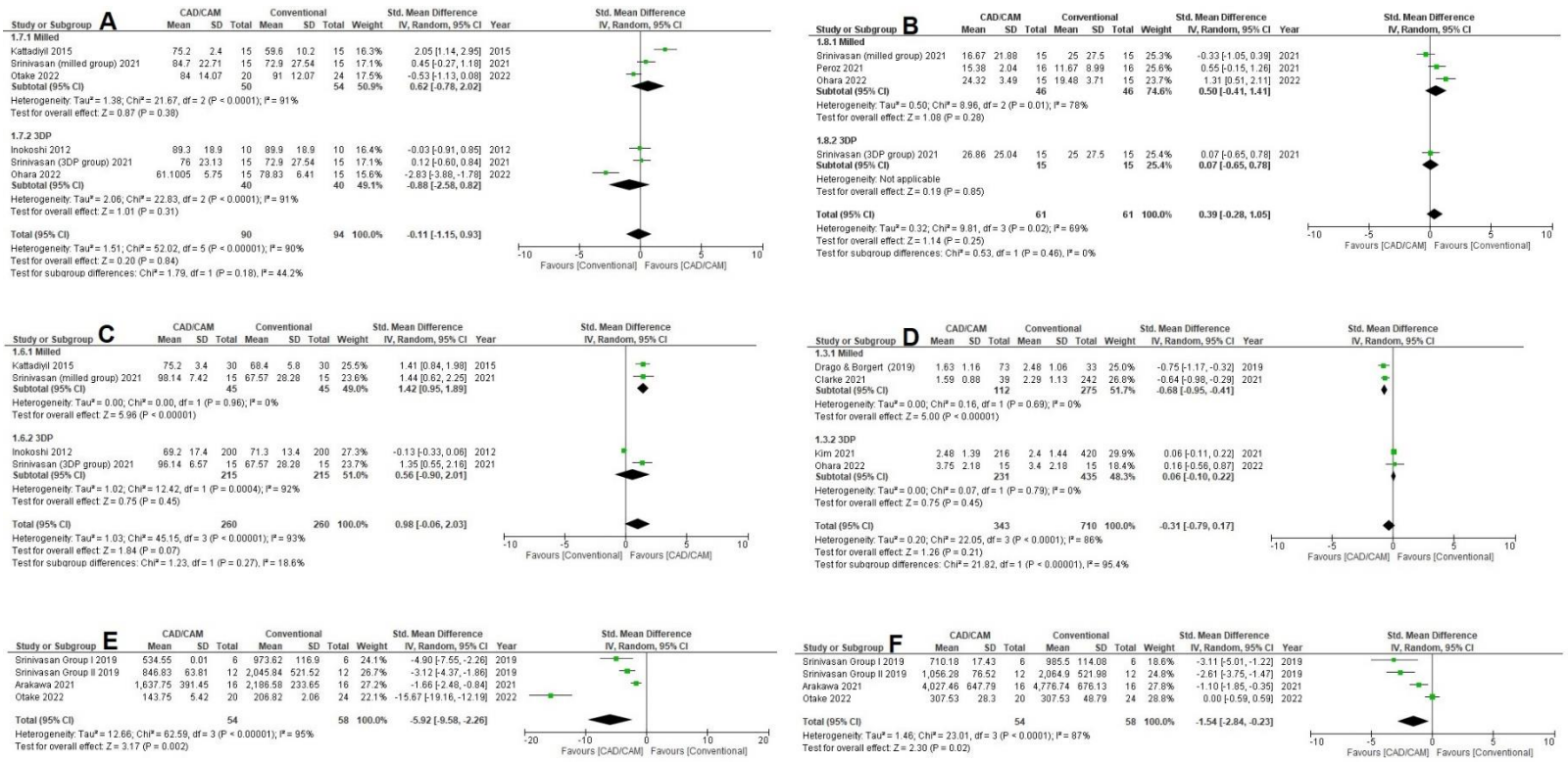

Figure 5-2. Meta-analysis of clinical studies comparing CAD/CAM with traditional CDs: A. patient rating of satisfaction (Negative values favor the traditional technique); B. overall OHIP scores (Negative values favor the CAD/CAM technique); C. clinician rating of satisfaction (Negative values favor the traditional technique); D. number of post-insertion adjustment visits (Negative values favor CAD/CAM technique); E. laboratory costs (Negative values favor CAD/CAM technique); F. total costs (Negative values favor CAD/CAM technique).

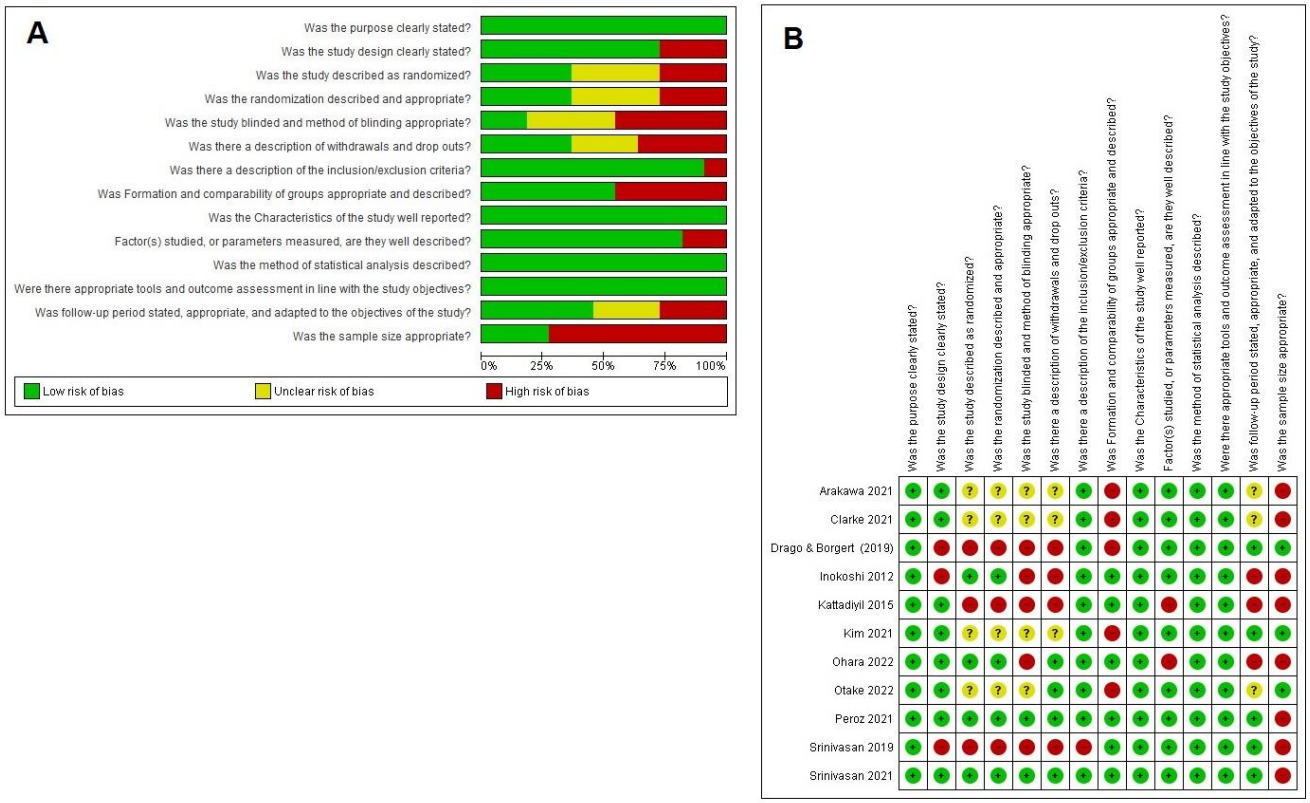

Figure 5-3. Risk of bias summary: A. review authors' judgements about each risk of bias item for each included study; B. Risk of bias graph: authors' judgements about each risk of bias item presented as percentages across all included studies

6. Chapter 6: Manuscript IV- Post-processing of 3D-printed denture base resins built in different printing orientations: An *in vitro* study of mechanical and surface properties

Before moving on to our clinical trial on 3D-printed overdentures, we found the need to examine the printing settings and post-printing processing methods *in vitro* in order to improve and determine the optimal physical and mechanical attributes of the 3D-printed dentures. For this reason, we conducted this *in vitro* study, in which the effect of print orientation (0°, 45°, 90°) and post-processing treatments (UV, Heat, or combination) was assessed on the mechanical and surface properties of 3D-printed denture base resin. The manuscript has been prepared for submission to the Journal of Prosthetic Dentistry.

Title: Post-processing of 3D-printed denture base resins built in different printing orientations: An *in vitro* study of mechanical and surface properties

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Abstract

Statement of problem: The variety of post-processing techniques and printing parameters recommended by manufacturers complicates the process for clinicians in determining the best approach to 3D-print dentures.

Purpose: The aim of this *in vitro* study was to assess the effect of print orientation (0°, 45°, 90°) and post-processing treatments (UV, Heat, or combination) on the mechanical and surface properties of 3D-printed denture base resin.

Material and methods: 3D-printed denture base resin specimens were fabricated in 0°, 45°, and 90° print orientations, followed by four post-processing techniques (UV, Heat, UV+Heat, and control). Microhardness was assessed using a Vickers microhardness tester. Additionally, the flexural strength (FS) was analyzed through a three-point bending test. Wettability was measured according to the sessile drop test. The fractured surfaces were observed under scanning electron microscopy.

Results: FS significantly increased ($p < 0.05$) when the print orientation was altered from 0° to 90°. There was no significant difference in FS between different post-processing treatments (all met the minimum requirement by ISO). The UV group had the highest Modulus of Elasticity, followed by the heat-treated groups. The 45° print orientation showed the highest contact angle in almost all groups, and UV led to higher hydrophilicity. The effect of build orientation on the microhardness depended on the post-processing technique.

Conclusions: The optimal flexural strength of 3D-printed denture base resin is achieved when printed in a vertical orientation (90° relative to the platform base). Thermal annealing as a post-

processing technique combined with UV, can effectively enhance flexural strength, induce favorable wettability, and reduce stiffness.

Clinical Implications: This research sought to enhance the qualities of the 3D-printed denture base materials through examining printing settings and post-printing processing methods. The research findings allow the clinicians to tailor the post-processing approaches of the 3D-printed dentures to meet the unique requirements of each patient. Thermal treatment may prove beneficial for processing voluminous denture bases, particularly when concerns arise regarding the penetration of UV light.

Keywords: CAD/CAM, 3D-printing, print orientation, post-processing, thermal curing, denture bases, acrylic resins

Introduction

Computer-aided design and manufacturing (CAD/CAM) technology has shown promising results in various fields of dentistry (1), with a rising popularity for denture fabrication (2-4). In general, digital denture manufacturing comprises two main methods: the subtractive and the additive manufacturing (5). The subtractive technique uses milling/machining to create a custom shape by subtracting materials (6) whereas the additive manufacturing (AM), also known as rapid prototyping (RP) or 3D-printing, refers to the printing of products in a layer-by-layer manner using digital images (6). There are several techniques for AM, including stereolithography (SLA), digital light processing (DLP), fused deposition modeling (FDM), polyjet/multijet, and selective laser melting (SLM) (7), all of which consist of the following main steps: CAD, transforming to a .stl file, slicing, printing, and post-processing (8).

3D-printing techniques possess evident advantages over the subtractive methods including cost effectiveness due to less time needed for prosthesis manipulation, less material waste, and less

wear and fracture of the rotary instruments, lending to lower upkeep costs (9). Moreover, AM is a straightforward manufacturing protocol, which enables the concurrent fabrication of multiple restorations with increased strength and fit (10, 11).

The outcome of printing can be directly influenced during each step, i.e. the printing parameters (including the printing direction and print layer thickness), choice of the material, selected additive manufacturing technology, and the post-processing technique (12, 13). Hence, the selection of appropriate parameters for 3D-printing is the key to achieving optimal outcomes (14).

The primary parameter affecting the mechanical and surface properties of the 3D-printed denture during the initial stages of AM is the printing orientation (15). Surface geometry and the layer-by-layer configuration of a 3D-printed material is defined by the printing orientation. In the existing literature, there is a diversity of views on how print orientation impacts the mechanical properties of 3D-printed objects. Some researchers argue that printing in a horizontal orientation (0°) relative to the build platform results in superior flexural strength when compared to vertical (90°) (16, 17). Conversely, other studies (18-20) contend that a vertical layer orientation yields the greatest flexural strength in comparison to a horizontal orientation, attributing this to the equivalence of bond strength between successive layers and the internal bond strength within each layer.

Another indispensable factor affecting the properties of the 3D-printed material during additive manufacturing is the post-processing step (8, 21). The post-processing process involves the removal of the support structures, post-rinsing, and post-polymerization of the printed material (21). Notoriously, the polymerization of the photosensitive resins is not completely accomplished following the printing process (21). Various UV post-curing methods have been implemented by researchers to increase the 3D-printed parts' strength as a result of the complete curing of the remaining resin (8, 17, 18, 21-24). However, studies have shown that UV post-curing can only

harden the outer surface of the material and might not enhance the properties of the interior 3D-printed parts due to the "candy-shell" effect (8). For that reason, we hypothesize that post-printing thermal curing might induce the complete conversion of the material.

To date, no study has assessed the effects of thermal annealing on the mechanical properties of photopolymerized denture base resin printed in various orientations. Therefore, in this study, we aim to inspect: i) whether 3D-printed denture base resins printed in varying orientations (0°, 45°, and 90°) differ in terms of flexural strength (FS), Modulus of Elasticity (MoE), microhardness (VHN), and wettability; ii) whether thermal annealing impacts the above-mentioned mechanical and surface properties. The null hypothesis of this study was that neither the print direction nor the post-processing technique affect the mechanical and surface properties of 3D-printed denture base material.

Materials and Method

Specimen preparation

A total of 120 specimens were designed using a CAD software program (FlashDLPrint; Flashforge, Jinhua, China) prior to 3D-printing. To measure flexural strength, test bars were designed with a dimension of 64 mm × 10 mm x 3.3 mm as per International Standards Organization (ISO) 1567:1999 norm (25). Thereafter, the specimens were saved as standard tessellation language (.stl) files and exported to a 3D-printer (Hunter, Flashforge Corp., Jinhua, China).

A commercially available 3D-printed denture base resin (DETAX GmbH, Ettlingen, Germany) was used for denture fabrication. The 3D-printed resin bottle was homogenized with a roller mixer (LC-3D Mixer, NextDent, 3D systems, Vertex Dental B.V., Soesterberg, Netherland) prior to dispensing the material into the tank. The specimens were 3D-printed in three printing orientations

(0°, 45°, and 90°) (n=40), with a layer thickness of 100 μm (Fig. 6-1). For the 0° and 45° specimens, the widest side (64 x 10 mm) was turned down and directly facing the printing platform. After printing, the specimens were scrapped off from the platform, and had their support structures removed by using low-speed rotary instruments (Brasseler, Savannah, USA). Residual uncured resin on the 3D-printed specimens was rinsed with isopropyl alcohol (FormWash, Formlabs, USA) as recommended by the manufacturer. The surface of the specimens was ground using 800, 400, and 200 grit SiC paper (McMaster-Carr, Chicago, USA) and rinsed with water.

The specimens of each printing orientation were randomly divided into four groups based on the post-processing method (n=10): i) The inferior and upper surfaces of the next ten specimens were each post-cured for a duration of 30 minutes (to a total of 60 minutes) using a light-polymerization unit at 200 W (FormCure; FormLabs, Sommerville, USA) with a wavelength range of 390–540 nm (24). A minimum of 30 minutes curing time for each surface was chosen based on the best performance reported in previous studies (17, 18). ii) Another ten specimens were subjected to thermal curing by being placed in an oven (Shel Lab, Sheldon Manufacturing Inc, USA) at a temperature of 105±5 °C under vacuum for one hour (8). iii) The third group underwent 60 minutes of UV curing followed by one hour of thermal curing. iii) For the control group (n=10), no post-processing procedure was applied.

Flexural Strength Testing

FS was measured by conducting a three-point bending test using a universal testing machine (Shimadzu, Kyoto, Japan) operated by the Trapezium X software. Prior to the testing, dimensions of each specimen (width and height) were measured at three different points and the average was calculated using a digital caliper (Fowler Euro-Cal IV) with a measuring accuracy of ±0.1 mm. Following the ISO 20795–1 norm for denture base polymers, the specimens were centered on a

fixture with a span width of 50 mm (Fig. 6-2). The loading wedge applied force with crosshead speed of 5 mm/min. The specimens were loaded until fracture occurs. The peak load was recorded as the fracture load in the chart recorder, and the FS (σ) was measured using the following formula:

$$\sigma = \frac{3FL}{2bh^2}$$

where, σ = Flexural strength (N/mm^2 or MPa), F is the maximum load at fracture in Newton, L is the distance between jig supports/span length (50 mm), b is the width of specimen (10 mm), and h is the height of the specimen (3.3 mm). In addition, the flexural modulus (E) (in MPa), which defines the material's resistance to bending, was calculated using the following formula:

$$E = \frac{F \cdot L^3}{d \cdot 4bh^3}$$

where, F/d is the gradient of load versus deflection curve at the linear section, L is the distance between jig supports/span length (50 mm), b is the width of specimen (10 mm), and h is the height of the specimen (3.3 mm).

Vickers Microhardness test

After performing the flexural test, two fractured specimens from each group were randomly selected for further analysis. The samples were cut 10 mm away from the fracture line under water cooling (26). The intact surfaces of the fractured specimens were evaluated for microhardness testing. Each surface was subjected to three indentations by applying a load of 300g for 15 seconds using a digital hardness tester (CM-100AT, Sun-Tec, Novi, USA). The average number was recorded as the Vickers microhardness number (VHN).

Wettability

The angle created by a distilled water droplet on the surface of the specimens was determined using the sessile drop technique (27). A micropipette dispensed a 20-µl drop of distilled water onto the surface of the specimen positioned horizontally on a bench that had been previously verified for levelness. The water droplet spread was photographed using a camera equipped on a Goniometer (Dataphysics Instruments GmbH, Filderstadt, Germany) (Fig.6-3). The captured image was subsequently analyzed with the SCA20_U software V. 4.3.9 (Dataphysics Instruments GmbH). Measurements of the angle (ø) were taken on both the right and left sides of the water drop's tangent line to the specimen's solid edge, with the mean value being noted (28).

Scanning Electron Microscopy (SEM)

The texture and morphology of the fractured specimens were characterized by scanning electron microscope (SEM). The samples were subjected to coating with a 4 nm thick platinum layer using a Leica Microsystems EM ACE600 sputter coater (Vienna, Austria). After that, the fractured surfaces were observed by FlexSEM 1000 SEM (Hitachi Ltd., Tokyo, Japan) operated under high vacuum using an accelerating voltage of 10.0 kV at 100×. Fields characterized by smooth and compact surfaces tend to demonstrate brittle fracture patterns, while those with a rough and uneven texture exhibit a range of fracture behaviors from brittle to ductile.

Data Analysis

Statistical analyses were performed by using a statistical software program (SPSS, version 24, SPSS Inc., Chicago, IL, USA) and $P<0.05$ was considered as significant for all tests. Kolmogorov–Smirnov test was applied to assess normality assumption. All data was evaluated as mean and standard deviation. Two-way ANOVA with post hoc Tukey HSD test was used for further analysis of FS, MoE, Microhardness, and wettability in each group and to evaluate interactions between variables (printing orientations and post-processing method).

Results

Flexural Strength

Normality of data was confirmed with the Kolmogorov-Smirnov test. The two-way ANOVA was performed to examine the effect of post-processing treatment and printing angulation on the FS of 3D-printed denture material. The interaction between the effects of post-processing treatment and printing angulation on FS was statistically insignificant ($F= 2.168$, $P= .052$), meaning that the effect of post-processing treatment on the FS did not depend on the printing angulation.

The two-way ANOVA, however, resulted in significant main effects (Table 6-1). The effect of printing angulation on FS was significant ($P<0.001$). The 90° groups showed significantly higher FS compared to 45° ($P<0.001$) and 0° ($P<0.001$) groups. The specimens printed at 45° also showed significantly higher FS compared to 0° ($P=0.019$) specimens (Fig. 6-4).

The effect of post-processing technique on FS was also significant ($P<0.001$). The uncured groups had significantly lower FS compared to the groups that underwent post-processing ($P<0.001$) (Fig. 4). Although the heat-treated groups (Heat+UV or Heat alone) showed higher FS compared to the other post-processing method (UV), the difference was statistically insignificant ($P>0.05$).

Modulus of Elasticity

The two-way ANOVA showed a statistically significant interaction between the effects of post-processing treatment and printing angulation on the MoE of 3D-printed denture material ($F= 5.709$, $P<0.001$).

The UV treatment led to the highest MoE compared to other post-processing treatments ($P<0.05$),

followed by the combination of UV and heat, heat treatment alone, and uncured groups (Table 6-

2). The effect of printing angulation on MoE depended on the post-processing treatment (Fig. 6-5).

Wettability

There was a statistically significant interaction between the effects of post-processing treatment and printing angulation on the wettability of 3D-printed denture material, F= 7.912, P<0.001, meaning that the effect of printing angulation on the wettability depended on the post-processing treatment (Table 6-3).

Further simple main effects analysis showed that 45° printing angulation had significantly higher contact angle values compared to 90° angulations in all groups, except for the UV group in which the difference was insignificant (P<0.05). Moreover, 45° printing angulation had significantly higher contact angle values compared to 0° angulations in all groups (P<0.05), except for the UV+heat group (Figure 6-6).

With regards to the post-processing treatment, simple main effects analysis demonstrated that UV curing led to significantly lower contact angles and superior wettability values compared to all other post-processing treatments in all printing angulations (P<0.05). Adding heat to the UV treatment, however, substantially increased the hydrophilicity of the denture base material, regardless of the printing direction (P<0.05). Uncured specimens showed the highest contact angle and the lowest wettability compared to the processed specimens in 45° and 90° angulations (P<0.05).

Microhardness

There was a statistically significant interaction between the effects of post-processing treatment and printing angulation on the microhardness of 3D-printed denture material, F= 4.526, P<0.001. UV treatment resulted in significantly higher microhardness values compared to the uncured

samples ($p<0.05$) (Table 6-4). In UV-treated groups, there was no difference in microhardness between print angulations ($P>0.05$). However, 90° showed higher microhardness compared to other angulations in heat curing and uncured groups (Figure 6-7).

SEM

The 0° groups showed smooth and compact surfaces indicating a brittle fracture mode, while the more intermediate/ductile form of fracture (rough appearance with crack lines) can be more observed in 45° and 90° angulations. When the layers were more aligned with the direction of the load (in 45° and 90° angulation), the interface between the layers falls directly in line with the load path. This alignment can cause the layers to separate, or delaminate, when tensile stress is generated during force insertion (Fig. 6-8).

Discussion

Various post-processing methods and printing parameters suggested by the manufacturers make it challenging for the clinicians to find the optimal printing technique. To our best knowledge, this study is the first to investigate the effects of thermal curing techniques on the mechanical and surface characteristics of photopolymerized denture base resin printed in various orientations. Our null hypothesis was rejected as build orientation and post-processing treatments affected the mechanical strength and surface properties of the material.

In the course of clinical use, the denture base is subjected to a combination of compressive, tensile, and shear forces, which may result in prosthesis failure (29). Therefore, ensuring that the denture base conforms to standards regarding flexural strength and modulus is crucial to withstand breakage and deformation under chewing forces.

Our results indicated that the build orientation significantly affected the flexural strength of the 3D-printed denture base resin. We found that the specimens built in a direction parallel to the load

application (printed in 90°), demonstrated stronger mechanical properties. Our outcome was in agreement with the previous studies by Unkovskiy *et al*. (19), Vayrynen *et al*. (20), and Altarazi *et al*. (18). The observed results can be explained by anisotropy, which is the phenomenon in which the structural property of the material depends on its build orientation (30). Variations in fusion quality between adjoining layers (31) as well as diverse monomer exposure to varying light orientations are the mechanisms through which build orientation affects the mechanical properties of the 3D-printed product (16). Our finding substantiates that the adhesion between the successive layers was stronger than the intra-layer strength. Contrary to some previous studies reporting higher FS with 0° print orientation (16, 17), we noticed that only the 90° orientation with an average FS of 73 MPa met the ISO 20795-1 requirements for flexural strength (65 MPa) (32). The different results reported in literature could be due to the different resin (NextDent) tested, which might have different anisotropic properties and inter-layer adhesion compared to the resin (Detax) used in the current study.

The results of this study showed that thermal annealing could be comparable to UV curing in terms of FS. Regardless of the curing technique, the FS of all post-processed samples were above the minimum acceptable FS recommended by ISO. Therefore, our study approve that thermal curing alone can promote the cross-linking of the remaining monomers, and consequently, improve the mechanical properties of the 3D-printed photopolymers (23, 33, 34). A recent study on 3D-printed temporary crown material also showed that post-printing heat curing for 15 minutes can enhance the degree of conversion and decrease the release of residual monomer (35).

Flexural modulus is an essential mechanical property which dictates the extent to which the denture base can resist permanent plastic deformation under repetitive masticatory forces (36). The effect of build orientation on the MoE depended on the post-processing technique, however, in

most of the groups, the 90° orientation showed favorable MoE. Regardless of the print orientation, the UV group had the highest MoE, followed by the heat-treated groups. A potential explanation could be that heat treatment can reduce stiffness by stress relaxation and allowing the polymer chains more mobility, enabling them to reorganize in a way that can absorb and recover from deformation more effectively, whereas UV curing might increase stiffness due to increased cross-linking density. The high FS values combined with lower MoE achieved in thermally cured 3D-printed dentures could bring about a rehabilitation option for patients with a mandibular/palatine torus or severe undercuts, for which more flexibility is desirable. These types of dentures might also be used as a promising substitute treatment plan in rehabilitating the anomalies such as Ectodermal Dysplasia (37). Therefore, we propose that the use of thermally cured 3D-printed dentures can create an opportunity for clinicians to choose the post-processing method adjusted to each patient's exclusive needs.

Finest surface characteristics are required to minimize discoloration and microbial adhesion, and to improve the staining resistance of the denture base (38). Surface wettability represents how easily saliva and other liquids can spread across a surface, indicating how well it can either facilitate or inhibit the adherence of fluids to prosthetic surfaces (39). Surface hydrophilicity affects microbial adhesion variably. For instance, hydrophobic surfaces are conducive for the attachment of C. *albicans* (16, 40). On the other hand, increased hydrophilicity might promote staining, microorganism growth, and plaque accumulation on the oral prostheses (41).

Similar to the findings of a previous study (16), our results showed that the 45° printing orientation led to greater contact angles, indicating the lowest hydrophilicity of the 3D-printed resin material. Regarding the post-processing technique, as expected, the UV group showed the lowest contact angle and the highest hydrophilicity. UV is known to excite the radicals on the surface, which

results in increased hydrophilicity (42). We hypothesize that adding heat to the UV treatment can reverse this polarization of surface, resulting in a less hydrophilic surface compared to UV.

Surface hardness is described as the capacity of the surface of a material to withstand permanent penetration or indentation (28). In agreement with the literature (18), our findings showed an increasing trend in microhardness values when print orientation changed from 0° to 90°. Moreover, the UV treatment resulted in higher microhardness values compared to the uncured groups. This outcome was in line with a previous study (35) who reported a correlation between increased hardness and increased degree of conversion achieved by UV post-curing in a 3D-printed resin material.

In this study, we used a 100 μm layer thickness since a previous study (35) reported that the highest flexural strength occurred at 100 μm. The findings from our study can have implications for improved efficiency in the laboratories as well. Adopting printing orientations that are more vertical enables the concurrent production of multiple dentures, with support structures avoiding critical intaglio surfaces. This leads to improved accuracy and savings in both time and cost.

This study acknowledges certain limitations that future research could explore. Specifically, it suggests the need for clinical trials to assess the denture base shapes in a real-patient context, and calls for *in vivo* studies to test 3D-printed dentures in different orientations for practical relevance. Additionally, we did not examine how the thickness of the printing layers could affect the flexural properties along with the build orientation. Future studies could also benefit from evaluating various resin brands with the post-curing polymerization processes proposed in this study to uncover potentially valuable findings. We suggest further investigation on degree of monomer

conversion, and thermal analysis to understand the thermo-mechanical behavior of the 3D-printed resin following heat treatment.

Conclusions

Within the limitations of this study, the following conclusions were drawn:

1. The printing orientation affected the mechanical properties of 3D-printed denture base material, with the 90° orientation showing the highest FS with favorable MoE and microhardness.
2. Post-processing 3D-printed dentures with UV resulted in acceptable FS, and highest MoE, hydrophilicity, and microhardness among the tested techniques.
3. Thermal annealing, especially when combined with UV, offers high FS values, promising wettability and microhardness, and reduced stiffness.

Conflict of interest: None.

References

1. Miyazaki T, Hotta Y, Kunii J, Kuriyama S, Tamaki Y. A review of dental CAD/CAM: current status and future perspectives from 20 years of experience. Dental materials journal. 2009;28(1):44-56.

2. Busch M, Kordass B. Concept and development of a computerized positioning of prosthetic teeth for complete dentures. International journal of computerized dentistry. 2006;9(2):113-20.

3. Maeda Y, Minoura M, Tsutsumi S, Okada M, Nokubi T. A CAD/CAM system for removable denture. Part I: Fabrication of complete dentures. international Journal of Prosthodontics. 1994;7(1):17-21.

4. Sun Y, Lü P, Wang Y. Study on CAD&RP for removable complete denture. Computer methods and programs in biomedicine. 2009;93(3):266-72.

5. Schweigera J, Stumbaumb J, Edelhoffc D, Güthd J. Systematics and concepts for the digital production of complete dentures: risks and opportunities Systematik und Konzepte zur digitalen Herstellung von Totalprothesen–Chancen und Risiken. International journal of computerized dentistry. 2018;21(1):41-56.

6. Bidra AS, Taylor TD, Agar JR. Computer-aided technology for fabricating complete dentures: systematic review of historical background, current status, and future perspectives. The Journal of prosthetic dentistry. 2013;109(6):361-6.

7. Azari A, Nikzad S. The evolution of rapid prototyping in dentistry: a review. Rapid Prototyping Journal. 2009:15:3:216-225.

8. Dizon JRC, Gache CCL, Cascolan HMS, Cancino LT, Advincula RC. Post-processing of 3D-printed polymers. Technologies. 2021;9(3):61.

9. Berman B. 3-D printing: The new industrial revolution. Business horizons. 2012;55(2):155-62.

10. Abduo J, Lyons K, Bennamoun M. Trends in computer-aided manufacturing in prosthodontics: a review of the available streams. International journal of dentistry. 2014;2014: 783948.

11. Bilgin MS, Baytaroğlu EN, Erdem A, Dilber E. A review of computer-aided design/computer-aided manufacture techniques for removable denture fabrication. European journal of dentistry. 2016;10(02):286-91.

12. 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.

13. Hada T, Kanazawa M, Iwaki M, Arakida T, Minakuchi S. Effect of printing direction on stress distortion of three-dimensional printed dentures using stereolithography technology. Journal of the Mechanical Behavior of Biomedical Materials. 2020;110:103949.

14. Puebla K, Arcaute K, Quintana R, Wicker RB. Effects of environmental conditions, aging, and build orientations on the mechanical properties of ASTM type I specimens manufactured via stereolithography. Rapid Prototyping Journal. 2012:18:5:374-388.

15. Tymrak B, Kreiger M, Pearce JM. Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions. Materials & Design. 2014;58:242-6.

16. Shim JS, Kim J-E, Jeong SH, Choi YJ, Ryu JJ. Printing accuracy, mechanical properties, surface characteristics, and microbial adhesion of 3D-printed resins with various printing orientations. The Journal of Prosthetic Dentistry. 2020;124(4):468-75.

17. Al-Dulaijan YA, Alsulaimi L, Alotaibi R, Alboainain A, Akhtar S, Khan SQ, et al. Effect of Printing Orientation and Postcuring Time on the Flexural Strength of 3D-Printed Resins. Journal of Prosthodontics. 2023;32(S1):45-52.

18. Altarazi A, Haider J, Alhotan A, Silikas N, Devlin H. Assessing the physical and mechanical properties of 3D printed acrylic material for denture base application. Dental Materials. 2022;38(12):1841-54.

19. Unkovskiy A, Bui PH-B, Schille C, Geis-Gerstorfer J, Huettig F, Spintzyk S. Objects build orientation, positioning, and curing influence dimensional accuracy and flexural properties of stereolithographically printed resin. Dental Materials. 2018;34(12):e324-e33.

20. Väyrynen VO, Tanner J, Vallittu PK. The anisotropicity of the flexural properties of an occlusal device material processed by stereolithography. The Journal of Prosthetic Dentistry. 2016;116(5):811-7.

21. Li P, Lambart A-L, Stawarczyk B, Reymus M, Spintzyk S. Postpolymerization of a 3D-printed denture base polymer: Impact of post-curing methods on surface characteristics, flexural strength, and cytotoxicity. Journal of Dentistry. 2021;115:103856.

22. Uzcategui AC, Muralidharan A, Ferguson VL, Bryant SJ, McLeod RR. Understanding and improving mechanical properties in 3D printed parts using a dual-cure acrylate-based resin for stereolithography. Advanced engineering materials. 2018;20(12):1800876.

23. Kim D, Shim J-S, Lee D, Shin S-H, Nam N-E, Park K-H, et al. Effects of post-curing time on the mechanical and color properties of three-dimensional printed crown and bridge materials. Polymers. 2020;12(11):2762.

24. Aati S, Akram Z, Shrestha B, Patel J, Shih B, Shearston K, et al. Effect of post-curing light exposure time on the physico–mechanical properties and cytotoxicity of 3D-printed denture base material. Dental Materials. 2022;38(1):57-67.

25. Chhabra M, Kumar MN, RaghavendraSwamy K, Thippeswamy H. Flexural strength and impact strength of heat-cured acrylic and 3D printed denture base resins-A comparative in vitro study. Journal of Oral Biology and Craniofacial Research. 2022;12(1):1-3.

26. Faot F, Costa MA, Cury AADB, Garcia RCR. Impact strength and fracture morphology of denture acrylic resins. The Journal of prosthetic dentistry. 2006;96(5):367-73.

27. Zissis A, Yannikakis S, Jagger RG. Wettability of denture materials. Quintessence International. 2001;32(6):457-62.

28. Al-Dwairi ZN, Tahboub KY, Baba NZ, Goodacre CJ, Özcan M. A comparison of the surface properties of CAD/CAM and conventional polymethylmethacrylate (PMMA). Journal of Prosthodontics. 2019;28(4):452-7.

29. Li BB, Xu JB, Cui HY, Lin Y, Di P. In vitro evaluation of the flexural properties of All-on-Four provisional fixed denture base resin partially reinforced with fibers. Dental Materials Journal. 2016;35(2):264-9.

30. Zohdi N, Yang R. Material anisotropy in additively manufactured polymers and polymer composites: a review. Polymers. 2021;13(19):3368.

31. Sood AK, Ohdar RK, Mahapatra SS. Parametric appraisal of mechanical property of fused deposition modelling processed parts. Materials & Design. 2010;31(1):287-95.

32. International Organization for Standardization (ISO). Dentistry - base polymers - Part 1: Denture base polymers. ISO 20795-1. 2013.

33. Hardiman K. Post-processing considerations for biomedical 3D printing of polymers. Polymer-based additive manufacturing: Springer; 2019. p. 219-41.

34. Oskui SM, Diamante G, Liao C, Shi W, Gan J, Schlenk D, et al. Assessing and reducing the toxicity of 3D-printed parts. Environmental Science & Technology Letters. 2016;3(1):1-6.

35. Alshamrani AA, Raju R, Ellakwa A. Effect of printing layer thickness and postprinting conditions on the flexural strength and hardness of a 3D-printed resin. BioMed Research International. 2022;2022:8353137.

36. Anusavice KJ, Shen C, Rawls HR. Phillips' Science of Dental Materials, 12th ed. Elsevier Health Sciences; 2012.

37. Thumati P, Padmaja S, Raghavendra RK. Flexible dentures in prosthodontics--an overview. Indian Journal of Dental Advancements. 2013;5(4):1380-6.

38. Radford DR, Sweet S, Challacombe S, Walter J. Adherence of Candida albicans to denture-base materials with different surface finishes. Journal of dentistry. 1998;26(7):577-83.

39. Jin N-Y, Lee H-R, Lee H, Pae A. Wettability of denture relining materials under water storage over time. The journal of advanced prosthodontics. 2009;1(1):1-5.

40. Katsikogianni M, Missirlis Y. Concise review of mechanisms of bacterial adhesion to biomaterials and of techniques used in estimating bacteria-material interactions. Eur Cell Mater. 2004;8(3):37-57.

41. De Foggi CC, Machado AL, Zamperini CA, Fernandes D, Wady AF, Vergani CE. Effect of surface roughness on the hydrophobicity of a denture-base acrylic resin and C andida albicans colonization. Journal of Investigative and Clinical Dentistry. 2016;7(2):141-8.

42. Mitsuda S, Ino S, Nihei T, Umeda Y, Watanabe M, Takai O, et al. Effects of hydrophilic and hydrophobic surface modifications on poly (methyl methacrylate) denture base resins. Asian Pacific Journal of Dentistry. 2019;19(1):1-8.

Tables

Table 6-1. Mean±SD FS (MPa) values according to the post-processing treatment and printing angulation

Post-processing treatment	Printing angulation			Total	P Value
	0°	45°	90°		
UV	53.8±6.9	65.9±14.1	79.8±10.3	66.5±15.0^{A}	-
Heat	67.3±14.1	64.8±6.0	72.6±5.9	68.2±9.7^{A}	-
UV+Heat	59.8±13.6	71.3±13.0	84.9±6.3	72±15.2^{A}	-
Uncured	39.9±13.6	45±11.1	57.6±5.5	47.5±12.7^{B}	-
Total	55.2±15.7^{c}	61.8±15.0^{b}	73.7±12.5^{a}	63.6±16.3	<0.001
P Value	-	-	-	<0.001	-

*-Different upper case letters show significance in difference between the processing techniques.

-Different lower case letters show significance in difference between the printing angulations.

Table 6-2. Mean±SD MoE (MPa) values according to the post-processing treatment and printing angulation

Post-processing treatment	Printing angulation		
	0°	45°	90°
UV	2038.7±74.4^{A,a}	2024.2±99.9^{A,a}	2061.0± 46.3^{A,a}
Heat	1411.8±213.5^{C,a}	1283.9±162.9^{C,b}	1271.0±149.3^{C,b}
UV+Heat	1836.6±109.8^{B,a}	1789.6±68.5^{B,a}	1737.2±84.0^{B,a}
Uncured	820.1±108.6^{D,a}	879.8±101.4^{D,a}	1063.8±71.4^{D,b}

*-Different upper case letters show significance in difference between the processing techniques in each angulation (in a column)

-Different lower case letters show significance in difference between the printing angulations in each processing technique (in a row)

Table 6-3. Mean ± SD contact angle values according to the post-processing treatment and printing angulation.

Post-processing treatment	Printing angulation			Total
	0°	45°	90°	
UV	33.9±12.0^{B,b}	50.2±11.7^{D,a}	41.1±6.3^{C,ab}	41.7±12.0
Heat	83.6±8.6^{A,b}	103.6±17.6^{B,a}	73.8±2.4^{B,c}	87.0±16.7
UV+Heat	87.6±4.1^{A,a}	83.4±8.4^{C,a}	66.7±10.2^{B,b}	79.2±12.0
Uncured	84.1±10.4^{A,b}	117.6±11.7^{A,a}	84.4±6.2^{A,b}	95.4±18.5
Total	72.3±24.2	88.7±28.5	66.5±17.5	75.8±25.4

*-Different upper case letters show significance in difference between the processing techniques in each angulation (in a column)

-Different lower case letters show significance in difference between the printing angulations in each processing technique (in a row)

Table 6-4. Microhardness values (Mean±SD) according to the post-processing treatment and printing angulation.

Post-processing treatment	Printing angulation			Total
	0°	45°	90°	
UV	22.8±0.4^{A,a}	22.8±0.4^{A,a}	23.4±1.3^{A,a}	23.0±0.9
Heat	21.2±0.7^{B,b}	21.4±1.5^{B,ab}	22.4±0.5^{AB,a}	21.7±1.1
UV+Heat	23.3±1.6^{A,a}	22.7±1.4^{A,a}	22.4±1.0^{AB,a}	22.8±1.4
Uncured	20.1±1.3^{C,b}	18.2±0.7^{C,c}	21.4±1.8^{B,a}	19.9±1.8
Total	21.9±1.7	21.3±2.1	22.4±1.4	-

*-Different upper case letters show significance in difference between the processing techniques in each angulation (in a column)-Different lower case letters show significance in difference between the printing angulations in each processing technique (in a row)

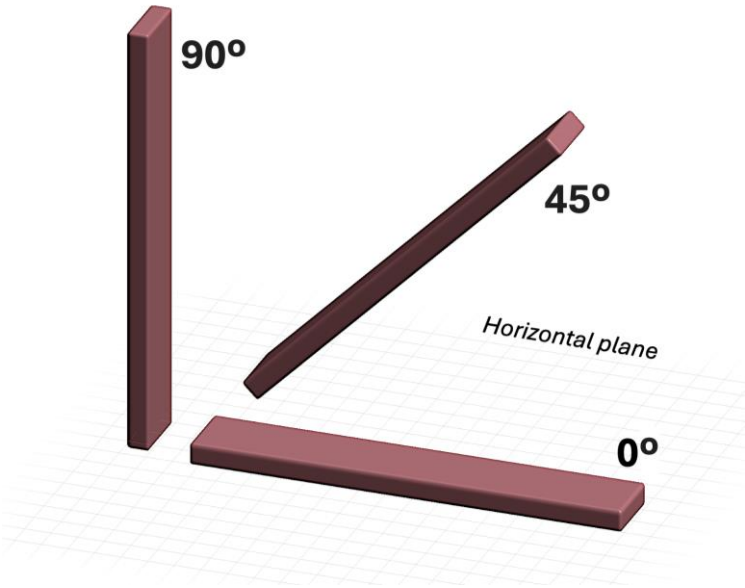

Figure 6-1. The specimens were 3D-printed in three printing orientations relative to the platform/horizontal plane (0°, 45°, and 90°).

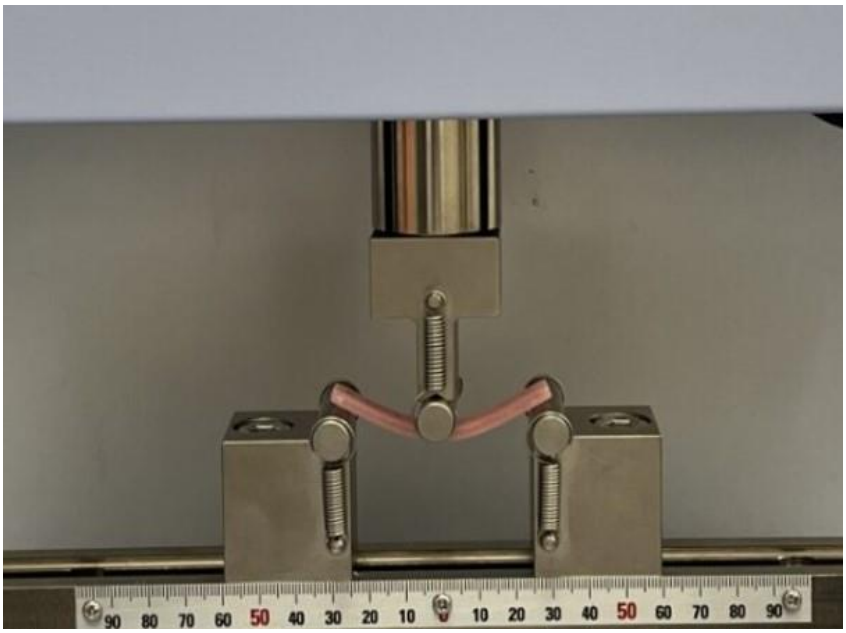

Figure 6-2. The specimen was loaded in the universal testing machine until fracture.

Figure 6-3. a. Representative photograph of the water droplet spread; b. Goniometer.

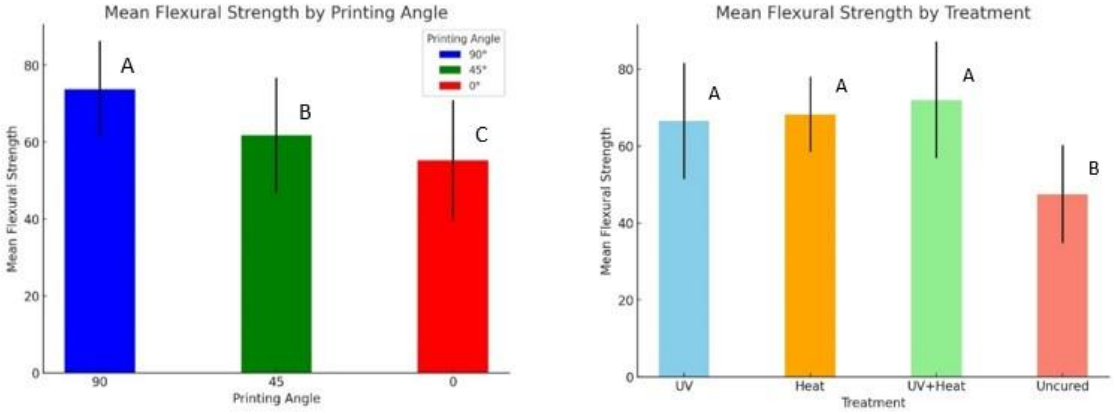

Figure 6-4. Mean Flexural strength (MPa) of the tested groups by printing angulation and post-processing treatment.

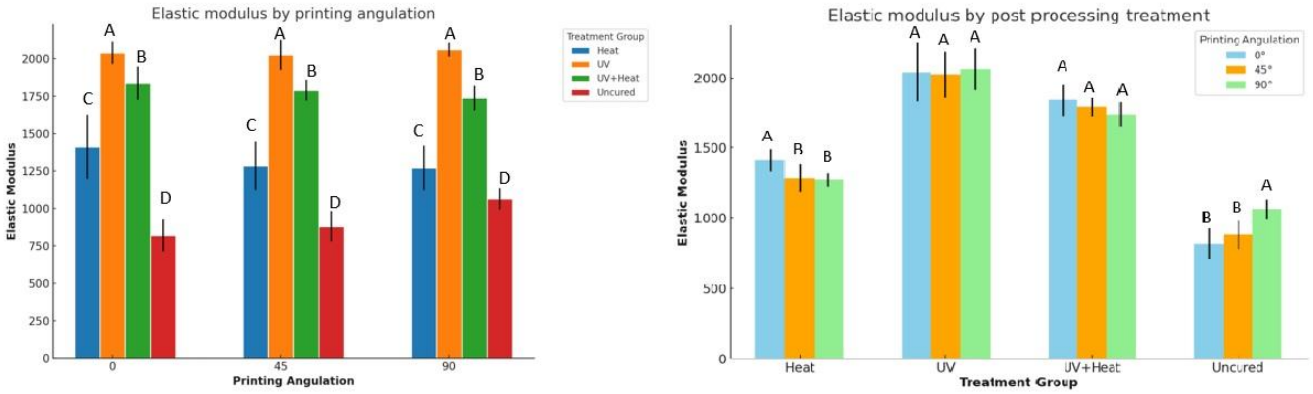

Figure 6-5. MoE of the tested groups based on printing angulation and post-processing treatment.

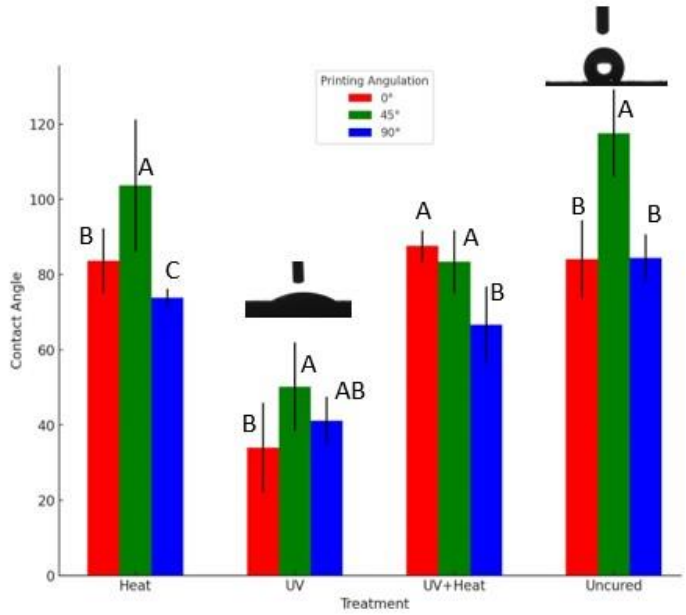

Figure 6-6. Contact angle values by treatment group and printing angulation.

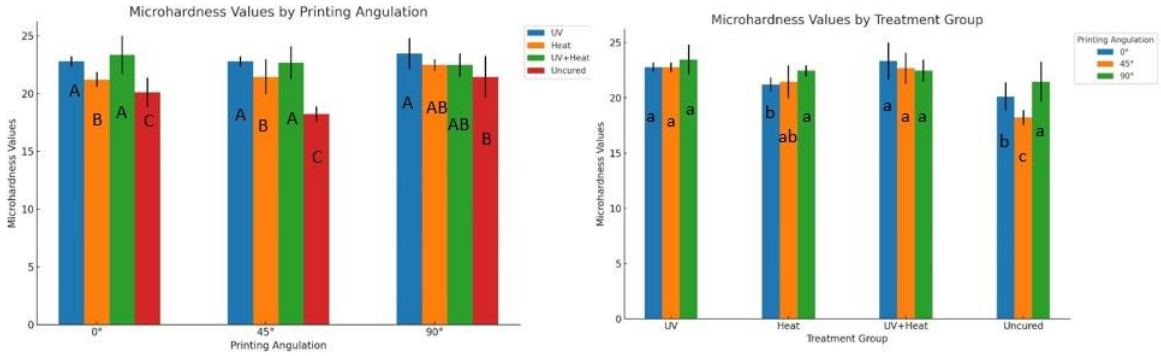

Figure 6-7. Microhardness values based on printing angulation and post-processing treatment.

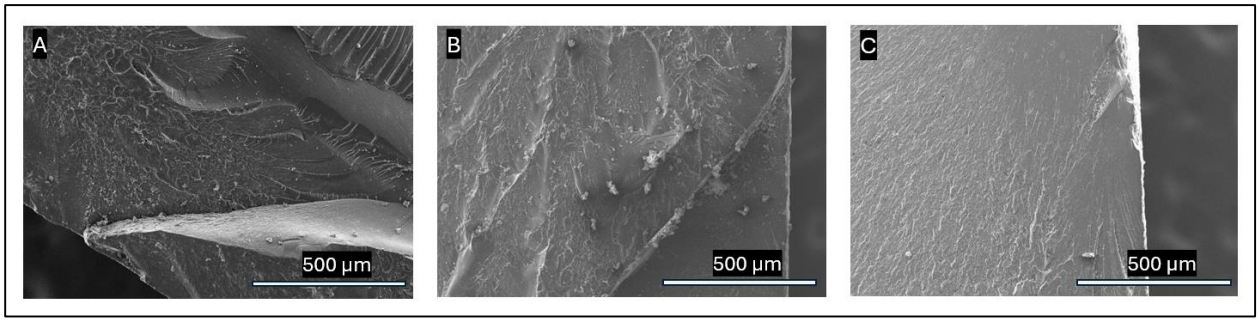

Figure 6-8. SEM scanning at 100× showing the fracture morphology of 3D-printed samples printed in: A) 90°, B) 45°, C) 0°. Delamination can be seen in 90° and 45° groups.

7. Chapter 7: Manuscript V-3D printing vs traditional workflow for the fabrication of mandibular implant overdentures: Study protocol for a mixed-methods cross-over RCT

Through our comprehensive review of literature, described in chapter 4, we found out that so far, no well-designed cross-over clinical trial has been conducted to investigate the clinical performance and patient satisfaction with 3D-printed IMOs. Therefore, we felt the need to carry out the first clinical trial to address this gap in knowledge and determine the patient and clinician perspectives of the 3D-printed implant overdentures. This is particularly of great interest since this study serves as the first qualitative study that considers the patient's experiences with this type of treatment. This chapter outlines the protocol for our mixed-methods cross-over RCT. The manuscript has been published in the Trials Journal.

Title: 3D printing vs traditional workflow for the fabrication of mandibular implant overdentures: Study protocol for a mixed-methods cross-over RCT

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Abstract

Background: Complete tooth loss is a significant global oral health issue, particularly impacting older individuals with lower socioeconomic status. Computer-assisted technologies enhance oral healthcare access by the elderly. Despite promising *in vitro* reports on digital denture materials, evidence from randomized clinical trials (RCTs) is lacking to verify their performance. This cross-over RCT will investigate whether 3D-printed implant-retained mandibular overdentures (IMO) are more satisfactory for edentulous seniors than those made through traditional methods.

Methods/design: We will recruit 26 completely edentulous participants (any sex/gender) based on the following eligibility criteria: age ≥ 60 years, no tooth extraction in the past 12 months, two implants in the lower jaw, and need for new dentures in both jaws. Each participant will receive two denture pairs, either manufactured by 3D printing or traditionally, to be worn in a random order. A timeline of three months with each denture pair will be considered for outcome assessment (total: six months). Patient satisfaction with dentures will be measured by the McGill Denture Satisfaction Questionnaire. We will evaluate other patient-reported outcomes (including oral health-related quality of life), as well as clinician-assessed quality and cost. At the end of the trial, participants will choose which denture pair they wish to keep, and interviewed about their experiences with the 3D-printed IMO. The quantitative and qualitative data will be incorporated through an explanatory mixed-methods strategy. A final quantitative assessment will happen after 12 months with the preferred IMO to assess the long-term performance and maintenance needs.

Discussion: This mixed-methods RCT will explore patient experiences with 3D-printed IMOs, aiming to assess the potential for altering clinical practice and dental public health policies. Our results will inform policies by showing whether 3D printing offers comparable outcomes at lower costs, facilitating greater access to oral care for the elderly.

Trial registration: ClinicalTrials.gov, NCT06155630, Registered on 04 December 2023. https://classic.clinicaltrials.gov/ct2/show/NCT06155630

Keywords: 3D printing, CAD/CAM, mandibular overdenture, Costs and cost analysis, Cross-over studies, Dental care for aged, Edentulous mouth, Implant-supported dental prosthesis, Patient satisfaction, Removable prosthodontics

Background

Complete tooth loss or edentulism remains one of the most burdensome oral health issues globally. Its prevalence is clustered in elderly populations and tends to remain high for many decades [1]. Edentulism can devastate well-being [2], with depressive symptoms worsening after complete tooth loss [3]. Poorer oral function after tooth loss, including impaired mastication [4], is closely linked to psychosocial discomfort and lower self-esteem [5, 6]. Moreover, edentulism has been shown to have likely systemic implications, as evidenced by its association with disability and earlier mortality in the elderly [7].

Even if implant-retained overdentures restore oral functionality and improve nutrition for the elderly [8-10], significant obstacles limit access to such care: (a) Public funding for adult oral healthcare is limited, generally excluding prosthetic treatments for most without teeth [11, 12]; (b) High costs of private care, often not reimbursed, disproportionately affect those in lower socioeconomic groups, restricting their access to necessary dental services [13, 14]; (c) The need for multiple clinical visits, sometimes over six, poses challenges in terms of mobility and costs, particularly for those in long-term care or during health crises like pandemics [15, 16].

Computer-assisted technologies can greatly improve access to oral healthcare by the elderly. Fewer appointments for denture treatment, i.e., two to four, instead of five as with the conventional

techniques, can reduce patient costs [17]. Patients can receive 3D images of their face with future dentures by internet, thus avoiding a clinical visit [18]. Moreover, digital files can be used to remake the same dentures in the absence of the patient, whereas analogic techniques need a repetition of the original workflow [19].

Among the computer-aided designed and manufactured (CAD/CAM) options for denture fabrication, 3D printing (or additive manufacturing) stands out as a highly promising technology. In comparison to traditional and other CAD/CAM workflows, 3D printed dentures have the potential to minimize material waste while achieving high speed and quality [20]. Even with promising *in vitro* reports of digital denture materials [21-24], however, evidence from randomized clinical trials (RCTs) is still missing to verify their clinical performance. Our recent scoping review (search update: March 1st 2023) [25] found no RCT on 3D-printed implant-retained mandibular overdentures (IMO), which have been considered the standard of care for complete edentulism by international consensuses [26, 27].

In addition, treatment success with dentures mostly depends on positive patient experiences. Integrating patient attitudes into the final dentures is vital for favorable results. Thus, patient-reported outcome measures (PROMs) are the core criteria in evaluating denture care, as for many healthcare interventions [23]. Yet, no study has explored patients' experiences with the CAD/CAM dentures. In other words, it is unclear how patients perceive CAD/CAM dentures and whether they have a satisfactory performance from patients' perspectives.

Objectives and hypothesis

We aim to conduct the first mixed-methods cross-over RCT to determine the efficacy and patients' experience with 3D-printed implant-retained mandibular overdentures (IMO), compared to the traditional method, for independently living edentulous seniors who have two implants in the

anterior mandible, as purported by the McGill Consensus on Implant Overdentures [26]. We hypothesize that IMOs produced by computer-aided design and 3D printing are as satisfactory to edentulous seniors as those fabricated using traditional methods.

Methods

Design and setting

This mixed-methods cross-over RCT will compare one experimental intervention (CAD/CAM dental prostheses) versus an active comparator (standard of care conventional methods). Outcome assessment will take place three months after each intervention, up to a total follow-up of six months. This will be a single-center RCT, conducted at the Faculty of Dental Medicine and Oral Health Sciences, McGill University (Montreal, Canada). The creation of this report adhered to the guidelines outlined in the Standard Protocol Items: Recommendations for Interventional Trials (SPIRIT) [28]. Figure 7-1 illustrates the standard protocol items diagram as suggested by SPIRIT, while the SPIRIT checklist for this study is provided in Additional file 1.

Eligibility Criteria

This trial will recruit edentulous patients seeking treatment with IMOs and maxillary complete dentures at McGill University.

Inclusion criteria: (i) elderly according to the age cut-off purported by the World Health Organization (age ≥ 60 years) [29] and living independently; (ii) completely edentulous; (iii) no tooth extraction within the past 12 months; (iv) two implants symmetrically distributed in the anterior mandible for three or more months before the trial interventions; (v) desire to receive both upper denture and lower IMO with new stud attachments; (vi) good understanding of spoken and written English or French; (vii) ability to provide written informed consent.

Exclusion criteria: (i) severe systemic disease or needing frequent hospitalization (i.e. American Society of Anesthesiologists Physical Status class >II) [30]; (ii) evidence of cognitive or motor impairment; (iii) acute or chronic symptoms of parafunctional or temporomandibular disorders; (iv) intraoral pathologies, either acute, progressive, potentially malignant or capable to hamper denture fit; (v) signs of endosseous lesions or residual dental structures in panoramic radiographs; (vi) signs of implant failure, including clinical mobility, peri-implant radiolucency, unacceptable bone loss (0.2mm/year after 1st year, or <2 mm any time) and/or persistent signs/symptoms of pain, neuropathy, infection and/or exudate [31].

Participant Recruitment

We will recruit participants from the Greater Montreal area by verifying lists of prospective and past patients in our Faculty. This will be done directly with the Faculty's clinical staff to reach those patients. Priority will be given to patients treated in recent years who may need to have their old IMOs replaced; e.g., 63 patients from 2010-2018 (around eight patients/year). Staff involved in clinical services will mention this study to patients and, if the latter have interest, refer them to our trial coordinator (TC). Patients without implants will be included if they comply with inclusion criteria #4 (two implants in the lower jaw) within the recruitment period.

Recruitment rate will be based on the ability of the researchers to provide treatment rather than participant availability, which is set at three patients/ month. Recruiting 37% of the 63 patients available from 2010 to 2018 would reach the planned sample size (n=26). Participants will be assigned to interventions with the recruitment flow, which will take nine months (from the 5^{th} to the 14^{th} month). Recruitment and care provision to participants will be spread over a 9-month period to reduce seasonal variation in their responses.

Trial Interventions

After screening and obtaining patient consent, participants will return to start denture fabrication (Fig. 2). Both denture pairs will be fabricated simultaneously and delivered in random order. Existing attachments will be replaced by Novaloc abutments of adequate cuff height (external margins 1 mm above the mucosa) and yellow/medium retentive matrices.

Participants will come for a first appointment for scanning their existing dentures, with new abutments (manual torque) and attachment housings in place. The first visit will be the same for both conventional and digital pathways and will consist of scanning the patients' existing upper complete denture and IMO. The existing dentures will be scanned by using a desktop scanner (Autoscan DS-EX, Shining 3D Ltd., Hangzhou, China). In the lab, the resulting .stl files will be 3D printed using a Max DLP 3D printer (Asiga, Alexandria, Australia).

In a second clinical appointment, the interim printed dentures will be adjusted with wax for the desired lip support, occlusal plane, occlusal vertical dimension (OVD) and centric relation (CR). Secondary impressions (regular PVS) will be taken under the intaglio to refine fit, with the new abutments and housings in place. Maxillary and mandibular interim printed dentures will be scanned separately and in occlusion (Autoscan DS-EX). The face of the patients will also be scanned by a face scanner (Shining 3D face scanner, Shining 3D Ltd.).

In the second lab session, .stl files will be superimposed for the digital pathway. Another software (Exocad Full Denture Module, Exocad GmbH, Darmstadt, Germany) will be used to set teeth and denture bases virtually; virtual dentures will be superimposed to the facial images to estimate final results.

Denture bases will be manufactured by a Max DLP 3D printer with Dentca Denture Base Resin (Dentca Inc., Torrance, USA) at 100 μm/layer and supports on the flanges' facial surface. A 0.3 mm relief will be applied in the sockets dedicated to receive teeth and attachment housings. Following washing in isopropyl alcohol (five minutes), dentures will receive Portrait 3D teeth (Dentsply Sirona, Charlotte, USA), treated

by the Fuse 3D Denture Bonding System (Dentsply Sirona). Uncured base resin will be used to lute teeth and cured under UV. Final polymerization will take place in a dental polymerization equipment (Flash, Asiga) for 30 min. Dentures will be finished and polished, and sandblasted (50μm aluminum oxide) in the attachment sockets.

For the conventional pathway, the second lab session will consist of pouring the impressions (Type IV stone), mounting the casts in an Arcon semi-adjustable articulator, removing the printed teeth, and replacing them with wax rim and acrylic tooth setup (Portrait, Dentsply Sirona – same shape, size and shade used for 3D-printed dentures).

A third appointment will be used for wax try-in for the conventional pathway. For the digital pathway, participants will have a chance to appraise their smile on a computer screen (virtual try-in, done remotely) and request modifications.

Denture bases will be manufactured with conventional heat-polymerized resins, and participants will return for a fourth appointment for delivery, including chairside pick-up of attachments (GC Reline resin; GC America Inc., Alsip, USA). Two short-term adjustments will be scheduled 24-72 h and seven days after delivery, and then weekly until the dentures are comfortable.

In the fourth appointment, the following will be done for the digital pathway: denture delivery, including abutment insertion (torque: 35Ncm), chairside attachment pick-up, and first adjustments. Chairside pick-up will use a hard reline resin (GC Reline), to be handled as per manufacturer recommendations.

For both interventions, we expect to adjust most dentures at two post-delivery appointments. In a previous RCT on conventional complete dentures, 10% needed more than four appointments, with a maximum of six appointments for a single participant (total n=39) [32].

Participants will be scheduled for outcome assessment at three months following the delivery of each denture pair. A three-month period is enough to elicit stable patient perception of existing dentures, but will not induce significant wear/degradation of dental biomaterials or poor fit due to changes in intraoral

tissues. Moreover, extending each follow-up from three to six months is not expected to result in changes of ratings of patient satisfaction with received dentures, even if denture adjustments are part of the three-month period [33, 34].

Participant Allocation and Minimization of Bias

Assignment to either experimental or comparator as the first method will take place immediately after delivery adjustments of both denture pairs. The sequence for the interventions will be decided at the individual level following a list of random numbers (1:1 ratio), according to permuted blocks of varying sizes. Randomization will be performed by the trial coordinator (TC; uninvolved with clinical and follow-up procedures) and will take place at the individual level. The TC will retain a list of fabrication methods per denture pair and identify them as #1 and #2, depending on which will be used first. Random allocation to each intervention sequence will be concealed until both denture pairs are ready for delivery.

The TC will be the only person with access to the randomization codes. It is known that gender influences patient perceptions of received dentures, e.g., elderly women tend to give a higher value to esthetics than their male counterparts [35, 36]. Therefore, the sample will be stratified based on male/female, to analyze possible effects of gender on trial outcomes.

Regarding blinding, participants will be unaware of received interventions, and a researcher uninvolved in the clinical procedures will collect outcome data. Blinding will be lifted only after data collection is complete. Since digital manufacturing may have some specific features (like a subtle staircase topography), blinding effectiveness will be verified at each three-month follow-up. Participants will answer which denture pair is in use, and to grade their conviction of their response from 0-10 (“not at all certain” and “extremely certain,” respectively) [37].

Outcome measures

The primary outcome of this trial will be the general satisfaction of participants with their full dentures, in line with its ultimate goal. In addition, secondary measures will include satisfaction-specific aspects

(e.g., chewing ability and aesthetics), oral health related quality of life (OHQoL), clinical quality of the dentures, and treatment costs, all based on a public health system perspective.

1. The McGill Denture Satisfaction Questionnaire (MDSQ) [38, 39] will be used to measure overall satisfaction, and satisfaction with specific aspects of the denture – ability to chew, comfort, stability, aesthetics (appearance), ability to speak, and ability to clean. Participants will rate their satisfaction on a 100 mm visual analogue scales (VAS) with anchors representing "no satisfaction at all" to "complete satisfaction". Participants will receive training with VAS before answering the MDSQ. Previous studies have shown good properties for the MDSQ. Besides good internal consistency and reproducibility [39, 40], its ability to discriminate between different clinical conditions denotes good construct validity [39, 41, 42]. At the last follow-up, participants will be asked about which denture pair they prefer, if any, and their reasons.

2. OHQoL: This construct, conceptualized as the "subjective evaluation of the individual's oral health, functional well-being, emotional well-being, expectations and satisfaction with care, and sense of self" [43], will be assessed by the Oral Health Impact Profile for Edentulous Patients (OHIP-EDENT) questionnaire. OHIP-EDENT is a short version (20 questions) of the original 49-question OHIP (Oral Health Impact Profile) tested specifically with edentulous individuals [44]. Questions can be grouped into subscales, corresponding to domains/dimensions of perceived impact, including functional limitation or social disability. This short version shows good reliability and discriminant validity, akin to the original OHIP [44]. Despite the seven original subscales, a four-domain model based on recent factor analysis studies will be used [45, 46].

3. Clinical denture quality: This trial will use the Functional Assessment of Dentures (FAD) instrument to assess denture quality [47, 48]. FAD is composed of questions about relevant clinical parameters, including dental occlusion/articulation, denture retention and stability. A single dentist will apply the instrument without removing the dentures from the mouth, which will ensure that s/he cannot see the

staircase topography of CAD/CAM fabrication. The color of the denture base materials will be verified at baseline and after three months with a Vita EasyShade portable spectrophotometer [49]. Upper dentures will be placed on a black background and three measures will be taken from the center of the palatal vault, at the polished side. Color measures will be expressed according to the CIELCh and CIELab systems. Clinically evident damage (e.g., fractured base or teeth, stains) to denture constituents will be also reported.

4. Cost: Data on both the direct and indirect costs of each fabrication method will be gathered, as done previously [32, 50]. The number of clinical visits for denture fabrication and adjustments will be reported separately, including non-scheduled visits. Total cost per fabrication method will be described in terms of expenses with human resources (time and CAD$) and materials (consumables/equipment use, CAD$). Yearly cost differences, or $(Δ), will be calculated based on the expected lifetime of five years for a pair of dentures, by dividing total cost differences by five. After the last follow-up, participants will answer four questions on their willingness-to-pay for each denture pair: (1) If you were to choose A over B, how much are you willing to pay for it? (2) Are you willing to pay the $(Δ) to have A over B? (3) Are you willing to pay the $(Δ) to have A over B by monthly installments (12 months)? (4) Do you think that a public health plan should cover the cost of these treatments? Both or only A or B.

The cost-effectiveness of both methods will be compared by using overall patient satisfaction to measure the effect of interventions. Economic analysis will have the perspective of the public health system of Quebec. All expenditures and resources through all stages of dental care (from clinical exam to denture adjustments) will be included, considering a short-term/three-month time frame. Results will be expressed by the incremental cost-effectiveness ratio (ICER).

5. Adverse effects: All adverse events during the RCT will be recorded at each post-delivery appointment and follow-up. Common events, i.e. mucosal injuries and difficulties with new dentures, will be rated on

a three-point ordinal scale [51]. More uncommon (nausea, change in taste and lingering speech difficulties) and rare events (allergy to denture materials) will be reported on a binary scale.

6. Choice of overdenture and patient experiences: A qualitative analysis will be carried out to better understand patients' perception of CAD/CAM dentures and to find out any emergent themes besides: (1) patients' reasons for choosing a specific denture pair; and (2) their experience of using a 3D-printed IMO. By adopting a descriptive approach, individual semi-structured interviews will be carried out to obtain an in-depth understanding of patients' experiences and preferences [52].

Outcome Assessment Timeline

1. Screening: The RA will invite potential participants, answer questions, and gather informed consent. The RA will complete a screening form checking eligibility criteria for all approached individuals. Panoramic radiographs will be requested, and recruitment will be conditional based on the results from the imaging (as in Exclusion Criteria). As a piloting process, we collect data on gender conformity by two questionnaires, the Conformity to Feminine Norms Inventory-45 and Conformity to Masculine Norms Inventory-30 [53, 54].

2. Baseline: Participants will return for baseline evaluation, intraoral scanning, and collection of sociodemographic information (including gender questionnaires), medical and dental history (including patient experience with previous dentures). Participants will be asked to complete the MDSQ and OHIP-EDENT, and a dentist with experience in providing full dentures will apply the FAD instrument.

3. Delivery and denture adjustments: Immediately after the end of the delivery appointments, the FAD instrument will be applied for each denture pair (same dentist as on baseline). The adverse effects form will be completed at the same time, as well as during each post-delivery appointment, scheduled or not.

4. First follow-up (three months): Participants will complete the outcome data questionnaires, the MDSQ and OHIP-EDENT. We will administer both questionnaires with a tablet computer away from the clinical

setting. In turn, we will complete the FAD and adverse effects form, as described in the previous paragraph plus the colorimetric evaluation of denture bases.

5. Second follow-up (six months): Same as in previous time point (questionnaires and colorimetric analysis). At the end of the trial, participants will choose which overdenture they wish to keep. When faced with a choice, one is presented with the choices and the associated costs, which allows for a rationale decision. This is particularly important as dentures are typically not covered by the health care provider. Then we will conduct individual semi-structured interviews about their experiences with the IMOs. The rich descriptive data obtained by qualitative interviews will help further explicate the quantitative findings. An experienced qualitative researcher will be responsible to conduct the interviews outside of the clinic using an interview guide with open-ended questions. Given the explanatory nature of this mixed-methods design, the interview guide will be created iteratively based on the quantitative outcomes which require further explanation. Each interview will be audio-recorded and transcribed verbatim.

At baseline, we will register time (professional and patient) and materials use for cost analyses. The same procedures will be repeated during every appointment in the trial, scheduled or not.

6. Long-term follow-up: Once participants provide 6-month data and choose the denture pair they wish to keep, we will continue their follow-up. For those participants who have no preference for one specific pair, the last pair used will be kept. Then, we will schedule them for yearly appointments until five years, during which the same outcome data will be gathered. In the meantime, participants may contact the research team for unscheduled appointments. Any event such as maintenance and clinical complications, as well as time and procedures done, will be reported as part of collected outcome data.

Sample size estimation

The planned enrollment comprises 26 participants, based on overall patient satisfaction. A minimal important difference of 10mm (10% of the VAS) was used for the estimation, as done in previous RCTs [42, 55]. A standard deviation of 7.5mm was chosen for the difference in satisfaction [56]. Considering a

2-sided alpha of 0.01 to compensate for the number of secondary outcomes and a power of 90%, the RCT requires n=21 for superiority hypothesis testing (i.e., the confidence interval for between-treatment differences would exclude zero) [57]. The final sample size is drawn from including further 20% to the planned n to compensate for possible dropouts; although withdrawals will unlikely pass 10% [42, 56, 58], additional participants may be lost due to aging-related issues (e.g., worsening of systemic diseases, and death).

Adherence to Protocol and Losses to Follow-Up

Previous studies by our group reveal high study adherence rates, with >90% wearing their full dentures over the course of six months [42, 58-60]. This RCT provides variations of a treatment sought by participants at university clinics, with no major change in their routine. Subsequent follow ups following the end of this RCT will also elucidate adherence rates for longer periods. As much as possible, we set up the intervention schedule, follow-up and data collection to resemble traditional oral healthcare procedures. We will also have the RA communicate with the participants using their preferred communication method (e.g., phone, text, e-mail) to verify possible adverse events, such as pain under the denture base, that may require a rapid adjustment visit. Those events and consequent conducts will be reported as part of the outcome variable "5. Adverse effects".

Analytical plan

Quantitative Analysis

We will enter and analyze outcome data in a blind fashion at the end of data collection. The TC will enter data in spreadsheets by randomly coding the interventions as 1 and 2, and the data analyst will be unaware of their meaning until the end of statistical testing. Data will undergo descriptive analysis, with substantial deviations from normality leading to variable transformation. Generalized estimating equations (GEE) will be used to test the effect of interventions, follow-up time and gender as independent variables, with

95% confidence intervals. Other approaches to assess the primary outcome will involve the inclusion of age, baseline results and previous denture wearing in separate models, one covariate at a time.

A limitation with regards to GEE is that compared to parametric normal theory methods that necessitate the missing data to be missing at random, GEE methods impose a more stringent condition, requiring the data to be missing completely at random. Our results will be evaluated according to the intention-to-treat principle. In the case of unbalanced missing data among interventions or loss of 5% ($n > 2$) or more of participants, different strategies will be attempted for imputing primary outcome data, as recommended by Dziura *et al*. [61]; multiple imputation will be used for patient satisfaction based on least squares regression with at least five datasets. In the case of "missing not at random" (MNAR) data, analyses will be repeated after a baseline-observation-carried-forward approach (i.e., withdrawn participants will be considered as dissatisfied as prior to receiving dentures). A second analysis will be performed with imputed values and cross-checked.

Qualitative Analysis

Once the interviews are completed and transcribed, we will use the MaxQDA software for thematic analysis. Transcripts will be cut into meaningful segments and coded. Analysis will initiate by a deductive coding strategy based on the interview questions and the theoretical framework of denture satisfaction [39, 62]. Then, we will proceed by adopting an inductive analysis to add any emerging codes. By an iterative process, the coded segments will be regrouped into relevant themes linked to our study objectives [63, 64]. Methodological rigor will be warranted in the study, including member checking before or during data analysis, to meet trustworthiness, credibility, and transferability [65]. That is, the results of the study will be formally or informally discussed with participants. To enhance coding quality, the qualitative researcher and one of the team members will independently code two transcripts chosen at random and then meet to compare/revise the codes if needed. Lastly, the qualitative data will be integrated into quantitative data by an explanatory strategy.

Data management, monitoring, and auditing

Two independent researchers will regularly review the collected data as part of a data monitoring committee. Additionally, McGill University's Research Ethics Board (REB) Office retains the authority to conduct an independent audit at any point in time.

Risks, participant safety, and trial adherence

This study represents minimal safety risk for participants, since all procedures are comparable with nonsurgical oral healthcare (i.e., clinical exam, intraoral molding). The number of appointments to fabricate and adjust provided dentures is similar to what is done in standard practice, and all materials to be used are approved for patient use by Health Canada. Potential participants will receive a complete explanation of the RCT, including potential risks before invitation to sign the informed consent.

All denture materials are licensed for patient use and sold in Canada and United States. This way, risks associated with treatment are the same expected for minor oral surgery and standard dental implants/dentures. Participants may experience sore spots under the dentures after the placement of retentive components. If this happens, the dentures will be adjusted as necessary. Allergic reactions to dental materials (such as the acrylic mixture used to bond components and denture) are rare but might also occur. We also highlight that any operative procedures will be done as part of standard dental management and not as part of the research protocol per se. We do not expect risks or complications from the x-rays or other exams. This includes data collection and interviews.

We will monitor the participants for the duration of the research appointments. If lower denture breakage happens after installing retentive components during the study timeline, we will fix/repair it at no cost. Any dental treatment need will be managed by our research team or referred to professionals outside our research team. The latter case may arise, for example, if a participant request more implants to retain their dentures.

Confidentiality

Each participant's quantitative and qualitative data will be assigned an identification code to ensure confidentiality. The information connecting participants' identities to the codes will be securely stored in a password-protected file and computer. The final research forms, x-rays, and collected data will be sent to the primary investigator's office and stored for 25 years for the exclusive objectives of this study and then destroyed. These will be kept secure by a password to which only the principal doctor will have access.

Dissemination and knowledge transfer

Knowledge translation will target (i) the scientific community, and (ii) the public health and professional sectors. For the first, the team will publish reports in high-impact dental journals, as done with our previous clinical studies [59, 66]. The group will present results in scientific conferences aiming at dental professionals and researchers, as well as industry professionals, including the General Session of the International Association for Dental Research (IADR). For the second, our team will describe clinical and laboratory procedures as appendices of our scientific papers, besides a short book and YouTube videos, both directed to clinicians. The results of this study will be used to develop continuing education courses and webinars that explain the use of digital dentures based on our experiences and research findings. In addition, we will produce patient education materials, including a brochure and a video that describe the potential benefits and limitations of CAD/CAM technology for denture fabrication.

Discussion

Despite promising results, there is a scarcity of RCTs comparing CAD/CAM to conventional full denture fabrication methods, either implant-retained or conventional [25]. As of March 2018, only two clinical studies have compared full dentures fabricated by CAD/CAM and conventional methods [67]. Both of these studies were non-randomized, with one based on treatment provided by dental students [68] and the other considering surrogate measures [69]. A recent systematic review (updated: Oct-2019) confirms that CAD/CAM technologies produce dentures that fit intraoral tissues better than conventional methods [70].

That review was restricted to *in vitro* studies, however. To appraise the state of the current literature regarding digital removable dentures, we re-ran the electronic search strategies of those reviews and found no cross-over clinical trial comparing CAD/CAM to conventional implant-retained dentures. Amongst those newly published comparative studies on CAD/CAM conventional dentures, two were prospective clinical studies [68, 71], two were retrospective studies [72, 73], one was cross-sectional [74] (all five conducted in student clinics), and one was a non-randomized trial [75], besides one RCT on conventional dentures made with a closed workflow (Dentca) [76]. Besides, no study has so far explored patient experiences with the CAD/CAM dentures. Given the impact of dental prostheses on the oral health of edentulous patients, it is essential to document the clinical and patient-reported performance of digitally fabricated dentures.

Determining the potential benefits of CAD/CAM full dentures for seniors demands high-quality comparative evidence (i.e. RCT). This proposal is the first step to determine the advantages and limitations of that novel technology in treating the elderly with implant overdentures. Utilizing qualitative methods allows for a comprehensive exploration of patients' experiences, as evidenced by a previous study conducted by our team, which examined the reasons for declining treatment with implant overdentures [39]. Employing a mixed-methods approach will integrate the quantitative findings from the clinical trial by offering an in-depth interpretation of patient perspectives through qualitative methods [59].

Anticipated outcomes are expected to hold significant relevance for clinicians administering implant-assisted treatment to edentate patients. The resulting guidelines and recommendations have the potential to enhance dental prosthetic care for the edentate elderly population, a substantial portion of whom face challenges accessing more intricate treatment modalities.

Results will be important to guide public health systems and practitioners in the adoption of CAD/CAM to streamline denture provision. Better outcomes will enhance the potential access to care by edentulous seniors; government-subsidized programs, such as the recently launched Canadian Dental Care Plan for

seniors, will be able to provide IMOs with lower costs and/or fewer restrictions. Less appointments and better infection control will also reduce risks for elders to contract diseases such as COVID-19 and flu-like infections in the dental setting. Possible remote care (virtual try-in of new dentures, ordering remakes at distance) also reduces infection risk. Better knowledge of patient perceptions of CAD/CAM IMOs will highlight the potential barriers and opportunities for using digital prostheses in dental practice. It will also help understand if the CAD/CAM technology has reached its goal of offering a superior/cost-effective treatment.

Trial Status

Recruiting since January 2024.

Additional Files

Additional file 1: SPIRIT Checklist.

Additional file 2: Funding documentation.

Additional file 3: Ethical approval document.

Additional file 4: Consent form in English.

Declarations

Acknowledgements

Dana Jafarpour is the recipient of Vanier Canada Graduate Scholarship for this protocol.

Funding

This project will be supported by a grant from the ITI Foundation, Switzerland (Grant No. 1744-2023) (Additional file 2).

Availability of data and materials

For depositing research data, we might deposit anonymized datasets in the McGill Dataverse repository upon request. According to McGill, all data are stored securely on servers located in Canada. The

anonymized data may be published or shared during scientific meetings; however, it will not be possible to identify the participants.

Authors' contributions

RFS designed and will coordinate the trial. DJ drafted the manuscript and will execute the trial. NE helped to draft this manuscript and will help with the clinical interventions. CB contributed with the study design and is overseeing the qualitative data gathering and analysis. SE contributed with the study design and is overseeing the economic data collection and analysis. SAN is assisting in the prosthetic stages and integration phase/knowledge translation. TS has advised in the data analysis plan. JSF provided important contributions to study design and drafted this manuscript. EZ will assist with knowledge transfer and assessment of material performance. All authors revised and approved the final manuscript.

Ethics approval and consent to participate

Before enrolling in this trial, all participants will be required to give informed written consent and will be made aware of their right to withdraw at any point. Only in this case will unblinding be permissible. The consent process, study documentation, and the entire trial will adhere to the guidelines outlined in the Tri-Council Policy Statement [77]. The McGill University REB Office approved this protocol under the reference A00-M29-23B (22-07-089). Ethical approval documents can be found in Additional file 3. A version of this protocol has also been registered in the Clinicaltrials.gov registry under the identifier NCT03126942.

Any amendments or modifications to the protocol during the trial will be formally communicated to the REB Office. If approved, these changes will be documented on Clinicaltrials.gov and disclosed to participants, allowing them time to consider continued participation.

Participants will be officially enrolled in the trial only after obtaining a signed informed consent form (Additional file 4). A researcher will explain the study's aims and nature to each participant before they

sign the consent form. It will be clarified that participation is voluntary, and participants are free to withdraw from the study at any time without providing a reason.

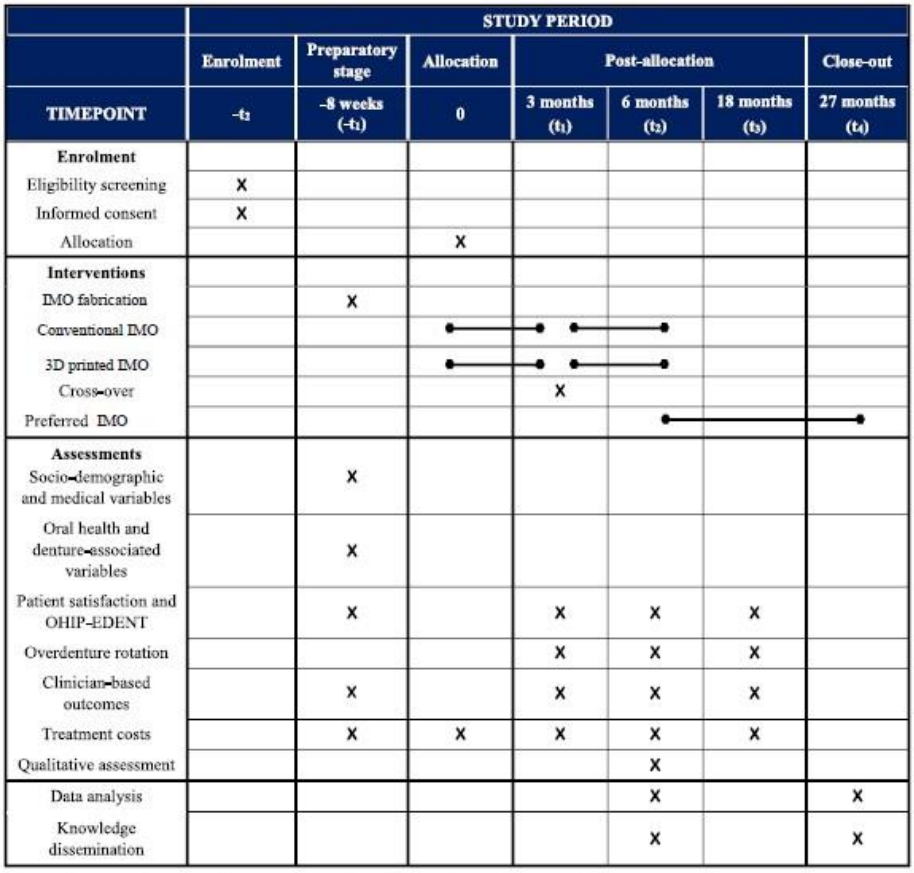
Compensation for participants will cover the cost of transportation to data collection appointments, including the baseline assessment. Participants will receive implant overdenture treatment at no cost, along with maintenance during the follow-up period.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.



	STUDY PERIOD						
	Enrolment	Preparatory stage	Allocation	Post-allocation			Close-out
TIMEPOINT	$-t_2$	−8 weeks ($-t_1$)	0	3 months (t_1)	6 months (t_2)	18 months (t_3)	27 months (t_4)
Enrolment							
Eligibility screening	X						
Informed consent	X						
Allocation			X				
Interventions							
IMO fabrication		X					
Conventional IMO			●	———	● ———	●	
3D printed IMO			●	———	● ———	●	
Cross-over				X			
Preferred IMO					●	———	●
Assessments Socio-demographic and medical variables		X					
Oral health and denture-associated variables		X					
Patient satisfaction and OHIP-EDENT		X		X	X	X	
Overdenture rotation				X	X	X	
Clinician-based outcomes		X		X	X	X	
Treatment costs		X	X	X	X	X	
Qualitative assessment					X		
Data analysis					X		X
Knowledge dissemination					X		X

Fig. 1 Study schedule: enrolment, allocation, interventions, baseline, and post-intervention assessments

Figure 7-1. The study protocol based on Standard Protocol Items: Recommendations for Interventional Trials (SPIRIT)

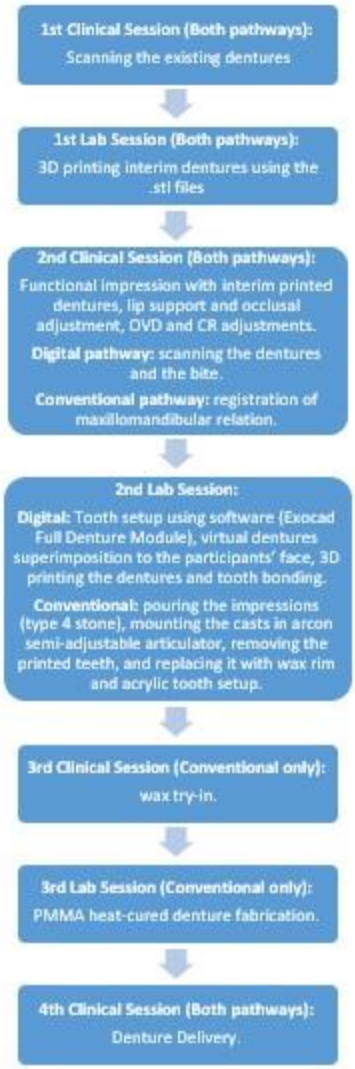


Figure 7-2. The trial intervention procedures.

References

1. Cardoso M, Balducci I, Telles DdM, Lourenço EJV, Nogueira Júnior L: Edentulism in Brazil: trends, projections and expectations until 2040. Cien Saude Colet 2016, 21:1239-1246.

2. Gerritsen AE, Allen PF, Witter DJ, Bronkhorst EM, Creugers NH: Tooth loss and oral health-related quality of life: a systematic review and meta-analysis. Health Qual Life Outcomes 2010, 8(1):1-11.

3. Rouxel P, Tsakos G, Chandola T, Watt RG: Oral health—a neglected aspect of subjective well-being in later life. J Gerontol B Psychol Sci Soc Sci 2018, 73(3):382-386.

4. Meaney S, Connell BO, Elfadil S, Allen F: A qualitative investigation into patients' perspectives on edentulousness. Gerodontology 2017, 34(1):79-85.

5. Naik AV, Pai RC: Study of emotional effects of tooth loss in an aging north Indian community. Int Sch Res Notices 2011, 2011.

6. Rodrigues SM, Oliveira AC, Vargas AMD, Moreira AN, e Ferreira EF: Implications of edentulism on quality of life among elderly. Int J Environ Res Public Health 2012, 9(1):100-109.

7. Holm-Pedersen P, Schultz-Larsen K, Christiansen N, Avlund K: Tooth loss and subsequent disability and mortality in old age. J Am Geriatr Soc 2008, 56(3):429-435.

8. Sharka R, Abed H, Hector M: Oral health-related quality of life and satisfaction of edentulous patients using conventional complete dentures and implant-retained overdentures: An umbrella systematic review. Gerodontology 2019, 36(3):195-204.

9. Suzuki H, Kanazawa M, Komagamine Y, Iwaki M, Jo A, Amagai N, Minakuchi S: The effect of new complete denture fabrication and simplified dietary advice on nutrient intake and masticatory function of edentulous elderly: A randomized-controlled trial. Clin Nutr 2018, 37(5):1441-1447.

10. Afrashtehfar KI, Schimmel M: Muscular activity may improve in edentulous patients after implant treatment. Evid.-Based Dent 2016, 17(4):119-120.

11. Peres MA, Macpherson LM, Weyant RJ, Daly B, Venturelli R, Mathur MR, Listl S, Celeste RK, Guarnizo-Herreño CC, Kearns C: Oral diseases: a global public health challenge. The Lancet 2019, 394(10194):249-260.

12. Association CD: The state of oral health in Canada. Canadian Dental Association: Ottawa, ON, Canada 2017.

13. Petersen PE, Bourgeois D, Ogawa H, Estupinan-Day S, Ndiaye C: The global burden of oral diseases and risks to oral health. Bull World Health Organ 2005, 83:661-669.

14. Brothwell DJ, Jay M, Schönwetter DJ: Dental service utilization by independently dwelling older adults in Manitoba, Canada. J Can Dent Assoc 2008, 74(2).

15. Kawai Y, Murakami H, Takanashi Y, Lund JP, Feine JS: Efficient resource use in simplified complete denture fabrication. J Prosthodont 2010, 19(7):512-516.

16. Vecchia MPD, Regis RR, Cunha TR, de Andrade IM, da Matta JCS, de Souza RF: A randomized trial on simplified and conventional methods for complete denture fabrication: cost analysis. *J Prosthodont* 2014, 23(3):182-191.

17. Schweiger J, Stumbaum J, Edelhoff D, Güth J-F: Systematics and concepts for the digital production of complete dentures: risks and opportunities. Int J Comput Dent 2018, 21(1).

18. Cristache CM, Totu EE, Iorgulescu G, Pantazi A, Dorobantu D, Nechifor AC, Isildak I, Burlibasa M, Nechifor G, Enachescu M: Eighteen months follow-up with patient-centered outcomes assessment of complete dentures manufactured using a hybrid nanocomposite and additive CAD/CAM protocol. J Clin Med 2020, 9(2):324.

19. Bidra AS, Taylor TD, Agar JR: Computer-aided technology for fabricating complete dentures: systematic review of historical background, current status, and future perspectives. J Prosthet Dent 2013, 109(6):361-366.

20. Goodacre BJ, Goodacre CJ: Additive Manufacturing for Complete Denture Fabrication: A Narrative Review. J Prosthodont, 31(S1):47-51.

21. Srinivasan M, Kamnoedboon P, McKenna G, Angst L, Schimmel M, Özcan M, Müller F: CAD-CAM removable complete dentures: A systematic review and meta-analysis of trueness of fit, biocompatibility, mechanical properties, surface characteristics, color stability, time-cost analysis, clinical and patient-reported outcomes. J Dent 2021, 113:103777.

22. de Oliveira Limírio JPJ, de Luna Gomes JM, Rezende MCRA, Lemos CAA, Rosa CDDRD, Pellizzer EP: Mechanical properties of polymethyl methacrylate as a denture base: Conventional versus CAD-CAM resin–A systematic review and meta-analysis of in vitro studies. J Prosthet Dent 2022, 128(6):1221-1229.

23. Wang C, Shi Y-F, Xie P-J, Wu J-H: Accuracy of digital complete dentures: A systematic review of in vitro studies. J Prosthet Dent 2021, 125(2):249-256.

24. Lee C-G, Jin G, Lim J-H, Liu Y, Afrashtehfar KI, Kim J-E: Influence of hydrothermal aging on the shear bond strength of 3D printed denture-base resin to different relining materials. J Mech Behav Biomed Mater. 2024, 149:106221

25. Jafarpour D, Feine JS, Morris M, Souza RF: Patient-reported outcomes and clinical performance of CAD/CAM removable dentures: A scoping review. Int J Prosthodont 2023; https://doi.org/10.11607/ijp.8556 .

26. Feine JS, Carlsson GE, Awad MA, Chehade A, Duncan WJ, Gizani S, Head T, Heydecke G, Lund JP, MacEntee M et al: The McGill consensus statement on overdentures. Mandibular two-implant overdentures as first choice standard of care for edentulous patients. Gerodontology 2002, 19(1):3-4.

27. Thomason JM, Feine J, Exley C, Moynihan P, Muller F, Naert I, Ellis JS, Barclay C, Butterworth C, Scott B et al: Mandibular two implant-supported overdentures as the first choice standard of care for edentulous patients--the York Consensus Statement. Br Dent J 2009, 207(4):185-186.

28. Moher D, Chan AW. SPIRIT (standard protocol items: recommendations for interventional trials). In: Moher D, Altman DG, Schulz KF, Simera I, Wager E, editors. Guidelines for Reporting Health Research: a user's manual. Chichester: Wiley; 2014. p. 56–67.

29. Ageing [https://www.who.int/health-topics/ageing#tab=tab_1]

30. ASA Physical Status Classification System [https://www.asahq.org/standards-and-guidelines/asa-physical-status-classification-system]

31. Souza RF: Chapter 16 - Clinical Outcomes. In: Mandibular Implant Prostheses - Guidelines for Edentulous Geriatric Populations. edn. Edited by Emami E, Feine J. Cham: Springer; 2018.

32. Vecchia MP, Regis RR, Cunha TR, de Andrade IM, da Matta JC, de Souza RF: A randomized trial on simplified and conventional methods for complete denture fabrication: cost analysis. J Prosthodont 2014, 23(3):182-191.

33. Regis RR, Cunha TR, Della Vecchia MP, Ribeiro AB, Silva-Lovato CH, de Souza RF: A randomised trial of a simplified method for complete denture fabrication: patient perception and quality. J Oral Rehabil 2013, 40(7):535-545.

34. Kawai Y, Murakami H, Shariati B, Klemetti E, Blomfield JV, Billette L, Lund JP, Feine JS: Do traditional techniques produce better conventional complete dentures than simplified techniques? J Dent 2005, 33(8):659-668.

35. Al-Omiri MK, Sghaireen MG, Al-Qudah AA, Hammad OA, Lynch CD, Lynch E: Relationship between impacts of removable prosthodontic rehabilitation on daily living, satisfaction and personality profiles. J Dent 2014, 42(3):366-372.

36. Pan S, Awad M, Thomason JM, Dufresne E, Kobayashi T, Kimoto S, Wollin SD, Feine JS: Sex differences in denture satisfaction. J Dent 2008, 36(5):301-308.

37. Turner JA, Jensen MP, Warms CA, Cardenas DD: Blinding effectiveness and association of pretreatment expectations with pain improvement in a double-blind randomized controlled trial. Pain 2002, 99(1-2):91-99.

38. Awad MA, Feine JS: Measuring patient satisfaction with mandibular prostheses. Community Dent Oral Epidemiol 1998, 26(6):400-405.

39. de Souza RF, Ribeiro AB, Oates TW, Feine JS: The McGill Denture Satisfaction Questionnaire revisited: Exploratory factor analysis of a binational sample. Gerodontology 2020, 37(3):233-243.

40. Caetano TA, Ribeiro AB, Della Vecchia MP, Cunha TR, Chaves CA, de Souza RF: Comparing a tablet computer and paper forms for assessing patient-reported outcomes in edentulous patients. J Adv Prosthodont 2016, 8(6):457-464.

41. Cerutti-Kopplin D, Emami E, Hilgert JB, Hugo FN, Rivaldo E, Padilha DMP: Predictors of Satisfaction with Dentures in a Cohort of Individuals Wearing Old Dentures: Functional Quality or Patient-Reported Measures? J Prosthodont 2017, 26(3):196-200.

42. de Souza RF, Ribeiro AB, Della Vecchia MP, Costa L, Cunha TR, Reis AC, Albuquerque RF, Jr.: Mini vs. Standard Implants for Mandibular Overdentures: A Randomized Trial. J Dent Res 2015, 94(10):1376-1384.

43. Sischo L, Broder HL: Oral health-related quality of life: what, why, how, and future implications. J Dent Res 2011, 90(11):1264-1270.

44. Allen F, Locker D: A modified short version of the oral health impact profile for assessing health-related quality of life in edentulous adults. Int J Prosthodont 2002, 15(5):446-450.

45. John MT, Feuerstahler L, Waller N, Baba K, Larsson P, Celebic A, Kende D, Rener-Sitar K, Reissmann DR: Confirmatory factor analysis of the Oral Health Impact Profile. J Oral Rehabil 2014, 41(9):644-652.

46. Souza RF, Leles CR, Guyatt GH, Pontes CB, Della Vecchia MP, Neves FD: Exploratory factor analysis of the Brazilian OHIP for edentulous subjects. J Oral Rehabil 2010, 37(3):202-208.

47. Anastassiadou V, Naka O, Heath MR, Kapari D: Validation of indices for functional assessment of dentures. Gerodontology 2002, 19(1):46-52.

48. Corrigan PJ, Basker RM, Farrin AJ, Mulley GP, Heath MR: The development of a method for functional assessment of dentures. Gerodontology 2002, 19(1):41-45.

49. Al-Qarni FD, Goodacre CJ, Kattadiyil MT, Baba NZ, Paravina RD: Stainability of acrylic resin materials used in CAD-CAM and conventional complete dentures. J Prosthet Dent 2020, 123(6):880-887.

50. Della Vecchia MP, Leles CR, Cunha TR, Ribeiro AB, Sorgini DB, Muglia VA, Reis AC, Albuquerque RF, Jr., de Souza RF: Mini-Implants for Mandibular Overdentures: Cost-Effectiveness Analysis alongside a Randomized Trial. JDR Clin Trans Res 2018, 3(1):47-56.

51. de Resende GP, Nogueira TE, Leles CR: Effectiveness of a simplified method for final impression in complete denture treatment: A pragmatic clinical trial. Gerodontology 2019, 36(4):365-373.

52. Lesaffre E, Feine J, Leroux B, Declerck D: Statistical and methodological aspects of oral health research. Chichester: Wiley Online Library; 2009.

53. Levant RF, McDermott R, Parent MC, Alshabani N, Mahalik JR, Hammer JH: Development and evaluation of a new short form of the Conformity to Masculine Norms Inventory (CMNI-30). J Couns Psychol 2020, 67(5):622-636.

54. Parent MC, Moradi B: An abbreviated tool for assessing feminine norm conformity: psychometric properties of the Conformity to Feminine Norms Inventory-45. Psychol Assess 2011, 23(4):958-969.

55. Ellis JS, Burawi G, Walls A, Thomason JM: Patient satisfaction with two designs of implant supported removable overdentures; ball attachment and magnets. Clin Oral Implants Res 2009, 20(11):1293-1298.

56. de Souza RF, Bedos C, Esfandiari S, Makhoul NM, Dagdeviren D, Abi Nader S, Jabbar AA, Feine JS: Single-implant overdentures retained by the Novaloc attachment system: study protocol for a mixed-methods randomized cross-over trial. Trials 2018, 19(1):243.

57. Julious SA: Sample sizes for clinical trials with normal data. Stat Med 2004, 23(12):1921-1986.

58. Cunha TR, Della Vecchia MP, Regis RR, Ribeiro AB, Muglia VA, Mestriner W, Jr., de Souza RF: A randomised trial on simplified and conventional methods for complete denture fabrication: masticatory performance and ability. J Dent 2013, 41(2):133-142.

59. de Souza R, Jabbar A, Jafarpour D, Bedos C, Esfandiari S, Makhoul N, Dagdeviren D, Abi Nader S, Feine J: Single-implant overdentures retained by a novel attachment: A mixed methods crossover randomized clinical trial. JDR Clin Trans Res 2024, 9(1):27-41.

60. Albuquerque IS, Regis RR, de Souza RF, Gurgel KF, Silva PG, Pinto-Fiamengui LMS, Freitas-Pontes KM: Is a two-step impression mandatory for complete denture fabrication on the severely resorbed mandible? A randomized trial on patient perception and denture quality. J Dent 2020, 98:103356.

61. Dziura JD, Post LA, Zhao Q, Fu Z, Peduzzi P: Strategies for dealing with missing data in clinical trials: from design to analysis. *Yale J Biol Med* 2013, 86(3):343.

62. Awad MA, Feine JS: Measuring patient satisfaction with mandibular prostheses. Community Dent Oral Epidemiol 1998, 26(6):400-405.

63. Braun V, Clarke V, Hayfield N, Terry G. Thematic Analysis. In: Liamputtong P, editor. Handbook of Research Methods in Health Social Sciences. Singapore: Springer; 2018. p. 843-860.

64. Thorogood N, Green J: Qualitative methods for health research. Qualitative methods for health research 2018:1-440.

65. Sandelowski M: The problem of rigor in qualitative research. ANS Adv Nurs Sci 1986, 8(3):27-37.

66. De Souza R, Ribeiro A, Della Vecchia M, Costa L, Cunha T, Reis ACd, Albuquerque Jr R: Mini vs. standard implants for mandibular overdentures: a randomized trial. J Dent Res 2015, 94(10):1376-1384.

67. Janeva NM, Kovacevska G, Elencevski S, Panchevska S, Mijoska A, Lazarevska B: Advantages of CAD/CAM versus Conventional Complete Dentures - A Review. Open Access Maced J Med Sci 2018, 6(8):1498-1502.

68. Kattadiyil MT, Jekki R, Goodacre CJ, Baba NZ: Comparison of treatment outcomes in digital and conventional complete removable dental prosthesis fabrications in a predoctoral setting. J Prosthet Dent 2015, 114(6):818-825.

69. AlHelal A, AlRumaih HS, Kattadiyil MT, Baba NZ, Goodacre CJ: Comparison of retention between maxillary milled and conventional denture bases: A clinical study. J Prosthet Dent 2017, 117(2):233-238.

70. Wang C, Shi YF, Xie PJ, Wu JH: Accuracy of digital complete dentures: A systematic review of in vitro studies. J Prosthet Dent 2021, 125(2):249-256.

71. Srinivasan M, Schimmel M, Naharro M, C ON, McKenna G, Muller F: CAD/CAM milled removable complete dentures: time and cost estimation study. J Dent 2019, 80:75-79.

72. Arakawa I, Al-Haj Husain N, Srinivasan M, Maniewicz S, Abou-Ayash S, Schimmel M: Clinical outcomes and costs of conventional and digital complete dentures in a university clinic: A retrospective study. J Prosthet Dent. 2022;128(3):390-395.

73. Kim TH, Huh JB, Lee J, Bae EB, Park CJ: Retrospective Comparison of Postinsertion Maintenances Between Conventional and 3D Printed Complete Dentures Fabricated in a Predoctoral Clinic. *J Prosthodont* 2021, 30(S2):158-162.

74. Clark WA, Brazile B, Matthews D, Solares J, De Kok IJ: A Comparison of Conventionally Versus Digitally Fabricated Denture Outcomes in a University Dental Clinic. *J Prosthodont* 2021, 30(1):47-50.

75. Drago C, Borgert AJ: Comparison of nonscheduled, postinsertion adjustment visits for complete dentures fabricated with conventional and CAD-CAM protocols: A clinical study. J Prosthet Dent 2019, 122(5):459-466.

76. Ohara K, Isshiki Y, Hoshi N, Ohno A, Kawanishi N, Nagashima S, Inoue M, Kubo D, Yamaya K, Inoue E et al: Patient satisfaction with conventional dentures vs. digital dentures fabricated using 3D-printing: A randomized crossover trial. J Prosthodont Res 2022, 66(4):623-629.

77. TCPS-2: Canadian Institutes of Health Research, Natural Sciences and Engineering Research Council of Canada, and Social Sciences and Humanities Research Council of Canada. Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans 2014.

8. Discussion

Through detailed analysis and exploration, this thesis aims to contribute to the improvement of IODs by identifying potential areas for advancement and proposing solutions to overcome existing obstacles. This section provides a summary of the research presented in the papers, highlighting their contributions to the outlined objectives and examining their strengths and weaknesses.

8.1. Comparison between Novaloc and Locator attachment systems for IOD

In evidence-based dentistry, conducting *in vitro* research serves as the preliminary step in a structured approach to addressing oral health issues (118). Aligning with this methodology, our thesis initiated with an *in vitro* examination of implant overdenture attachments. Our investigation emerged as the first to analytically compare the structural integrity and thermal properties of the Novaloc attachment system against the established Locator system. This comparative analysis of attachments' change in crystallinity and thermal behavior is critically important as it offers further insights into the performance and resilience of these materials under load conditions akin to those encountered within the oral cavity.

Understanding the thermal characteristics of dental polymers is crucial for forecasting their durability, optimizing fabrication techniques, and identifying the impact of aging. Thus, it is important to study how these polymers react to various heat conditions (119). Thermal Gravimetric Analysis (TGA) is a method that measures the mass of a material as it is either heated or cooled at a steady pace, tracking the changes over time or with temperature variations. This technique allows for the observation of weight alterations in samples due to temperature changes (120). Additionally, Differential Scanning Calorimetry (DSC) was employed to examine material changes like melting, crystallization, and the glass transition phase. Analyzing data from both TGA and DSC can reveal the composition and resilience of the material under study (119).

In addition to the factors delineated within the manuscript, an additional contributory factor to the comparatively stable retention force exhibited by Novaloc may pertain to the presence of a gap due to the ring slot shape of Novaloc. This interspace facilitates expansion devoid of considerable tension or intense friction, thereby substantially prolonging the functional longevity of the attachment (121).

Furthermore, the outcomes of our *in vitro* research serve as a complement to the conclusions drawn from our previous clinical trial on single implant overdentures (SIMOs), as documented by de Souza *et al*. (59). Within the scope of that investigation, we recognized that among elderly edentulous patients utilizing SIMOs, the Novaloc attachment system was associated with enhanced patient satisfaction and preference, presumably attributed to the superior patient-perceived denture stability provided by the Novaloc system.

Given the foundational nature of our findings, we propose that the subsequent investigation should involve empirical assessment in a clinical context. This step is crucial for validating the *in vitro* findings. As during function, removable prostheses resist both axial and para-axial lateral and rotational dislodging forces at different locations intraorally. True unidirectional dislodging forces rarely occur in clinical scenarios, although unidirectional pulling test is considered an effective way of measuring retention of prostheses and attachments during *in vitro* laboratory investigations (122). For that reason, our forthcoming endeavor involves conducting a cross-over clinical trial aimed at verifying the clinical performance of Novaloc attachment in a two-implant mandibular overdenture setup.

In our *in vitro* study, the Novaloc attachment featured a coating of amorphous diamond-like carbon (ADLC), reputed for its wear resistance properties. However, this coating is not yet approved to be used in certain countries, e.g. the United States. An alternative option could be the titanium nitride coating (TiN) which is a permissible option in countries, including the United States, aligning with specific regulatory standards. Moreover, some patients have raised concern regarding the unpleasant black color of the ADLC-coated Novaloc. Given the importance of aesthetic considerations for certain patients (10),

there is a need to evaluate the more aesthetic Novaloc attachments coated with titanium nitride (TiN). Consequently, a forthcoming phase of our future *in vitro* research will involve the experimental assessment of these attachments with the newly applied TiN coating.

The limitations of our *in vitro* study are intrinsically linked to its design. While a substantial number of cycles were utilized *in vitro*, these only approximate one year of real-world usage within the oral cavity. This duration is relatively brief when contrasted with the extended period during which patients typically utilize such dental prostheses in reality. Consequently, we propose that an expanded experimental setup, incorporating a significantly greater number of compression and insertion-removal cycles to simulate masticatory actions over a minimum duration of five years, would substantially enhance the applicability of our findings. Moreover, the application of a unidirectional force without accounting for the influence of factors such as pH levels, temperature, saliva, and the food impaction on the performance of attachments are among the other limitations of this study.

8.2. Conventional vs CAD/CAM dentures

Recognizing the advancements documented in literature is crucial to avoid redundancy in research efforts. This rationale led us to carry out a scoping review of digital dentures. The aim was to chart the current evidence concerning digital dentures, and identifying existing knowledge gaps prior to embarking on a clinical trial. Our review indicated that CAD/CAM technology for complete and partial dentures could potentially offer significant savings in terms of time and cost, while maintaining or enhancing patient and clinician satisfaction compared to traditional prosthetic solutions (123). However, we also identified that the evidence base underpinning these advantages is currently weak, highlighting the necessity for future, rigorously designed randomized controlled trials, particularly on implant-overdentures, with larger sample sizes to validate these preliminary findings (123).

A primary limitation of our review was its susceptibility to bias. Despite our efforts to conduct a comprehensive search and retrieval of a broad array of studies, the absence of a quality assessment tool to evaluate the included studies left room for potential biases in our conclusions. Thus, we hypothesized that a systematic review, known for its stringent methodological framework, may offer a more balanced and critical evaluation of the available evidence on this subject (124).

Nevertheless, the scoping review methodology selected for our study brings its own distinct advantages, particularly suited to exploring an expansive topic such as digital dentures. Scoping reviews are carried out to uncover gaps in knowledge, map out the extent of research literature, clarify theoretical concepts, or examine how research is carried out (124). They also accommodate a variety of study designs beyond, for instance, just randomized controlled trials. This broader inclusion criterion facilitates a more comprehensive understanding of the topic. Additionally, the process of conducting a systematic review requires a narrowly defined research question, for which our scoping review laid the groundwork, assisting in the formulation of such a question (124).

Moving on to our meta-analysis, the emphasis was placed on patient-reported outcomes, with a specific focus on evaluating patient satisfaction and oral health-related quality of life post CAD/CAM treatment. The findings of our analysis reinforced those identified in the scoping review, underscoring the necessity for more robust clinical trials and qualitative studies to lay the groundwork for the development of clinical guidelines.

A significant strength of our meta-analysis is its novelty in pooling patient-reported outcomes, especially regarding the oral health-related quality of life of patients. To the best of our knowledge, this has not been done in any previous work. The findings from our systematic review highlighted a notable gap in qualitative research on this topic. Furthermore, this meta-analysis provided data on the cost-effectiveness of different digital and conventional methods. In the case of dentures, understanding which techniques

offer the best balance of cost and effectiveness can make this treatment more accessible and justify investment in the relative field. When interpreting the results of the meta-analysis, it is important to consider that interpretation of 'cost savings' must account for the target population of the studies. In certain societies, the availability of scanners can significantly influence these costs. For instance, in Brazil, reliance on scanning services might render digital workflows more expensive than the conventional procedures. There is need to consider country-specific factors before generalizing the findings on cost-effectiveness.

One of the limitations encountered in our study was the relatively small number of studies included, which may have contributed to considerable heterogeneity in our findings. This variability underscores the need for caution in interpreting the results, as the diversity of study designs, patient populations, and treatment modalities (open vs. closed workflows) could influence the outcomes and conclusions drawn from our analysis.

8.3. Optimizing the 3D printing CAD/CAM technique

Upon identifying the necessity for a clinical trial focused on CAD/CAM IODs using 3D printing technology, we turned our attention to refining the technical aspects of this emerging field. Given that fabricating 3D printed dentures is still in its inception phase (125), there is no consensus on which printing technique yields the most advantageous outcomes. Consequently, the evaluation of optimal parameters through *in vitro* studies emerges as a critical preliminary step before the adoption of 3D printed CAD/CAM IODs in the clinic.

Our study distinguishes itself as the first to evaluate the singular effects of thermal annealing as a post-processing technique on the properties of 3D-printed denture base resin. The findings of this investigation elucidated that the mechanical and surface characteristics of 3D-printed denture base materials are significantly influenced by the processing parameters. It was ascertained that an angulation of 90 degrees

during printing offers the optimal mechanical properties, and reduces both time and expenditure on the material.

However, it is important to acknowledge the limitations encountered in this study, notably, the potential influence of environmental conditions on the experimental outcomes. Specifically, the duration for which the specimens were exposed to ambient conditions on the bench may have inadvertently affected the results, given that natural light contains ultraviolet (UV) radiation, which could alter the properties of the specimens. This aspect underscores the necessity for controlled environmental conditions in future research to ensure the reliability and validity of findings. Subsequently, it is proposed to apply the identical parameters in an *in vivo* context to corroborate these preliminary results as intraoral pH levels, temperature, saliva, and food impaction may affect performance of the 3D-printed bases.

8.4. Designing a clinical trial on 3D-printed CAD/CAM IODs

Upon establishing the optimal parameters through our preliminary *in vitro* investigations, we have progressed to the initiation of a clinical trial phase. This phase has been meticulously designed with the intent of examining Canadian seniors' satisfaction with 3D-printed IODs, in comparison to the traditional treatment modalities. This clinical trial is currently being conducted in a double-blind, cross-over mixed-methods randomized controlled trial format at the McGill Dental Clinic. The study has been registered with the ClinicalTrials.gov registry (NCT06155630), underscoring our commitment to transparency and adherence to research governance standards.

This trial serves as a feasibility study which could help assess the viability of the study's methodology, specifically inspecting the participant recruitment strategy and retention rate. Initiated in January 2024, the screening process is anticipated to extend over a nine-month period. The significance of this research

cannot be overstated, as it possesses the potential to formulate treatment guidelines, thereby facilitating a paradigm shift in the clinical management of mandibular edentulism.

Moreover, this study distinguishes itself by being the first qualitative investigation to delve into patient experiences with 3D-printed IODs. Since quantitative research does not offer an in-depth insight into complex psychosocial dynamics, the qualitative dimension of this research is particularly invaluable, offering profound insights into the benefits and challenges associated with the adoption of digital technologies in the fabrication of IODs (126). This holistic approach not only enriches our understanding of patient satisfaction and treatment efficacy but also illuminates the broader implications of integrating digital innovations into clinical practices. Through this lens, the study contributes significantly to the body of knowledge on the application of qualitative research methodologies in dental medicine, particularly in the exploration of patient-centered outcomes and the facilitation of technology-driven advancements in treatment protocols.

8.5. Public Health Implications

Our chosen population adheres to the Canadian Dental Association's public dental health standards (127). Seniors in Canada face numerous barriers in accessing healthcare (128), especially those who are frail (129) or part of marginalized groups like ethnic minorities, immigrants (130), and Indigenous communities (131). These challenges have been underscored by the COVID-19 pandemic. By early September 2020, individuals aged 60 and older made up a large majority of the deaths, even though they constituted a significantly smaller proportion of the reported cases. Therefore, implementing tele-dentistry to reduce the frequency of dental visits could greatly assist this group by providing more accessible healthcare.

The study's outcomes will be crucial for informing public health strategies and dental practitioners. Adopting CAD/CAM techniques and IOD attachments with minimum maintenance could showcase an opportunity for increasing access to dental care for edentulous elderly patients. The reduction in clinic visits, and the possibility of remote dental services could lower the risk of infectious diseases for elderly patients. Understanding patients' views on CAD/CAM-fabricated dentures will shed light on the potential challenges and benefits of using digital prosthetics in dental practices. Should the ongoing RCT confirm the preliminary findings, the implications for clinical practice are profound. This will not only enhance patient outcomes, but also contribute to the efficiency and cost-effectiveness of dental treatments. This transition supports a more inclusive approach to oral healthcare, promising greater access and improved quality of life for individuals affected by mandibular edentulism, thus highlighting the thesis's substantial contribution to public health objectives.

8.6. Knowledge translation and future directions

Knowledge translation represents a critical component of my thesis, illustrating a comprehensive journey from theoretical research to practical application within the domain of 3D-printed denture fabrication. This journey encompasses an initial focus on a systematic review and meta-analysis—the pinnacle of evidence synthesis in clinical research, advancing through *in vitro* studies, and culminating in a clinical trial.

In this thesis, knowledge translation is effectively achieved by bridging the gap between our *in vitro* findings and their application in clinical settings through our clinical trial. Initially, we synthesized the existing research and engaged with stakeholders (including the manufacturers) to ensure the study addresses relevant clinical gaps and needs. Throughout the trial, rigorous evidence is generated about the advantages, performance, and challenges of using 3D-printed implant overdentures, accompanied by transparent reporting for critical appraisal. The findings will then be widely disseminated through

academic and professional channels, translated into accessible formats for various audiences, including the incorporation into clinical guidelines and educational programs for dental professionals. This ensures that the trial's results inform clinical decision-making and policy, improving the quality of dental care by integrating innovative 3D printing technologies into practice.

As 3D printing technology is in its emerging stages, there is a compelling necessity to explore methodologies for enhancing the functionality of 3D-printed dentures. A notable limitation associated with these digitally fabricated prostheses is the challenge involved in relining; that is the process of improving the fit of the intaglio surface of a denture by adding a relining material to its base. Moreover, during the fabrication of the overdentures, reline resin is used to adapt the internal surface of the denture base to the attachment systems in a procedure called attachment pick-up. The process of relining is critical as it mitigates the need for complete denture fabrication once again, thereby emphasizing the importance of optimizing the adhesion between reline resins and the 3D-printed denture base resin. Our forthcoming *in vitro* investigations are aimed at focusing on this pivotal issue. Preliminary efforts in our pilot study involved evaluating the effectiveness of various surface treatments to augment the shear bond strength of hard reline resin materials to 3D-printed denture bases. Should our ultimate *in vitro* results confirm enhancements in the bond strength, it would not only validate the clinical applicability of these modifications, but also facilitate the overdenture attachment pick-up procedure in our forthcoming trial of the 3D-printed overdentures.

Additionally, the aesthetics of 3D-printed dental prostheses remain a concern, primarily due to the use of monochromatic teeth, which fail to imitate the natural gradations of human teeth effectively. In response, emerging techniques for multi-chromatic printing, such as those developed by Stratasys, are under investigation. Also, the wear resistance of the vast commercially available pre-fabricated stock-teeth against the printed or milled one still remains a concern. It is imperative that future research continues to

advance these innovative printing technologies to enhance the visual and functional outcomes of 3D-printed dental prostheses.

9. Conclusion

- The *in vitro* study showed that during the cycling period, Novaloc attachment system showed stable retentive forces relative to the Locator system, despite lower overall retentive force.
- The scoping review and meta-analysis suggested that CAD/CAM dentures are comparable to the conventional dentures regarding patient- and clinician-centered outcomes, yet they offer lower fabrication costs.
- The review and meta-analysis showed that there is a need for well-designed randomized clinical trials with large sample size to verify the findings for CAD/CAM dentures.
- In our set of experimental tests on 3D-printed denture base material, it was found that both printing orientation and post-processing technique affect the mechanical and surface properties of these materials.
- The results, if confirmed *in vivo*, can improve patients' access to oral health care, by offering them a cost-effective, fast, and efficient treatment for mandibular edentulism.

10. References

1. WHO. Working together for health: the World Health Report 2006 [Available from: https://www.who.int/whr/2006/whr06_en.pdf.

2. Cardoso M, Balducci I, Telles Dde M, Lourenco EJ, Nogueira Junior L. Edentulism in Brazil: trends, projections and expectations until 2040. Ciencia & saude coletiva. 2016;21(4):1239-46.

3. Holm-Pedersen P, Schultz-Larsen K, Christiansen N, Avlund K. Tooth loss and subsequent disability and mortality in old age. Journal of the American Geriatrics Society. 2008;56(3):429-35.

4. Carlsson GE, Omar R. The future of complete dentures in oral rehabilitation. A critical review. J Oral Rehabil. 2010;37(2):143-56.

5. Cunha TR, Della Vecchia MP, Regis RR, Ribeiro AB, Muglia VA, Mestriner W, Jr., et al. A randomised trial on simplified and conventional methods for complete denture fabrication: masticatory performance and ability. Journal of dentistry. 2013;41(2):133-42.

6. Redford M, Drury TF, Kingman A, Brown LJ. Denture use and the technical quality of dental prostheses among persons 18-74 years of age: United States, 1988-1991. J Dent Res. 1996;75 Spec No:714-25.

7. Thomason JM, Feine J, Exley C, Moynihan P, Muller F, Naert I, et al. Mandibular two implant-supported overdentures as the first choice standard of care for edentulous patients--the York Consensus Statement. British dental journal. 2009;207(4):185-6.

8. Feine J, Carlsson G, Awad M, Chehade A, Duncan W, Gizani S, et al. The McGill consensus statement on overdentures. Mandibular two-implant overdentures as first choice standard of care for edentulous patients. Gerodontology. 2002;19(1):3-4.

9. Ramadan RE, Mohamed FS. Retention of mandibular implant-retained overdentures with two different attachment designs: An in vitro study. The Journal of prosthetic dentistry. 2020;123(5):738. e1-. e6.

10. de Souza R, Jabbar A, Jafarpour D, Bedos C, Esfandiari S, Makhoul N, et al. Single-implant overdentures retained by a novel attachment: A mixed methods crossover randomized clinical trial. JDR Clin Trans Res. 2024 Jan;9(1):27-41..

11. Abi Nader S, De Souza R, Fortin D, De Koninck L, Fromentin O, Albuquerque Junior R. Effect of simulated masticatory loading on the retention of stud attachments for implant overdentures. Journal of Oral Rehabilitation. 2011;38(3):157-64.

12. Sharaf M, Eskander A, Afify M. Novel PEEK retentive elements versus conventional retentive elements in mandibular overdentures: a randomized controlled trial. International Journal of Dentistry. 2022;2022:6947756.

13. Setz J, Lee SH, Engel E. Retention of prefabricated attachments for implant stabilized overdentures in the edentulous mandible: an in vitro study. The Journal of prosthetic dentistry. 1998;80(3):323-9.

14. Schweiger J, Stumbaum J, Edelhoff D, Guth JF. Systematics and concepts for the digital production of complete dentures: risks and opportunities. Int J Comput Dent. 2018;21(1):41-56.

15. Cristache CM, Totu EE, Iorgulescu G, Pantazi A, Dorobantu D, Nechifor AC, et al. Eighteen Months Follow-Up with Patient-Centered Outcomes Assessment of Complete Dentures Manufactured Using a Hybrid Nanocomposite and Additive CAD/CAM Protocol. J Clin Med. 2020;9(2):324.

16. Bidra AS, Taylor TD, Agar JR. Computer-aided technology for fabricating complete dentures: systematic review of historical background, current status, and future perspectives. J Prosthet Dent. 2013;109(6):361-6.

17. Bryant SR, Walton JN, MacEntee MI. A 5-year randomized trial to compare 1 or 2 implants for implant overdentures. J Dent Res. 2015;94(1):36-43.

18. Kattadiyil MT, Jekki R, Goodacre CJ, Baba NZ. Comparison of treatment outcomes in digital and conventional complete removable dental prosthesis fabrications in a predoctoral setting. Journal of Prosthetic Dentistry. 2015;114(6):818-25.

19. Srinivasan M, Schimmel M, Naharro M, O' Neill C, McKenna G, Müller F. CAD/CAM milled removable complete dentures: time and cost estimation study. Journal of dentistry. 2019;80:75-9.

20. Arakawa I, Al-Haj Husain N, Srinivasan M, Maniewicz S, Abou-Ayash S, Schimmel M. Clinical outcomes and costs of conventional and digital complete dentures in a university clinic: A retrospective study. Journal of Prosthetic Dentistry.; 2022;128(3):390-395 21. Kim TH, JungHuh B, Lee J, Bae EB, Park CJ. Retrospective Comparison of Postinsertion Maintenances Between Conventional and 3D Printed Complete Dentures Fabricated In A Predoctoral Clinic. Journal of Prosthodontics. 2021; 30(S2):158-162.

22. Clark WA, Brazile B, Matthews D, Solares J, De Kok IJ. A Comparison of Conventionally Versus Digitally Fabricated Denture Outcomes in a University Dental Clinic. Journal of Prosthodontics. 2021;30(1):47-50.

23. Drago C, Borgert AJ. Comparison of nonscheduled, postinsertion adjustment visits for complete dentures fabricated with conventional and CAD-CAM protocols: A clinical study. Journal of Prosthetic Dentistry. 2019;122(5):459-66.

24. Al-Rafee MA. The epidemiology of edentulism and the associated factors: A literature Review. Journal of family medicine and primary care. 2020;9(4):1841-3.

25. Cunha-Cruz J, Hujoel P, Nadanovsky P. Secular trends in socio-economic disparities in edentulism: USA, 1972–2001. Journal of dental research. 2007;86(2):131-6.

26. Cooper LF. The current and future treatment of edentulism. Journal of Prosthodontics: Implant, Esthetic and Reconstructive Dentistry. 2009;18(2):116-22.

27. Eklund SA, Burt BA. Risk factors for total tooth loss in the United States; longitudinal analysis of national data. Journal of public health dentistry. 1994;54(1):5-14.

28. Kapp JM, Boren SA, Yun S, LeMaster J. Peer reviewed: Diabetes and tooth loss in a national sample of dentate adults reporting annual dental visits. Preventing chronic disease. 2007;4(3):A59.

29. Santo A, Tagliaferro E, Ambrosano G, Meneghim M, Pereira A. Dental status of Portuguese HIV+ patients and related variables: a multivariate analysis. Oral diseases. 2010;16(2):176-84.

30. Meisel P, Wilke P, Biffar R, Holtfreter B, Wallaschofski H, Kocher T. Total tooth loss and systemic correlates of inflammation: role of obesity. Obesity. 2012;20(3):644-50.

31. Chapple IL, Bouchard P, Cagetti MG, Campus G, Carra MC, Cocco F, et al. Interaction of lifestyle, behaviour or systemic diseases with dental caries and periodontal diseases: consensus report of group 2 of the joint EFP/ORCA workshop on the boundaries between caries and periodontal diseases. Journal of clinical periodontology. 2017;44:S39-S51.

32. Latif TM, Vieira A. Risk factors and comorbidities associated with complete edentulism in individuals younger than fifty years of age. Journal of Dentistry and Oral Health. 2017;4(1):1-6.

33. Krogh HW. Permanent tooth mortality: A clinical study of causes of loss. The Journal of the American Dental Association. 1958;57(5):670-5.

34. Khazaei S, Firouzei MS, Sadeghpour S, Jahangiri P, Savabi O, Keshteli AH, et al. Edentulism and tooth loss in Iran: SEPAHAN systematic review No. 6. International journal of preventive medicine. 2012;3(Suppl1):S42.

35. Müller F, Naharro M, Carlsson GE. What are the prevalence and incidence of tooth loss in the adult and elderly population in Europe? Clinical oral implants research. 2007;18:2-14.

36. Dye BA, Thornton-Evans G, Li X, Iafolla T. Dental caries and tooth loss in adults in the United States, 2011-2012. 2015.

37. Slade G, Akinkugbe A, Sanders A. Projections of US edentulism prevalence following 5 decades of decline. Journal of dental research. 2014;93(10):959-65.

38. Canada CH. Summary Report on the Findings of the Oral Health Component of the Canadian Health Measures Survey, 2007-2009: Health Canada; 2010.

39. Millar WJ, Locker D. Edentulism and denture use. Health Rep. 2005;17(1):55-8.

40. Locker D. Measuring oral health. A conceptual framework. Community Dent Health. 1988;5:3-18.

41. Felton DA. Complete edentulism and comorbid diseases: an update. Journal of Prosthodontics. 2016;25(1):5-20.

42. Emami E, de Souza RF, Kabawat M, Feine JS. The impact of edentulism on oral and general health. International journal of dentistry. 2013;2013:498305.

43. Felton D, Cooper L, Duqum I, Minsley G, Guckes A, Haug S, et al. Evidence-based guidelines for the care and maintenance of complete dentures: A publication of the American College of Prosthodontists. Journal of Prosthodontics: Implant, Esthetic and Reconstructive Dentistry. 2011;20:S1-S12.

44. Rouxel P, Tsakos G, Chandola T, Watt RG. Oral health—a neglected aspect of subjective well-being in later life. The Journals of Gerontology: Series B. 2018;73(3):382-6.

45. Meaney S, Connell BO, Elfadil S, Allen F. A qualitative investigation into patients' perspectives on edentulousness. Gerodontology. 2017;34(1):79-85.

46. Naik AV, Pai RC. Study of emotional effects of tooth loss in an aging north Indian community. ISRN Dent. 2011;2011:395498.

47. Holm-Pedersen P, Schultz-Larsen K, Christiansen N, Avlund K. Tooth loss and subsequent disability and mortality in old age. Journal of the American Geriatrics Society. 2008;56(3):429-35.

48. Zitzmann NU, Hagmann E, Weiger R. What is the prevalence of various types of prosthetic dental restorations in Europe? Clinical oral implants research. 2007;18:20-33.

49. Carlsson G, Omar R. The future of complete dentures in oral rehabilitation. A critical review. Journal of Oral Rehabilitation. 2010;37(2):143-56.

50. Nogueira T, Dias D, Leles C. Mandibular complete denture versus single-implant overdenture: a systematic review of patient-reported outcomes. Journal of Oral Rehabilitation. 2017;44(12):1004-16.

51. Jacob RF. The traditional therapeutic paradigm: complete denture therapy. The Journal of prosthetic dentistry. 1998;79(1):6-13.

52. Feine J, Carlsson G, Awad M, Chehade A, Duncan W, Gizani S, et al. The McGill consensus statement on overdentures. Mandibular two-implant overdentures as first choice standard of care for edentulous patients. Montreal, Quebec, May 24-25, 2002. The International journal of oral & maxillofacial implants. 2002;17(4):601-2.

53. Lee DJ, Saponaro PC. Management of edentulous patients. Dental Clinics. 2019;63(2):249-61.

54. Kordatzis K, Wright PS, Meijer HJ. Posterior mandibular residual ridge resorption in patients with conventional dentures and implant overdentures. International Journal of Oral & Maxillofacial Implants. 2003;18(3):447-52.

55. Thomason JM, Lund JP, Chehade A, Feine JS. Patient satisfaction with mandibular implant overdentures and conventional dentures 6 months after delivery. International Journal of Prosthodontics. 2003;16(5):467-73.

56. Morais J, Heydecke G, Pawliuk J, Lund J, Feine J. The effects of mandibular two-implant overdentures on nutrition in elderly edentulous individuals. Journal of dental research. 2003;82(1):53-8.

57. Bakke M, Holm B, Gotfredsen K. Masticatory function and patient satisfaction with implant-supported mandibular overdentures: a prospective 5-year study. International Journal of prosthodontics. 2002;15(6):575-81.

58. Goodacre C, Goodacre B. Fixed vs removable complete arch implant prostheses: a literature review of prosthodontic outcomes. Eur J Oral Implantol. 2017;10(Suppl 1):13-34.

59. de Souza R, Jabbar A, Jafarpour D, Bedos C, Esfandiari S, Makhoul N, et al. Single-implant overdentures retained by a novel attachment: a mixed methods crossover randomized clinical trial. JDR Clinical & Translational Research. 2024;9(1):27-41.

60. Thomason JM, Feine J, Exley C, Moynihan P, Müller F, Naert I, et al. Mandibular two implant-supported overdentures as the first choice standard of care for edentulous patients-the York Consensus Statement. British dental journal. 2009;207(4):185-6.

61. Swain MV. Attachment systems for mandibular two-implant overdentures: a review of in vitro investigations on retention and wear features. Int J Prosthodont. 2009;22(5):429-40.

62. Wakam R, Benoit A, Mawussi KB, Gorin C. Evaluation of retention, wear, and maintenance of attachment systems for single-or two-implant-retained mandibular overdentures: a systematic review. Materials. 2022;15(5):1933.

63. Kim H-Y, Lee J-Y, Shin S-W, Bryant SR. Attachment systems for mandibular implant overdentures: a systematic review. The journal of advanced prosthodontics. 2012;4(4):197-203.

64. Harder S, Wolfart S, Egert C, Kern M. Three-year clinical outcome of single implant-retained mandibular overdentures—results of preliminary prospective study. Journal of dentistry. 2011;39(10):656-61.

65. Chang H-S, Hsieh Y-D, Hsu M-L. Long-term survival rate of implant-supported overdentures with various attachment systems: A 20-year retrospective study. Journal of Dental Sciences. 2015;10(1):55-60.

66. Bryant S, Walton J, MacEntee M. A 5-year randomized trial to compare 1 or 2 implants for implant overdentures. Journal of dental research. 2015;94(1):36-43.

67. Choi J-W, Bae J-H, Jeong C-M, Huh J-B. Retention and wear behaviors of two implant overdenture stud-type attachments at different implant angulations. The Journal of prosthetic dentistry. 2017;117(5):628-35.

68. Gotfredsen K, Holm B. Implant-supported mandibular overdentures retained with ball or bar attachments: a randomized prospective 5-year study. International Journal of Prosthodontics. 2000;13(2):125-30.

69. Fayad MI, Osman M, Haddad D, Quassemc M. Locator versus ball and socket attachment systems for single implant retained mandibular overdenture (retention-oral health related quality of life). Al-Azhar Assiut Dental Journal. 2019;2(2):109-15.

70. Daou EE. Stud attachments for the mandibular implant-retained overdentures: Prosthetic complications. A literature review. The Saudi Dental Journal. 2013;25(2):53-60.

71. Miler A, Correia ARM, Rocha JdC, Campos JCR, da Silva M. Locator® attachment system for implant overdentures: a systematic review. Stomatologija. 2017;19(4):124-9.

72. Guédat C, Nagy U, Schimmel M, Müller F, Srinivasan M. Clinical performance of LOCATOR® attachments: A retrospective study with 1–8 years of follow-up. Clinical and experimental dental research. 2018;4(4):132-45.

73. Geckili O, Bilhan H, Bilgin T. Locator attachments as an alternative to ball attachments in 2-implant retained mandibular overdentures. Journal of the Canadian Dental Association. 2007;73(8):691-4.

74. Kleis WK, Kämmerer PW, Hartmann S, Al-Nawas B, Wagner W. A comparison of three different attachment systems for mandibular two-implant overdentures: One-year report. Clinical implant dentistry and related research. 2010;12(3):209-18.

75. Bilhan H, Geckili O, Mumcu E, Bilmenoglu C. Maintenance requirements associated with mandibular implant overdentures: clinical results after first year of service. Journal of Oral Implantology. 2011;37(6):697-704.

76. Passia N, Ghazal M, Kern M. Long-term retention behaviour of resin matrix attachment systems for overdentures. Journal of the mechanical behavior of biomedical materials. 2016;57:88-94.

77. Arnold C, Stampa C, Schweyen R, Hey J, Boeckler A. Retentive characteristics of a new attachment system for hybrid dentures. Materials. 2020;13(15):3434.

78. Maniewicz S, Badoud I, Herrmann FR, Chebib N, Ammann P, Schimmel M, et al. In vitro retention force changes during cyclic dislodging of three novel attachment systems for implant overdentures with different implant angulations. Clinical oral implants research. 2020;31(4):315-27.

79. Anthony D, Peyton F. Dimensional accuracy of various denture-base materials. The Journal of Prosthetic Dentistry. 1962;12(1):67-81.

80. Dimitrova M, Corsalini M, Kazakova R, Vlahova A, Chuchulska B, Barile G, et al. Comparison between conventional PMMA and 3D printed resins for denture bases: A narrative review. Journal of Composites Science. 2022;6(3):87.

81. Prpić V, Schauperl Z, Ćatić A, Dulčić N, Čimić S. Comparison of mechanical properties of 3D-printed, CAD/CAM, and conventional denture base materials. Journal of prosthodontics. 2020;29(6):524-8.

82. Gad MM, Fouda SM, Abualsaud R, Alshahrani FA, Al-Thobity AM, Khan SQ, et al. Strength and surface properties of a 3D-printed denture base polymer. Journal of Prosthodontics. 2022;31(5):412-8.

83. Alshamrani AA, Raju R, Ellakwa A. Effect of printing layer thickness and postprinting conditions on the flexural strength and hardness of a 3D-printed resin. BioMed Research International. 2022;2022:8353137.

84. Awad MA, Lund JP, Dufresne E, Feine JS. Comparing the efficacy of mandibular implant-retained overdentures and conventional dentures among middle-aged edentulous patients: satisfaction and functional assessment. International Journal of Prosthodontics. 2003;16(2):117-22.

85. Kodama N, Singh B, Cerutti-Kopplin D, Feine J, Emami E. Efficacy of mandibular 2-implant overdenture: an updated meta-analysis on patient-based outcomes. JDR Clinical & Translational Research. 2016;1(1):20-30.

86. Dard M, Kuehne S, Obrecht M, Grandin M, Helfenstein J, Pippenger B. Integrative performance analysis of a novel bone level tapered implant. Advances in dental research. 2016;28(1):28-33.

87. Reddy MS, Geurs NC, Wang I-C, Liu P-R, Hsu Y-T, Jeffcoat RL, et al. Mandibular growth following implant restoration: Does Wolff's law apply to residual ridge resorption? International Journal of Periodontics & Restorative Dentistry. 2002;22(4):315-21.

88. Carlsson GE. Implant and root supported overdentures-a literature review and some data on bone loss in edentulous jaws. The journal of advanced prosthodontics. 2014;6(4):245-52.

89. Al-Harbi FA. Mandibular implant-supported overdentures: Prosthetic overview. Saudi Journal of Medicine & Medical Sciences. 2018;6(1):2-7.

90. Andreiotelli M, Att W, Strub J-R. Prosthodontic complications with implant overdentures: a systematic literature review. International Journal of Prosthodontics. 2010;23(3):195-203.

91. Zarb GA, Hobkirk J, Eckert S, Jacob R. Prosthodontic treatment for edentulous patients: complete dentures and implant-supported prostheses: Elsevier Health Sciences; 2012.

92. Mojon P, Oberholzer J-P, Meyer J-M, Belser UC. Polymerization shrinkage of index and pattern acrylic resins. The Journal of prosthetic dentistry. 1990;64(6):684-8.

93. Busch M, Kordass B. Concept and development of a computerized positioning of prosthetic teeth for complete dentures. International journal of computerized dentistry. 2006;9(2):113-20.

94. Yilmaz B, Azak AN, Alp G, Ekşi H. Use of CAD-CAM technology for the fabrication of complete dentures: An alternative technique. The Journal of prosthetic dentistry. 2017;118(2):140-3.

95. Lee SJ, Kim SW, Lee JJ, Cheong CW. Comparison of intraoral and extraoral digital scanners: Evaluation of surface topography and precision. Dentistry journal. 2020; 8(2):52.

96. Borbola D, Berkei G, Simon B, Romanszky L, Sersli G, DeFee M, Renne W, Mangano F, Vag J. In vitro comparison of five desktop scanners and an industrial scanner in the evaluation of an intraoral scanner accuracy. Journal of dentistry. 2023 Feb 1;129:104391.

97. Schweigera J, Stumbaumb J, Edelhoffc D, Güthd J. Systematics and concepts for the digital production of complete dentures: risks and opportunities Systematik und Konzepte zur digitalen Herstellung von Totalprothesen–Chancen und Risiken. International journal of computerized dentistry. 2018;21(1):41-56.

98. Bidra AS, Taylor TD, Agar JR. Computer-aided technology for fabricating complete dentures: systematic review of historical background, current status, and future perspectives. The Journal of prosthetic dentistry. 2013;109(6):361-6.

99. Azari A, Nikzad S. The evolution of rapid prototyping in dentistry: a review. Rapid Prototyping Journal. 2009;15(3):216-225.

100. Dizon JRC, Gache CCL, Cascolan HMS, Cancino LT, Advincula RC. Post-processing of 3D-printed polymers. Technologies. 2021;9(3):61.

101. Berman B. 3-D printing: The new industrial revolution. Business horizons. 2012;55(2):155-62.

102. Abduo J, Lyons K, Bennamoun M. Trends in computer-aided manufacturing in prosthodontics: a review of the available streams. International journal of dentistry. 2014;2014:783948.

103. Bilgin MS, Baytaroğlu EN, Erdem A, Dilber E. A review of computer-aided design/computer-aided manufacture techniques for removable denture fabrication. European journal of dentistry. 2016;10(02):286-91.

104. Puebla K, Arcaute K, Quintana R, Wicker RB. Effects of environmental conditions, aging, and build orientations on the mechanical properties of ASTM type I specimens manufactured via stereolithography. Rapid Prototyping Journal. 2012;18(5):374-388.

105. 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.

106. Hada T, Kanazawa M, Iwaki M, Arakida T, Minakuchi S. Effect of printing direction on stress distortion of three-dimensional printed dentures using stereolithography technology. Journal of the Mechanical Behavior of Biomedical Materials. 2020;110:103949.

107. Tymrak B, Kreiger M, Pearce JM. Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions. Materials & Design. 2014;58:242-6.

108. Alharethi NA. Evaluation of the influence of build orientation on the surface roughness and flexural strength of 3D-printed denture base resin and its comparison with CAD-CAM milled denture base resin. European Journal of Dentistry. 2024;18(1):321-328.

109. Shim JS, Kim J-E, Jeong SH, Choi YJ, Ryu JJ. Printing accuracy, mechanical properties, surface characteristics, and microbial adhesion of 3D-printed resins with various printing orientations. The Journal of Prosthetic Dentistry. 2020;124(4):468-75.

110. Al-Dulaijan YA, Alsulaimi L, Alotaibi R, Alboainain A, Akhtar S, Khan SQ, et al. Effect of printing orientation and postcuring time on the flexural strength of 3D-printed resins. Journal of Prosthodontics. 2023;32(S1):45-52.

111. Wang CI. Effect of Different Print Orientations on the Flexural Strength of 3D Printed Denture Base Resin 2020.

112. Altarazi A, Haider J, Alhotan A, Silikas N, Devlin H. Assessing the physical and mechanical properties of 3D printed acrylic material for denture base application. Dental Materials. 2022;38(12):1841-54.

113. Li P, Lambart A-L, Stawarczyk B, Reymus M, Spintzyk S. Postpolymerization of a 3D-printed denture base polymer: Impact of post-curing methods on surface characteristics, flexural strength, and cytotoxicity. Journal of Dentistry. 2021;115:103856.

114. Hardiman K. Post-processing considerations for biomedical 3D printing of polymers. Polymer-based additive manufacturing: Springer; 2019. p. 219-41.

115. Kim D, Shim J-S, Lee D, Shin S-H, Nam N-E, Park K-H, et al. Effects of post-curing time on the mechanical and color properties of three-dimensional printed crown and bridge materials. Polymers. 2020;12(11):2762.

116. Oskui SM, Diamante G, Liao C, Shi W, Gan J, Schlenk D, et al. Assessing and reducing the toxicity of 3D-printed parts. Environmental Science & Technology Letters. 2016;3(1):1-6.

117. Aati S, Akram Z, Shrestha B, Patel J, Shih B, Shearston K, et al. Effect of post-curing light exposure time on the physico–mechanical properties and cytotoxicity of 3D-printed denture base material. Dental Materials. 2022;38(1):57-67.

118. Faggion Jr CM. Guidelines for reporting pre-clinical in vitro studies on dental materials. Journal of Evidence Based Dental Practice. 2012;12(4):182-9.

119. Benli M, Gümüş BE, Kahraman Y, Yağcı Ö, Erdoğan D, Huck O, et al. Thermal, structural and morphological characterization of dental polymers for clinical applications. Journal of Prosthodontic Research. 2021;65(2):176-85.

120. Mathar MI. Evaluation of physical properties of denture base resin in two different media by using thermal gravimetric analysis and differential thermal analysis. 2020;4(8).

121. Shehata R-H, Cheta N, Alkady D, Borg H. Retention and Wear Evaluation of Rigid Telescopic and Nova Loc Attachments for Two Implant-Supported Mandibular Overdentures (An in vitro study). Br J Med Health Res. 2022;8:1-15.

122. El-Amier N, Elsaih E, Gibreel M, El-Motaiam H. Effect of implant location on palateless complete overdenture retention: an in vitro study. Journal of oral & maxillofacial research. 2018;9(3).

123. Jafarpour D, Feine JS, Morris M, Souza R. Patient-reported outcomes and clinical performance of CAD/CAM removable dentures: A scoping review. The International Journal of Prosthodontics. 2023.

124. Munn Z, Peters MD, Stern C, Tufanaru C, McArthur A, Aromataris E. Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach. BMC medical research methodology. 2018;18:1-7.

125. Anadioti E, Musharbash L, Blatz MB, Papavasiliou G, Kamposiora P. 3D printed complete removable dental prostheses: A narrative review. BMC Oral Health. 2020;20:1-9.

126. Silva JdCM, dos SANTOS JFF, Marchini L. Factors influencing patients' satisfaction with complete dentures: a qualitative study. Brazilian Dental Science. 2014;17(2):83-8.

127. Association CD. The state of oral health in Canada. Canadian Dental Association: Ottawa, ON, Canada. 2017.

128. Tzeng H-M, Okpalauwaekwe U, Yin C-Y. Older adults' suggestions to engage other older adults in health and healthcare: A qualitative study conducted in western Canada. Patient preference and adherence. 2019:331-7.

129. Giguere AM, Farmanova E, Holroyd-Leduc JM, Straus SE, Urquhart R, Carnovale V, et al. Key stakeholders' views on the quality of care and services available to frail seniors in Canada. BMC geriatrics. 2018;18:1-14.

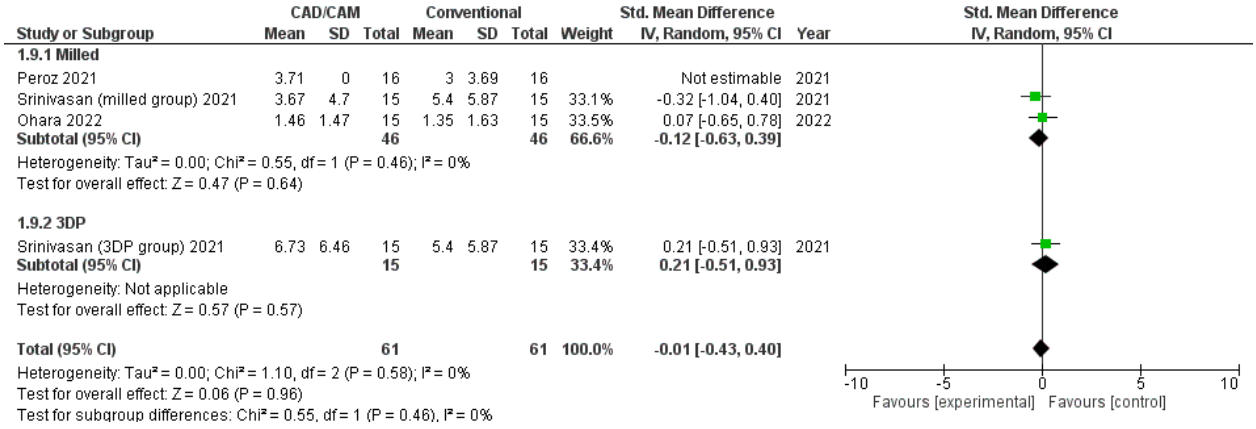
130. Ahmed S, Shommu NS, Rumana N, Barron GR, Wicklum S, Turin TC. Barriers to access of primary healthcare by immigrant populations in Canada: a literature review. Journal of immigrant and minority health. 2016;18:1522-40.

131. Habjan S, Prince H, Kelley ML. Caregiving for elders in first nations communities: social system perspective on barriers and challenges. Canadian Journal on Aging/La Revue canadienne du vieillissement. 2012;31(2):209-22.

11. Appendices

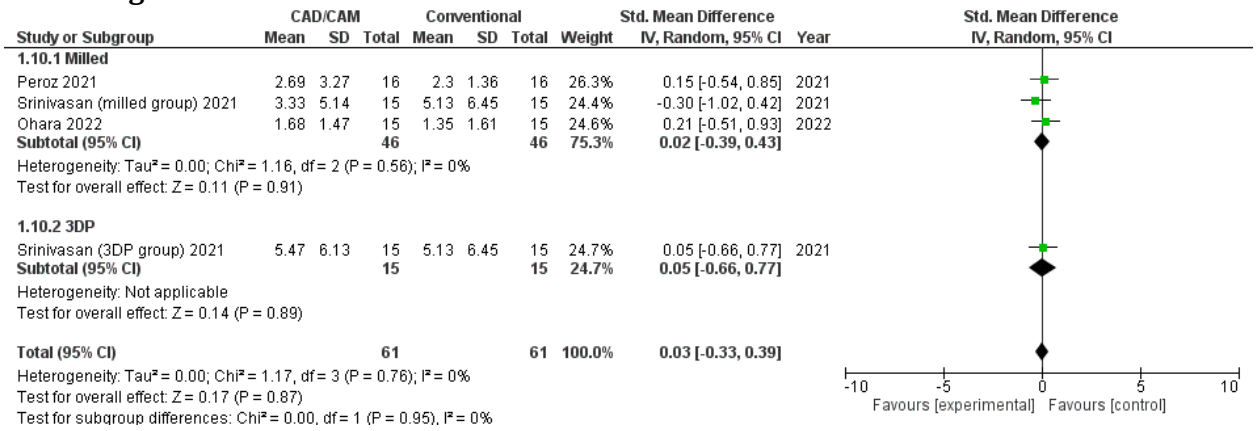
11.1. Appendix 1: Supplementary files for Manuscript III

11.1.1. Figure 1



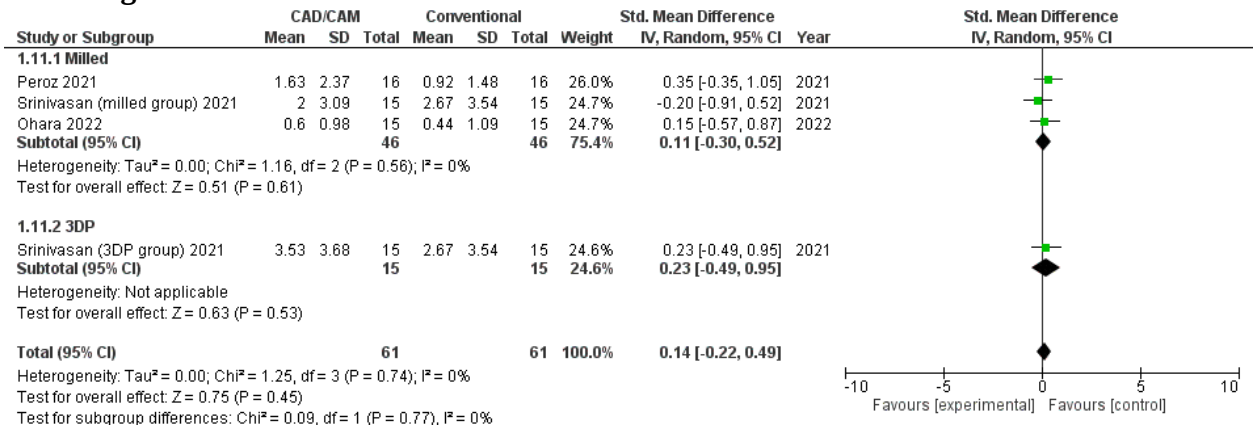
Supplementary Figure 1- Subgroup analysis for a clinically relevant OHIP dimension: Physical pain.

11.1.2. Figure 2



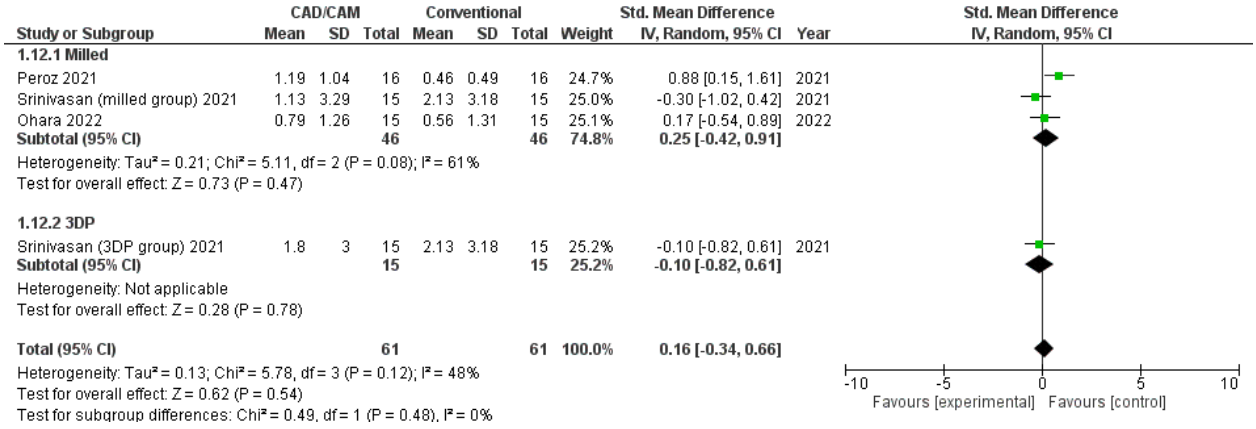
Supplementary Figure 2- Subgroup analysis for a clinically relevant OHIP dimensions: Physical disability

10.1.3.Figure 3



Supplementary Figure 3- Subgroup analysis for a clinically relevant OHIP dimension: Psychological disability

11.1.4. Figure 4



Supplementary Figure 4- Subgroup analysis for a clinically relevant OHIP dimension: Handicap

11.2. Appendix 2: Supplementary material for Manuscript V

11.2.1. Additional File 1

SPIRIT Checklist for *Trials*

		Reporting Item	Page and Line Number	Reason if not applicable
Administrative information				
Title	#1	Descriptive title identifying the study design, population, interventions, and, if applicable, trial acronym	P1 L1,2	
Trial registration	#2a	Trial identifier and registry name. If not yet registered, name of intended registry	P3 L45	
Trial registration: data set	#2b	All items from the World Health Organization Trial Registration Data Set	N/a	The protocol is not registered in WHO dataset
Protocol version	#3	Date and version identifier	P3 L45	
Funding	#4	Sources and types of financial, material, and other support	P21 L456	
Roles and responsibilities: contributorship	#5a	Names, affiliations, and roles of protocol contributors	P21 L461	
Roles and responsibilities: sponsor contact information	#5b	Name and contact information for the trial sponsor	N/A	The trial does not have any sponsors
Roles and responsibilities:	#5c	Role of study sponsor and funders, if any, in study design;	L17 P377	The funders only provided the grant for this study

sponsor and funder		collection, management, analysis, and interpretation of data; writing of the report; and the decision to submit the report for publication, including whether they will have ultimate authority over any of these activities		
Roles and responsibilities: committees	#5d	Composition, roles, and responsibilities of the coordinating centre, steering committee, endpoint adjudication committee, data management team, and other individuals or groups overseeing the trial, if applicable (see Item 21a for data monitoring committee)	L17 P374	
Introduction			P3 L50	
Background and rationale	#6a	Description of research question and justification for undertaking the trial, including summary of relevant studies (published and unpublished) examining benefits and harms for each intervention	P3-5 L51-95	
Background and rationale: choice of comparators	#6b	Explanation for choice of comparators	P4,5 L81-89	
Objectives	#7	Specific objectives or hypotheses	P 5 L 96-100	
Trial design	#8	Description of trial design including type of trial (eg, parallel group, crossover, factorial, single group), allocation ratio, and framework (eg, superiority,	P 5 L 102	

		equivalence, non-inferiority, exploratory)		
Methods: Participants, interventions, and outcomes				
Study setting	#9	Description of study settings (eg, community clinic, academic hospital) and list of countries where data will be collected. Reference to where list of study sites can be obtained	P 5,6 L 110,111	
Eligibility criteria	#10	Inclusion and exclusion criteria for participants. If applicable, eligibility criteria for study centres and individuals who will perform the interventions (eg, surgeons, psychotherapists)	P 6 L 115	
Interventions: description	#11a	Interventions for each group with sufficient detail to allow replication, including how and when they will be administered	P7 L147	
Interventions: modifications	#11b	Criteria for discontinuing or modifying allocated interventions for a given trial participant (eg, drug dose change in response to harms, participant request, or improving / worsening disease)	P16 L339-340, P 9 L 185-186	Denture adjustments will be done if required.
Interventions: adherance	#11c	Strategies to improve adherence to intervention protocols, and any procedures for monitoring adherence (eg, drug tablet return; laboratory tests)	P 15 L331	
Interventions: concomitant care	#11d	Relevant concomitant care and interventions that are permitted or prohibited during the trial	N/A	Concomitant care is of no concern in this trial. This RCT provides variations of a

				treatment sought by participants at university clinics, with no major change in their routine.
Outcomes	#12	Primary, secondary, and other outcomes, including the specific measurement variable (eg, systolic blood pressure), analysis metric (eg, change from baseline, final value, time to event), method of aggregation (eg, median, proportion), and time point for each outcome. Explanation of the clinical relevance of chosen efficacy and harm outcomes is strongly recommended	P 10 L 219	
Participant timeline	#13	Time schedule of enrolment, interventions (including any run-ins and washouts), assessments, and visits for participants. A schematic diagram is highly recommended (see Figure)	P 13 L 281	
Sample size	#14	Estimated number of participants needed to achieve study objectives and how it was determined, including clinical and statistical assumptions supporting any sample size calculations	P15 L321	
Recruitment	#15	Strategies for achieving adequate participant enrolment to reach target sample size	P6 L133	
Methods: Assignment of interventions (for controlled trials)				

Allocation: sequence generation	#16a	Method of generating the allocation sequence (eg, computer-generated random numbers), and list of any factors for stratification. To reduce predictability of a random sequence, details of any planned restriction (eg, blocking) should be provided in a separate document that is unavailable to those who enrol participants or assign interventions	P9 L200	
Allocation concealment mechanism	#16b	Mechanism of implementing the allocation sequence (eg, central telephone; sequentially numbered, opaque, sealed envelopes), describing any steps to conceal the sequence until interventions are assigned	P9,10 L200-212	
Allocation: implementation	#16c	Who will generate the allocation sequence, who will enrol participants, and who will assign participants to interventions	P9,10 L 200-212	
Blinding (masking)	#17a	Who will be blinded after assignment to interventions (eg, trial participants, care providers, outcome assessors, data analysts), and how	P 10 L 213-218	
Blinding (masking): emergency unblinding	#17b	If blinded, circumstances under which unblinding is permissible, and procedure for revealing a participant's allocated intervention during the trial	P 21 L470,471	We anticipate that there will be no emergency case in which the unblinding needs to be done. This study represents minimal safety risk for participants, since all procedures are comparable

				with nonsurgical oral healthcare. Only if the participant wants to withdraw from the study, then unblinding will be possible.
Methods: Data collection, management, and analysis				
Data collection plan	#18a	Plans for assessment and collection of outcome, baseline, and other trial data, including any related processes to promote data quality (eg, duplicate measurements, training of assessors) and a description of study instruments (eg, questionnaires, laboratory tests) along with their reliability and validity, if known. Reference to where data collection forms can be found, if not in the protocol	P10 L219	
Data collection plan: retention	#18b	Plans to promote participant retention and complete follow-up, including list of any outcome data to be collected for participants who discontinue or deviate from intervention protocols	P15,16 L334-337	
Data management	#19	Plans for data entry, coding, security, and storage, including any related processes to promote data quality (eg, double data entry; range checks for data values). Reference to where details of data management	P17 L373; P16 L344-346	

		procedures can be found, if not in the protocol		
Statistics: outcomes	#20a	Statistical methods for analysing primary and secondary outcomes. Reference to where other details of the statistical analysis plan can be found, if not in the protocol	P16,17 L347-372	
Statistics: additional analyses	#20b	Methods for any additional analyses (eg, subgroup and adjusted analyses)	P16 L358-359	
Statistics: analysis population and missing data	#20c	Definition of analysis population relating to protocol non-adherence (eg, as randomised analysis), and any statistical methods to handle missing data (eg, multiple imputation)	P16 L352-359	
Methods: Monitoring				
Data monitoring: formal committee	#21a	Composition of data monitoring committee (DMC); summary of its role and reporting structure; statement of whether it is independent from the sponsor and competing interests; and reference to where further details about its charter can be found, if not in the protocol. Alternatively, an explanation of why a DMC is not needed	P 17 L373	
Data monitoring: interim analysis	#21b	Description of any interim analyses and stopping guidelines, including who will have access to these interim results and make	P 17 L373, P 16 L356-358	As all denture materials are licensed for patient use and are currently being used and sold in Canada and United States, we do not except an

		the final decision to terminate the trial		event in which we will have to terminate the trial. The risks associated with treatment are the same expected for minor oral surgery and standard dental implants/dentures. Participants may experience sore spots under the dentures after the placement of retentive components. If this happens, the dentures will be adjusted as necessary. However, two independent researchers will regularly review the collected data as part of a data monitoring committee. Additionally, McGill University's Research Ethics Board (REB) Office retains the authority to conduct an independent audit at any point in time. In case of a withdrawn patient, an interim analysis will be performed.
Harms	#22	Plans for collecting, assessing, reporting, and managing solicited and spontaneously reported adverse events and other unintended effects of trial interventions or trial conduct	P 17 L377	
Auditing	#23	Frequency and procedures for auditing trial conduct, if any, and whether the process will be	P 17 L373	

		independent from investigators and the sponsor		
Ethics and dissemination				
Research ethics approval	#24	Plans for seeking research ethics committee / institutional review board (REC / IRB) approval	P 21 L474	
Protocol amendments	#25	Plans for communicating important protocol modifications (eg, changes to eligibility criteria, outcomes, analyses) to relevant parties (eg, investigators, REC / IRBs, trial participants, trial registries, journals, regulators)	P22 L482-484	
Consent or assent	#26a	Who will obtain informed consent or assent from potential trial participants or authorised surrogates, and how (see Item 32)	P 13 L282-283	
Consent or assent: ancillary studies	#26b	Additional consent provisions for collection and use of participant data and biological specimens in ancillary studies, if applicable	N/a	Not ancillary study
Confidentiality	#27	How personal information about potential and enrolled participants will be collected, shared, and maintained in order to protect confidentiality before, during, and after the trial	P 18 L392	
Declaration of interests	#28	Financial and other competing interests for principal investigators for the overall trial and each study site	P 22 L494	

Data access	#29	Statement of who will have access to the final trial dataset, and disclosure of contractual agreements that limit such access for investigators	P 10 L209, P 18 L395-398	
Ancillary and post trial care	#30	Provisions, if any, for ancillary and post-trial care, and for compensation to those who suffer harm from trial participation	P 18 L 387,390,391	
Dissemination policy: trial results	#31a	Plans for investigators and sponsor to communicate trial results to participants, healthcare professionals, the public, and other relevant groups (eg, via publication, reporting in results databases, or other data sharing arrangements), including any publication restrictions	P18 L396	
Dissemination policy: authorship	#31b	Authorship eligibility guidelines and any intended use of professional writers	P21 L465	
Dissemination policy: reproducible research	#31c	Plans, if any, for granting public access to the full protocol, participant-level dataset, and statistical code	P21 L460	
Appendices				
Informed consent materials	#32	Model consent form and other related documentation given to participants and authorised surrogates	P22 L485-86	
Biological specimens	#33	Plans for collection, laboratory evaluation, and storage of	N/A	No biological samples

		biological specimens for genetic or molecular analysis in the current trial and for future use in ancillary studies, if applicable		

It is strongly recommended that this checklist be read in conjunction with the SPIRIT 2013 Explanation & Elaboration for important clarification on the items. Amendments to the protocol should be tracked and dated. This checklist can be completed online using https://www.goodreports.org/, a tool made by the EQUATOR Network in collaboration with Penelope.ai

11.2.2. Additional File 2

Dr Raphael de Souza
McGill University
Faculty of Dental Medicine and Oral Health Sciences
3640, University St. # M/65A
Montreal H3A2B2
CA
raphael.desouza@mcgill.ca

Basel, 25 May 2023

Grant confirmation letter

To whom it may concern

With reference to your grant application submitted to the ITI, we take pleasure in confirming that the ITI Research Committee has agreed to support project "3D printing vs traditional workflow for the fabrication of mandibular implant overdentures: A randomized crossover clinical trial" to be led by Dr. de Souza with an ITI research grant to the amount of USD 139.734,00. This grant applies to the project as approved by the ITI Research Committee. Any changes to the protocol or design throughout the duration of the project must be communicated to ITI Headquarters in advance.

The research project begins in 01/08/2023 and the projected end date is 31/07/2026.

11.2.3. Additional File 3

McGill | Faculty of Medicine and Health Sciences | Faculté de médecine et des sciences de la santé

3655 Sir William Osler #633
Montreal, Quebec H3G 1Y6

3655, Promenade Sir William Osler #633
Montréal (Québec) H3G 1Y6

Tél/Tel: (514) 398-3124

September 21, 2023

Dr. Raphael F. de Souza
Faculty of Dental Medicine and Oral Health Sciences
2001, ave McGill College, Suite 534
Montreal, QC H3A 1G1

RE: **A00-M29-23B (22-07-089)**
3D printing vs traditional workflow for the fabrication of implant mandibular overdentures: A randomized cross-over clinical trial

Dear Dr. de Souza,

On September 11, 2023, at a meeting of the Institutional Review Board, the above-referenced re-submitted study received a full Board review.

The Committee identified the following concerns for your response.

Study Protocol

a) Science of the study is acceptable.

Consent form

b) Consent form needs to be on letterhead.
c) Please clarify if data is coded or anonymized. If the data is to be kept for 25 years, it needs to be anonymized.

The study was approved for a period of 12 months, pending the submission of an appropriate response and revisions to the above concerns.

Please send all correspondence to submit2irb.med@mcgill.ca.

Kind regards,

Roberta Palmour, PhD
Chair
Institutional Review Board

cc: A00-M29-23B (22-07-089)

11.2.4. Additional file 4

McGill | Faculty of Dental Medicine and Oral Health Sciences | Faculté de médecine dentaire et des sciences de la santé orale

INFORMATION AND CONSENT FORM

Research Study Title:	3D printing vs traditional workflow for the fabrication of implant mandibular overdentures: A randomized cross-over clinical trial
Protocol number:	A00-M29-23B (22-07-089)
Researcher responsible for the research study:	Dr. Raphael F de Souza Faculty of Dental Medicine and Oral Health Sciences, McGill University
Co-Investigator(s)/sites:	
Sponsor:	ITI (International Team for Implantology), grant 1744-2023

INTRODUCTION

We are inviting you to take part in this research study because you have no natural teeth and currently wear full dentures. You should be: (1) 60 years or older; (2) Not have had a tooth extraction within the past 12 months; (3) desire to receive new dentures; (3) two dental implants in the lower jaw; (4) desire to receive both upper and lower dentures; (5) good understanding of spoken English or French; (6) Ability to provide written informed consent.

However, before you accept to take part in this study and sign this information and consent form, please take the time to read, understand and carefully examine the following information. You may also want to discuss this study with your family doctor, a family member or a close friend.

This form may contain words that you do not understand. We invite you to speak to the researcher responsible for this study (the “study doctor”) or to other members of the research team and ask them to explain to you any word or information that is unclear to you before you sign this form.

BACKGROUND

Complete tooth loss or edentulism is still a grievous oral health problem in Canada and worldwide. It is more common in older adults and is expected to remain frequent for several decades.

Studies have suggested that complete tooth loss leads to worse general health in older adults and even earlier mortality. Some diseases are more common in toothless individuals, including gastrointestinal cancer, heart disease, dementia and stroke. Tooth loss can also reduce well-being, with depressive symptoms worsening after losing all teeth. Poorer chewing is also common with tooth loss and is closely associated with reduced self-esteem. Besides that, many toothless individuals avoid social activities due to shame when smiling, speaking or eating.

Digital technology can help older adults to receive dentures. For example, dentures can need up to 5 clinical sessions to be ready. With digital methods dentures can be delivered with 2 to 4 sessions. Also, denture patients can have certain steps done by distance, like checking the appearance of their future teeth. Two of the advantages of less sessions are: (1) a lower cost, (2) lower risk to get sicknesses like COVID-19 or the flu. Dentures done with digital methods also tend to fit better in the mouth than traditional dentures.

However, to make sure those advantages make sense for our patients, we need to run clinical studies. This way, this study will compare digital dentures to the traditional ones, regarding your satisfaction and preferences. We will also have a dentist checking their quality and estimate what would be their cost for patients in general. Our results will guide dentists and patients when choosing the most appropriate method for their needs.

PURPOSE OF THE RESEARCH STUDY

The purpose of this study is to learn about your satisfaction with a novel computer-aided design and manufacturing (CAD/CAM) technology for providing full denture prostheses comparable to traditional methods, regarding patient-and clinician-perceived quality.

Secondary purposes are to compare if one of the two tested methods incur higher costs from the patient perspective.

For this research study, we will recruit 26 participants, men and women, aged 60 years or more.

DESCRIPTION OF THE RESEARCH PROCEDURES

This research study will take place at the following site:
1. Clinical research unit at the Faculty of Dental Medicine and Oral Health Sciences, McGill University, 2001 McGill College Ave, Montreal, Quebec H3A 1G1

1. Duration and number of visits

Your participation in this research project will last 8 months and will include 11 visits, besides the

screening visit: 5 for denture fabrication, 4 for post-delivery adjustments* and 2 for data collection. Each visit will last around 90 minutes.

**Adjusting dentures may demand you to come for some extra visits, as usual in a standard clinical practice.*

2. Study devices

We will recruit toothless participants (any sex/gender) among previous patients of McGill University, based on the following eligibility criteria: mandibular tooth loss, age ≥60 years, need for new mandibular overdentures, ability to complete questionnaires, and previous treatment with implants in the lower jaw.

Each participant will receive two pairs of mandibular overdentures: (i) one with 3D images of the mouth, virtual prosthetic design and 3D printing (CAD/CAM); (ii) a control pair, by traditional clinical and laboratory methods. Each pair will be used for 3 months according to a random sequence (total follow-up: 6 months).

3. Tests and procedures

During your participation in this research study, the study doctor or a member of the research team will conduct the following tests and procedures:

DESCRIPTION OF STUDY PROCEDURES	
Procedure	**Description**
1. Screening	- Initial questionnaire, mouth exam *(as the standard of care)* - Consent form *(only for the study)*
2.Molding, 1st time	- Completing your dental exam forms - Taking molds of your upper and lower jaws *(primary impressions)* - Obtaining 3D pictures of your upper and lower jaws *(intraoral scanning)*
3. Molding, 2nd time	- Taking more accurate molds of your mouth *(secondary impressions)*
4. Shaping denture bases	- Verifying provisional denture bases for their fit and shape - Shaping wax rims on denture bases for the desired position of denture teeth - Registering the position of your jaws when biting *(occlusal plane, vertical dimension and centric relation)* - Taking 3D pictures of your face and mouth with bases
5. Denture try-in	- A wax replica of your future denture will be checked in the mouth *(traditional denture try-in)* - Showing you a 3D photo with the denture teeth *(virtual try-in)*
6. Denture delivery	- Adjusting the fit of new dentures and their teeth - Hollowing your denture and installing retentive components
7. Denture adjustments	- Adjusting the fit of the dentures and their teeth. You may have some sore spots on the gums before adjustment (normal with new dentures)
8. Data collection	- Questionnaires and mouth exam *(only for the study)*
9. Interview	- You will discuss your feelings and preferences with each denture pair. This will happen in private and out of the clinic *(only for the study)*

The schedule of procedures for each visit is listed below:

SCHEDULE OF STUDY PROCEDURES										
Procedure	**Visit (V) 0**	**V 1**	**V 2**	**V 3**	**V 4**	**V 5 (Day 0)**	**V 6 & 7**	**V 8 (3 months)**	**V 9 & 10**	**Visit 11 (6 months)**
1. Screening*	X									
2.Molding, 1st time*		X								
3. Molding, 2nd time			X							
4. Shaping denture bases				X						
5. Denture try-in					X					
6. Denture delivery						X				
7. Denture adjustments							X		X	
8. Data collection						X		X		X
9. Interview										X
Study site	**McGill Faculty of Dental Medicine and Oral Health Sciences**									

* We may take new radiographs (panoramic and/or of the implants) if needed

PARTICIPANT'S RESPONSIBILITIES

- As for standard dental treatment, please communicate if you cannot come to any of the scheduled appointments. Plus, please tell us if something changes in your health, even if that may not seem relevant.
- Dentures need regular care; please brush them at least twice/daily. We recommend you to see a dentist regularly after the end of the study, at least once/year as participation in this study does not replace these regular checkups in any way.
- You will be responsible for the costs of dental care after the study ends. Eventual repairs and changes of components will be necessary, as normal for dentures and implants. Fees may vary in different clinics, but you may expect fees of nearly $100 for repairing a component. Other repairs may be more expensive, such as refitting the denture with acrylic ($394 or more, depending on how it is done).

BENEFITS ASSOCIATED WITH THE RESEARCH STUDY

You may or may not personally benefit from your participation in this research project. However, we hope that the study results will contribute to the advancement of scientific knowledge in this field and help us find better treatments for patients.

All treatment involved in this study (adapting your denture and changing implant components during the 6-month period) will be done free of charge.

RISKS ASSOCIATED WITH THE RESEARCH STUDY

Both study devices are licensed for patient use and sold in Canada and United States. This way, risks associated with treatment are the same expected for minor oral surgery and standard dental implants/dentures.

If you have noticed side effects, whatever they may be, during this research study, you must tell the study doctor immediately, regardless of whether you think these effects are related to the implants or components. Even once your participation in the study is over, do not hesitate to contact the study doctor if you experience a side effect that may be linked to the study devices.

The study doctor and members of his or her team will answer any questions that you may have regarding the risks, discomforts and side effect associated with this study. Also, at each visit, the study doctor and members of his or her team will ask you questions about any side effects you may have experienced.

Risks associated with dentures

You may experience some sore spots under your dentures after the placement of retentive components. If this happens, the dentures will be adjusted for you as necessary. Allergic reactions to dental materials (such as the acrylic mixture used to bond components and denture) are rare but might also occur.

Your lower denture might break after we place the implant retentive components. We may have to drill the denture before placing them. This can weaken the denture. If this happens during the study timeline, we will fix/repair it at no cost.

We do not expect risks or complications from the x-rays or other exams. This includes data collection and interviews.

OTHER POSSIBLE TREATMENTS

You do not have to take part in this study to receive medical care for your condition. Other options exist such as: (1) new full dentures or repairs (“relinings”); (2) more than two implants in the lower jaw; (3) implants in the upper jaw. We encourage you to discuss with the study doctor all available options.

VOLUNTARY PARTICIPATION AND THE RIGHT TO WITHDRAW

Your participation in this research project is voluntary. Therefore, you may refuse to participate. You may also withdraw from the project at any time, without giving any reason, by informing the study doctor or a member of the research team.

Your decision not to participate in the study, or to withdraw from it, will have no impact on the quality of care and services to which you are otherwise entitled, or on your relationship with the study doctor or clinical team.

The study doctor, the Research Ethics Board, the funding agency, or the Sponsor may put an end to your participation without your consent. This may happen if new findings or information indicate that participation is no longer in your interest, if you do not follow study instructions, or if there are administrative reasons to terminate the project.

However, for safety and future result analyses, before you withdraw from the study we ask you to notify the contact person in the research team, verbally or in writing.

If you withdraw or are withdrawn from the study, the information and biological material already collected for the study will be stored, analyzed and used to ensure the integrity of the study.

Any new findings that could influence your decision to stay in the research project will be shared with you as soon as possible.

CONFIDENTIALITY AND PRIVACY

During your participation in this study, the study doctor and their team will collect and record information about you in a study file. They will only collect information required to meet the scientific goals of the study. You will not be asked for personal or sensitive information in a public setting. Instead, information will be collected in a private space where the discussion cannot be observed or overheard by others. Investigators will also limit the information collected to the information that is essential for research purposes, and only once informed consent has been obtained from you.

The study file may include information from your medical chart, including your identity, concerning your past and present state of health, your lifestyle, as well as the results of the tests, exams, and procedures that you will undergo during this research project. Your research file could also contain other information, such as your name, sex, date of birth and ethnic origin.

The research forms and x-rays will be sent to Dr. de Souza's office and stored for 25 years for the exclusive objectives of this study and then destroyed. His office is located at McGill University, Strathcona Anatomy & Dentistry Building, 3640, University St., room M/65A, Montreal (QC) H3A 2B2.
The collected data will be only stored in the OneDrive cloud server of the principal doctor, the internal drive of the professional computer of the principal doctor, and the external hard drive of the principal doctor. These will be kept secure by a password to which only the principal doctor will have access.
For the purpose of any publications, your demographic information might be shared in the paper without any identification of you. Upon request of the sponsor, your anonymized data might be shared with them. The data will be stored anonymously, pertaining to your specific coded ID. That being said, you cannot be identified through the shared data.

All the information collected during the research project will remain strictly confidential to the extent provided by law. You will only be identified by a code number. The key to the code linking your name to your study file will be kept by the study doctor only.

To ensure your safety, a copy of this information and consent form (including the type of

implant/components in use and x-ray results) will be placed in your medical chart. As a result, any person or company to whom you give access to your medical chart will have access to this information.

The study doctor might forward your coded data to the sponsor or their representatives upon their request.

The Sponsor may share the coded study data with their commercial partners. However, the sponsor and any international partners will respect the confidentiality rules in effect in Quebec and Canada, regardless of the country to which your data may be transferred.

The study data will be stored for 25 years by the principal investigator (Dr de Souza).

For depositing research data, we might deposit anonymized datasets in the McGill Dataverse repository. According to McGill, all data are stored securely on servers located in Canada. The anonymized data may be published or shared during scientific meetings; however, it will not be possible to identify the participants.

For monitoring, control, safety, and security, your study file as well as your medical charts may be examined by a person mandated by Canadian or international regulatory authorities, such as Health Canada, as well as by representatives of the study sponsor, the institution, or the Research Ethics Board. All these individuals and organizations adhere to policies on confidentiality.

You have the right to consult your study file in order to verify the information gathered, and to have it corrected if necessary.

However, in order to protect the scientific integrity of the research project, accessing certain information before the project is ended may require that you be withdrawn from the study.

INCIDENTAL FINDINGS

Material incidental findings are findings made in the course of the study that may have significant impacts on your current or future wellbeing or that of your family members. A material incidental finding concerning you in the course of this research will be communicated to you and to a health professional of your choice.

We will examine you according to standard practices in dentistry during “visit 1”. This may reveal certain diseases that are outside our study goals but have importance for your well-being. Examples are: (1) infection of your mouth; (2) tumours or cysts only visible by x-ray. We will tell you about such a finding and refer you to adequate treatment when needed. This will happen regardless of your inclusion or not in this study. If we have any incidental finding during any visit, we will do the same.

MARKETING POSSIBILITIES

The research results, including those following your participation in this study, could lead to the creation of commercial products. However, you will not receive any financial benefits.

FUNDING OF THE RESEARCH PROJECT

The study doctor and the institution have received funding from the sponsor for the completion of the research project.

COMPENSATION

You will receive an amount of 25$ per study visits 8 and 11, for a total of 02 visits, for a total amount of 50$ for costs and inconveniences incurred during this research study. If you withdraw from the study, or are withdrawn before it is completed, you will receive compensation proportional to the number of visits you have completed. Denture repairs and replacement of implant attachment components will be offered to you for free for the duration of this research study.

SHOULD YOU SUFFER ANY HARM

Should you suffer harm of any kind following administration of the study drug, or following any other procedure related to the research study, you will receive the appropriate care and services required by your state of health.

By agreeing to participate in this research project, you are not waiving any of your legal rights nor discharging the study doctor, the sponsor or the institution, of their civil and professional responsibilities.

CLINICAL TRIAL REGISTRATION

A description of this clinical trial is available on http://www.ClinicalTrials.gov (project NCT06155630). This Website will not include information that can identify you. At most, the Website will include a summary of the results. You can search this Website at any moment, or access https://classic.clinicaltrials.gov/ct2/show/NCT06155630 directly.

CONTACT INFORMATION

If you have questions or if you have a problem you think may be related to your participation in this research study, or if you would like to withdraw, you may communicate with the study doctor or with someone on the research team at the following number: Dr. Raphael de Souza (principal investigator) at McGill University, telephone: (514) 913-7174; email: raphael.desouza@mcgill.ca.

For any question concerning your rights as a research participant taking part in this study, or if you have comments, or wish to file a complaint, you may communicate with:

(1) the Research Ethics Officer at McGill University (Mrs. Ilde Lepore) by email: ilde.lepore@mcgill.ca or by telephone at (514) 398-8302.

OVERVIEW OF ETHICAL ASPECTS OF THE RESEARCH

The McGill University Research Ethics Board reviewed this study and is responsible for monitoring it at all participating institutions in the health and social services network in Quebec.

Research Study Title:		3D printing vs traditional workflow for the fabrication of implant mandibular overdentures: A randomized cross-over clinical trial

SIGNATURES

Signature of the participant

I have reviewed the information and consent form. Both the research study and the information and consent form were explained to me. My questions were answered, and I was given sufficient time to make a decision. After reflection, I consent to participate in this research study in accordance with the conditions stated above.

I authorize the research study team to have access to my medical record for the purposes of this study.

- I authorize the doctor in charge of this research study to communicate with me directly to ask if I am interested in participating in other research:

  Yes ☐
  No ☐

- I authorize the study doctor to inform my treating physician that I am taking part in this study:

  Yes ☐ Name and contact information of treating physician: _____

  No ☐

  I do not have a treating physician/I am no longer being followed by my treating physician ☐

- I agree that my anonymized data be shared with the study sponsor and other commercial partners and may be made available in a data repository:

  Yes ☐
  No ☐

I understand that the study doctor will send my treating physician health information if it will be useful for my care.

Name of participant	Signature	Date

Signature of the person obtaining consent

I have explained the research study and the terms of this information and consent form to the research participant, and I answered all his/her questions.

Name of the person obtaining consent Signature Date

Commitment of the principal investigator

I certify that this information and consent form were explained to the research participant, and that the questions the participant had were answered.

I undertake, together with the research team, to respect what was agreed upon in the information and consent form, and to give a signed and dated copy of this form to the research participant.

Name of the principal investigator Signature Date

11.2.5. Screening form

Identification

Name:	1.		
Address: (street, number, apt.)	2.	**City**	3.
		Postal Code:	4.
Phone numbers:	5. Home:	6. Work:	7. Cell: / 8. Other (specify):
Date of birth:	_____/_____/_____ (dd) (mm) (yyyy)	**Age:** _____years	**Participant code (if eligible):**

Inclusion Criteria **(Checked during initial contact and brief clinical exam) – One 'no' precludes inclusion and will be used as the reason.**

9. Independent individual who has been completely edentulous for six months or more (ask the patient and then check with clinical exam)?
☐ Yes ☐ No

10. No tooth extraction within the past 12 mo? ☐ Yes ☐ No

11. Two Straumann tissue level RN implants symmetrically distributed in the anterior mandible for 3 or + mo before the trial interventions? (clinical exam, confirm with CBCT)? ☐ Yes ☐ No

12. Accept to receive both upper denture and lower IMO with new stud attachments?
☐ Yes ☐ No

13. Able to maintain adequate oral/denture hygiene (mark 'no' if there is any important neurological disease or abundant denture plaque. In doubt, 50% or more of plaque after the use of a disclosing solution precludes inclusion, as well as spread stains and calculus)?
☐ Yes ☐ No

13. Adequate general health?
☐ Yes ☐ No

If no, why:_____

14. Understands written and spoken English or French?
☐ Yes ☐ No

15. Accepts/is able to give written informed consent?
☐ Yes ☐ No

16. Acceptable dentures? ☐ Yes ☐ No (according to the criteria below):

17. Fractured bases or teeth? ○ Yes ○ No 18. Vertical dimension (esthetics and interocclusal distance- FS<7mm)? ○ Adequate ○ Inadequate

19. Tooth wear: ○ None ○ Flat wear facets ○ 1/3 worn ○ >1/3 worn 20. Border extension/fit? ○ Adequate ○ Inadequate

Exclusion Criteria **(To be filled after brief clinical exam and radiographic assessment) – Any 'yes' indicates exclusion and will be cited as the reason in the flowchart .**

CLINICAL CRITERIA

21. Any serious or severe illness that require frequent hospitalization?
☐ Yes ☐ No

22. Impaired cognitive function? ☐ Yes ☐ No

23. Unable to return for study recalls? ☐ Yes ☐ No

26. Evidence of chronic or acute parafunctional disorders or TMD?

RADIOGRAPHIC CRITERIA - CBCT

28. Intraoral pathologies? (either acute, progressive, potentially malignant or capable to hamper denture fit) ☐ Yes ☐ No

29. Evident endosseous lesions or residual dental structures?
☐ Yes ☐ No

☐ Yes ☐ No 27. Signs of implant failure, including clinical mobility, peri-implant radiolucency, unacceptable bone loss (0.2mm/year after 1st year, or <2mm any time) and persistent signs/symptoms (pain, neuropathy, infection or exudate)? ☐ Yes ☐ No	Comments:

11.2.6. MDSQ

VAS PRACTICE QUESTIONNAIRE

Date:
Identification Code:

We would like to know if you have a good understanding of how to respond to this questionnaire, which uses linear scales. Please place a vertical mark across the horizontal line in the place which best represents the number written on the left, as in the following example:

Example :

50% 0 ——|—— 100

25%	0	100	☐☐☐
80%	0	100	☐☐☐
10%	0	100	☐☐☐
45%	0	100	☐☐☐
75%	0	100	☐☐☐

ASSESSMENT OF PROSTHESIS

Date:

Identification Code:

We would like to know how satisfied you are with your present prosthesis. Read each of the following questions and draw a vertical line on the horizontal line, where you think your answer best fits. In the case where a question doesn't apply to you, for example if you don't eat a certain type of food, write a brief explanation on the line.

1. Ease of cleaning

Please indicate how difficult it is to clean your **lower** prosthesis and mouth?

Extremely difficult _____ Not at all difficult

2. General satisfaction

In general, are you satisfied with your **lower** prosthesis?

Not at all satisfied _____ Extremely satisfied

3. Ability to speak

Please indicate how difficult it is for you to speak because of your lower prosthesis?

Extremely difficult _____ Not at all difficult

4. Comfort

Are you satisfied with the comfort of your **lower** prosthesis?

Not at all satisfied _____ Extremely satisfied

5. Aesthetics

Are you satisfied with the appearance of your **lower** prosthesis?

Not at all satisfied _____ Extremely satisfied

6.Stability

Are you satisfied with the stability of your **lower** prosthesis?

Not at all satisfied _____ Extremely satisfied

7.Ability to chew

In general, do you find it difficult to chew food?

Extremely difficult _____ Not at all difficult

Please indicate how difficult it is for you to eat **fresh white bread**?

Extremely difficult _____ Not at all difficult

Please indicate how difficult it is for you to eat **hard cheese**?

Extremely difficult _____ Not at all difficult

Please indicate how difficult it is for you to eat **raw carrots**?

Extremely difficult _____ Not at all difficult

Please indicate how difficult it is for you to eat **dry salami**?

Extremely difficult _____ Not at all difficult

Please indicate how difficult it is for you to eat **sliced steak**?

Extremely difficult _____ Not at all difficult

Please indicate how difficult it is for you to eat **raw apples**?

Extremely difficult _____ Not at all difficult

Please indicate how difficult it is for you to eat **lettuce**?

Extremely difficult _____ Not at all difficult

8. Function

In general, is your food well chewed before swallowing?

Badly chewed _____ Very well chewed

Are pieces of **fresh white bread** well chewed before swallowing?

Badly chewed _____ Very well chewed

Are pieces of **hard cheese** well chewed before swallowing?

Badly chewed _____ Very well chewed

Are pieces of **raw carrot** well chewed before swallowing?

Badly chewed _____ Very well chewed

Are pieces of **dry salami** well chewed before swallowing?

Badly chewed _____ Very well chewed

Are pieces of **sliced steak** well chewed before swallowing?

Badly chewed _____ Very well chewed

Are pieces of **raw apple** well chewed before swallowing?

Badly chewed _____ Very well chewed

Are pieces of **lettuce** well chewed before swallowing?

Badly chewed _____ Very well chewed

9.Oral condition

In general, are you satisfied with your oral condition?

Not at all satisfied _____ Extremely satisfied

Do you believe that your oral condition has a negative effect on your general health?

No ○$_0$ Yes ○$_1$

If yes, why?

_____

_____

_____

_____

_____

Rotation of the mandibular overdenture (skip this for baseline)

1. Does **your denture lift** at the back when you chew?

No ○$_0$ Yes ○$_1$

2. How much does the **lifting** of your denture bother you?

Not at all bothered _____ Extremely bothered

11.2.7. OHIP

OHIP-20E Questionnaire

Identification code : Date :

This questionnaire was designed to evaluate how your oral condition has affected your quality of life during the past month. For each of the following questions, mark the response that you feel is the best. If a question does not apply to your situation, then please indicate this just below the question.

	In the last month:	Always	Most of thetime	Some of thetime	Occasionally	Rarely	Never
1	Have you had difficulty chewing any foods because of problems with your teeth, mouth or dentures?	○1	○2	○3	○4	○5	○6
2	Have you had food catching in your teeth or dentures?	○1	○2	○3	○4	○5	○6
3	Have you felt that your dentures have not been fitting properly?	○1	○2	○3	○4	○5	○6
4	Have you had painful aching in your mouth?	○1	○2	○3	○4	○5	○6
5	Have you found it uncomfortable to eat any foods becauseof problems with your teeth, mouth or dentures?	○1	○2	○3	○4	○5	○6
6	Have you had sore spots in your mouth?	○1	○2	○3	○4	○5	○6
7	Have you had uncomfortable dentures?	○1	○2	○3	○4	○5	○6
8	Have you been worried by dental problems?	○1	○2	○3	○4	○5	○6
9	Have you been self conscious because of problems withyour teeth, mouth or dentures?	○1	○2	○3	○4	○5	○6
10	Have you had to avoid eating some foods because of problems with your teeth, mouth or dentures?	○1	○2	○3	○4	○5	○6
11	Has your diet been unsatisfactory because of problemswith your teeth, mouth or dentures?	○1	○2	○3	○4	○5	○6
12	Have you been unable to eat with your dentures becauseof problems with them?	○1	○2	○3	○4	○5	○6
13	Have you had to interrupt meals because of problems with your teeth, mouth or dentures?	○1	○2	○3	○4	○5	○6

	In the last month:	Always	Most of thetime	Some of thetime	Occasionally	Rarely	Never
14	Have you been upset because of problems with your teeth, mouth or dentures?	○1	○2	○3	○4	○5	○6
15	Have you been a bit embarrassed because of problemswith your teeth, mouth or dentures?	○1	○2	○3	○4	○5	○6
16	Have you avoided going out because of problems with your teeth, mouth or dentures?	○1	○2	○3	○4	○5	○6
17	Have you been less tolerant of your spouse or family because of problems with your teeth, mouth or dentures?	○1	○2	○3	○4	○5	○6
18	Have you been a bit irritable with other people because of problems with your teeth, mouth or dentures?	○1	○2	○3	○4	○5	○6
19	Have you been unable to enjoy other people's company as much because of problems with your teeth, mouth or dentures?	○1	○2	○3	○4	○5	○6
20	Have you felt that life in general was less satisfying because of problems with your teeth, mouth or dentures?	○1	○2	○3	○4	○5	○6