Are CAD/CAM Materials the Superior Choice for Dentures:

A Critical Review of Material Properties among CAD/CAM Milled, 3-D Printed & Conventional Acrylic Denture Base Resins

PETER MEARS

ABSTRACT:

Purpose: To evaluate and compare the material properties of acrylic DBRs manufactured by CAD/CAM and conventional methods.
Methods: Electronic searches of Ovid MEDLINE and PubMed databases from 1996 to July 2020 were undertaken to identify papers in the English language related to the topic of the review, using a combination of key words. The search results were then subjected to a selection process adapted from the PRISMA statement.
Results: The selection process identified 14 papers for inclusion in this review. In vitro studies revealed conventional DBRs to provide improved bonding to synthetic polymer teeth; whilst milled DBRs were observed to offer advantages in surface characteristics and flexural properties. Meanwhile current 3-D printed DBR materials were found to perform the poorest in all properties investigated.
Conclusions: Conventional DBRs offer significant advantages in flexure bond strength and fracture toughness to synthetic polymer teeth. Milled fabrication techniques pose significant improvements in residual monomer release, surface characteristics and flexural properties when compared to conventional fabrication. Furthermore, monolithic milled DBRs may enhance the milled fabrication process, posing benefits to the bond strength to synthetic polymer teeth, colour stability and residual monomer release. In contrast, current 3-D printed DBRs offer significantly lower outcomes in all areas investigated, namely bond strength and fracture toughness to synthetic polymer teeth, surface hardness and ultimate flexural strength. Overall, a lack of published research exists surrounding the requirements outlined in ISO standard 20795-1:2013, especially regarding recent CAD/CAM techniques such as 3-D printed and monolithic milled DBRs; hence there is a need for further published research.

INTRODUCTION:

Computer-aided design/computer-aided manufacture (CAD/CAM) has brought a new era in complete denture fabrication, claiming advantages over conventional fabrication in terms of both clinical outcomes and material properties.[1, 2] This new era was ushered in by Maeda et al.[3], a Japanese research group, who in 1994 pioneered an additive manufacture technique involving 3-D laser lithography to rapidly prototype (print) a prosthesis. A subtractive manufacture technique was published 3 years later in 1997 by Kawahata et al.[4], whereby duplicates of existing dentures were digitally designed and milled using a computerised numerical control (CNC) machine. Since these publications, continuous advancements in CAD/CAM technologies have been made and a substantial rise in their prevalence has occurred; one survey reports over half (52.4%) of program directors for post-doctoral prosthodontic programs in the United States now include elements of CAD/CAM denture fabrication in their curriculum, whilst 38.1% intend to introduce it in the near future.[5]

Within the dental literature CAD/CAM technologies incorporate both additive and subtractive fabrication techniques.[1, 2] For both techniques, the CAD stage comprises data gathering, through digital impression scanning, virtual record base production and designing of the denture digitally.[2, 6, 7] Additive manufacture, also known as rapid prototyping or 3-Dimensional (3-D) printing, then uses this computerised 3-D data to create the prosthesis through the successive layering and curing of a material.[1, 2, 6] Alternatively, subtractive manufacture can be implemented in which the prosthesis is produced through the machining (milling) of a prefabricated blank.[1, 2, 6, 7] For consistency dentures constructed by these CAD/CAM processes shall be referred to as 3-D printed and milled throughout this review.

Manufactures of CAD/CAM denture base resins (DBRs) claim an array of both clinical and material advantages over conventional (pack-and-press) dentures, citing a superior manufacture process to be the cause. Of these claims the clinical side has been widely discussed, with clinical outcomes including adaptation (fit), retention and patient satisfaction investigated and reported.[8-14] In contrast, limited independent studies have been published on the in vitro testing of these materials.

Hence, the aim of this critical review of the literature is to compare the material properties of acrylic DBRs manufactured by CAD/CAM and conventional methods. Particular focus will be made to the material properties outlined for denture base polymers by the International Organization for Standardization (ISO) in ISO standard 20795-1:2013.[15]

METHODS:

Methodology for this critical review was adapted from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement.[16] Within this method, a review question was developed using a population, intervention, comparison and outcome (PICO) framework; a search strategy devised; inclusion and exclusion criteria defined and studies selected.

The PICO question developed for this review was as follows: Do acrylic denture base resins fabricated by CAD/CAM techniques offer superior material properties compared to those fabricated via conventional methods?

Search strategy:

A search strategy *(Fig 1)* was devised based on the PICO question, from which key terms were identified, electronic searches of Ovid MEDLINE and PubMed databases from 1996 to July 2020 were then performed before a selection process was undertaken.

Study selection process:

The study selection process *(Fig 1)* involved 3 stages: initial screening, through which duplicate articles were removed; abstract screening, where abstracts were assessed for relevance to the PICO question and full-text assessment, in which the predetermined inclusion and exclusion criteria *(Table 1)* were applied.

Table 1: Inclusion & Exclusion Criteria

INCLUSION CRITERIA

- Full-text articles written in the English language
- Articles published in peer-reviewed journals
- Studies comparing material properties of conventional & CAD/CAM denture base resins
- Reviews & systematic reviews on denture base resins

EXCLUSION CRITERIA:

- Non-acrylic denture base materials
- Modified/reinforced denture base resins
- No material requirement from section 5.2 of ISO standard 20795-1:2013 addressed

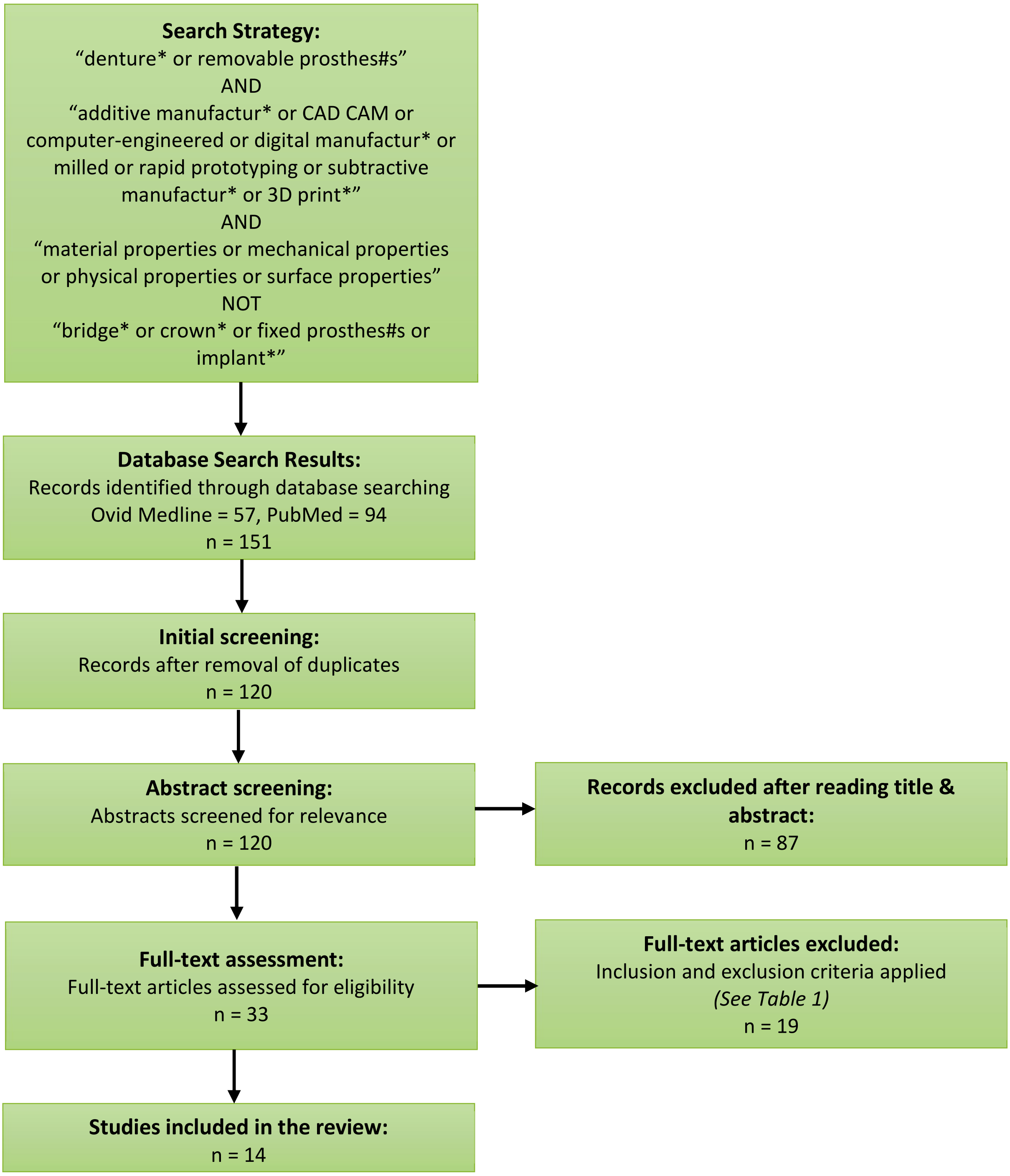

Figure 1: Search Strategy Flowchart

RESULTS:

Applying the search methodology described above, the electronic database searches yielded 151 articles in the English language, within which 31 duplicates were identified and removed. Of the 120 non-duplicated articles, 33 were deemed of relevance to the PICO question. Furthermore, the application of the predetermined inclusion and exclusion criteria during full-text assessment led to the exclusion of an additional 19 articles. The remaining 14 articles were selected for inclusion in this critical review. Of the 14 studies included, 13 were in-vitro studies, with the remaining paper being a review by Janeva et al.(17)

The results of this critical review shall be organized according to the requirements for polymerised materials outlined in Section 5.2 of ISO standard 20795-1:2013.(15) Table 2 presents a summary of the 13 in vitro studies selected for this critical review, including reference to which requirement or requirements they relate.

Biocompatibility:

Srinivasan et al.(18) report DBRs manufactured by milling and conventional means to be equally biocompatible, with cell proliferation of fibroblasts and osteoblasts shown to continue regularly on either surface. Although higher mean values of proliferation were observed in milled resins for both fibroblasts and osteoblasts, no significant differences were demonstrated statistically between the groups. (18)

Bonding to Synthetic Polymer Teeth:

Conventional DBRs are found by Choi et al.(19) to offer the highest flexure bond strength to synthetic teeth across all intervals (0, 6 & 12 months), followed by milled then 3-D printed resins. Although retaining a significantly increased flexure bond strength across these intervals, the effect of ageing – simulated by thermal cycling – was found to have a detrimental effect on conventional resins, significantly reducing the flexure bond strength over time.(19) Teeth bonded to conventional DBRs also showed the highest fracture toughness across all intervals, with ageing demonstrating the same trend.(19)

Whilst ageing was found to have no significant effect on the flexure bond strength and fracture toughness in milled resins, the type of synthetic teeth used were found to be of influence; Mondial teeth (PMMA with nano fillers) producing significantly increased values compared with Ivoclar SPE (unfilled PMMA) and Ivoclar DCL (double cross-linked PMMA) teeth.(19)

3-D printed resins offered the lowest flexural bond strength and fracture toughness in all intervals, with ageing causing no significant effect.(19)

Colour Stability:

Colour stability of DBRs is found by Alp et al.(20) to be unaffected by the method of fabrication, with conventional and milled resins showing no significant difference in CIEDE2000 units following coffee thermal cycling (CTC). Additionally, neither conventional nor milled resins demonstrated a perceptible difference following CTC – the CIEDE2000 units for all DBRs tested fell beneath the perceptibility threshold of 1.72 units.(20)

Residual Methyl Methacrylate (MMA) Monomer:

The results reported by Steinmassl et al.(21) present conventional and milled DBRs to release similar levels of monomer over the seven-day study period, with the exception of Whole You Nexteeth – a milled resin which released significantly higher amounts of monomer than the conventional resin (Candulor Aesthetic Red). Ayman(22) offers a contrasting set of results, with significantly lower residual monomer content observed across all time intervals (baseline, 2 & 7 days) for the milled resin (Polident) compared to the conventional DBR (Vertex RS).

Surface Characteristics:

Hardness:

Prpić et al.[23] observed two of the milled resins (Interdent & Polident) to offer the highest surface hardness among all the DBRs tested. This finding correlates with those of Al-Dwairi[24] and Ayman[22], both of whom demonstrate significantly higher surface hardness in milled compared to conventional DBRs. Srinivasan et al.[18] meanwhile notes no significant difference between the surface hardness of conventional and milled DBRs.

The third milled resin (IvoBase) investigated by Prpić et al.[23], showed significantly lower surface hardness than the other milled resins as well as the conventional and 3-D printed DBRs. Similarly, Al-Dwairi[24] and Perea-Lowery et al.[25] find surface hardness to vary significantly amongst milled denture base materials. Except for IvoBase, the 3-D printed resin (NextDent) was found by Prpić et al.[23] to have the lowest surface hardness value, though no significant difference was demonstrated between it and the conventional resin, Paladon 65.

Roughness:

Milled DBRs are observed by Al-Dwairi et al.[24] to produce significantly lower surface roughness values compared to conventional DBRs. The research of Murat[26] and Steinmassl et al.[27] supports this finding, with significantly lower mean R_a values reported across all investigated milled DBRs, bar the Baltic Denture System. In contrast, Srinivasan et al.[18] find milled resins to produce dentures of significantly higher surface roughness compared to conventional DBRs. On the other hand, Alp[20] and Arslan et al.[28] report no significant difference in R_a values between conventional and milled DBRs.

The study by Al-Dwairi et al.[24] also observes the R_a values of the milled resins to be less than the threshold value for microbial retention (0.2µm). Alp et al.[20] supports this, although it is important to note in their results the R_a values of conventional DBRs are found to fall below this threshold too.

Translucency:

The translucency of DBRs is demonstrated by Alp et al.[20] to be unaffected by the use of conventional or milled resins. However, the relative translucency parameter of one milled resin (Merz M-PM) was found to be significantly lower than all other DBRs tested, both pre- and post-CTC.[20]

Ultimate Flexural Strength & Flexural Modulus:

Ultimate Flexural Strength:

Ultimate flexural strength is reported by a number of studies to be significantly higher in milled DBRs, compared to their conventional alternatives.[18, 23, 28-30] In contrast, the results of Ayman[22] observe the flexural strength of conventional resin to be significantly higher.

In regards to 3-D printed resins, Prpić et al.[23] obtained results finding NextDent (a 3-D printed resin) to have the lowest flexural strength among all DBRs tested.

Flexural Modulus:

Milled DBRs are found by several studies to provide significantly higher flexural modulus compared to conventional resins.[22, 29, 30] Srinivasan et al.[18] on the other hand, reports no significant difference in the flexural modulus of milled and conventional resins.

STUDY	COMPARISON	MATERIALS INVESTIGATED	ISO REQUIREMENT/S INVESTIGATED	TESTING PROCEDURE (UNIT OF MEASUREMENT)	MATERIAL/S WITH SUPERIOR PROPERTIES
Aguirre et al. (2020)[30]	Conventional vs milled	**Conventional:** Lucitone 199 (HP) **Milled:** AvaDent	- Ultimate flexural strength & flexural modulus	- 3-point bend test (MPa)	**Flexural Strength & Modulus:** AvaDent
Al-Dwairi et al. (2020)[29]	Conventional vs milled	**Conventional:** Meliodent (HP) **Milled:** AvaDent & Tizian	- Ultimate flexural strength & flexural modulus	- 3-point bend test (MPa)	**Flexural Strength & Modulus:** AvaDent & Tizian
Al-Dwairi et al. (2019)[24]	Conventional vs milled	**Conventional:** Meliodent (HP) **Milled:** AvaDent & Tizian	- Surface characteristics: Hardness & Roughness	- Micro-hardness test (VHN) - Contact profilometry (R_a value)	**Hardness:** AvaDent **Roughness:** Tizian
Alp et al. (2019)[20]	Conventional vs milled	**Conventional:** Vynacron (HP) **Milled:** AvaDent, M-PM & Polident	- Colour stability - Surface characteristics: Roughness - Translucency	- Spectrometry (CIE colour parameters) - Contact profilometry (R_a value) Tests performed pre & post coffee thermal cycling (CTC)	**Colour Stability:** No difference **Roughness:** No difference **Translucency:** AvaDent, Polident & Vynacron (all pre & post CTC)
Arslan et al. (2018)[28]	Conventional vs milled	**Conventional:** Promolux (HP) **Milled:** AvaDent, M-PM & Polident	- Surface characteristics: Roughness - Ultimate flexural strength	- Contact profilometry (R_a value) - 3-point bend test (MPa) Tests performed pre & post thermal cycling	**Roughness:** No difference **Flexural Strength:** Polident (pre & post thermal cycling)
Ayman (2017)[22]	Conventional vs milled	**Conventional:** Vertex RS (HP) **Milled:** Polident	- Residual monomer content - Surface characteristics: Hardness - Ultimate flexural strength & flexural modulus	- Gas chromatography - Micro-hardness test (MPa) - 3-point bend test (MPa)	**Residual Monomer:** Polident **Hardness:** Polident **Flexural Strength:** Vertex RS **Flexural Modulus:** Polident
Choi et al. (2020)[19]	Conventional vs milled vs 3-D printed	**Conventional:** Vertex RS (HP) **Milled:** Ivobase CAD **3-D Printed:** Dima Print	- Bonding to synthetic polymer teeth	- 4-point bend test using chevron-notched beam method (MPa & MPa $m^{1/2}$)	**Flexure Bond Strength:** Vertex RS **Fracture Toughness:** Vertex RS
Murat et al. (2019)[26]	Conventional vs milled	**Conventional:** Promolux (HP) **Milled:** AvaDent, M-PM & Polident	- Surface characteristics: Roughness	- Contact profilometry (R_a value)	**Roughness:** AvaDent, M-PM & Polident

Table 2: Summary of in vitro studies (HP: Heat-polymerised, AP: Auto-polymerised)

STUDY	COMPARISON	MATERIALS INVESTIGATED	ISO REQUIREMENT/S INVESTIGATED	TESTING PROCEDURE (UNIT OF MEASUREMENT)	MATERIAL/S WITH SUPERIOR PROPERTIES
Perea-Lowery et al. (2020)[25]	Conventional vs milled	**Conventional:** Paladon 65 (HP) & Palapress (AP) **Milled:** Ivobase CAD, L-Temp & Zirkonzahn Temp Basic	- Surface characteristics: Hardness - Ultimate flexural strength	- Micro-hardness test (VHN) - 3-point bend test (MPa) performed pre & post repair	**Hardness:** Paladon 65 **Flexural Strength:** Paladon 65 (pre & post repair) & L-Temp (post repair)
Prpić et al. (2020)[23]	Conventional vs milled vs 3-D printed	**Conventional:** Interacryl Hot (HP), Paladon 65 (HP) & ProBase Hot (HP) **Milled:** Interdent CC disc, Ivobase CAD & Polident **3-D Printed:** NextDent	- Surface characteristics: Hardness - Ultimate flexural strength	- Brinell's test (MPa) - 3-point bend test (MPa)	**Hardness:** Interdent & Polident **Flexural Strength:** Ivobase
Srinivasan et al. (2018)[18]	Conventional vs milled	**Conventional:** Candulor Aesthetic Red (HP) **Milled:** AvaDent	- Biocompatibility - Surface characteristics: Hardness & Roughness - Ultimate flexural strength & flexural modulus	- Resazurin assays: Fibroblasts & osteoblasts (% growth) - Nanoindentation test (MPa) - Non-contact laser profilometry (R_a value) - 3-point bend test (GPa)	**Biocompatibility:** No difference (fibroblast & osteoclast assays) **Hardness:** No difference **Roughness:** Candulor Red **Flexural Strength:** AvaDent **Flexural Modulus:** No difference
Steinmassl et al. (2018)[27]	Conventional vs milled	**Conventional:** Candulor Aesthetic Red (HP) **Milled:** AvaDent, Baltic denture system, Vita VIONIC, Whole You Nexteeth, Wieland digital dentures	- Surface characteristics: Roughness	- Contact profilometry (R_a value)	**Roughness:** AvaDent, Vita VIONIC, Whole You Nexteeth, Wieland digital dentures
Steinmassl et al. (2017)[21]	Conventional vs milled	**Conventional:** Candulor Aesthetic Red (HP) **Milled:** Baltic denture system, Vita VIONIC, Whole You Nexteeth, Wieland digital dentures	- Residual monomer content	- High-performance liquid chromatography (MMA release, ppm)	**Residual Monomer:** Baltic denture system & Candulor red

Table 2 (Continued): Summary of in vitro studies (HP: Heat-polymerised, AP: Auto-polymerised)

DISCUSSION:

In this critical review of the literature 14 studies were selected to investigate the material properties of acrylic DBRs produced by different fabrication techniques, with emphasis being placed on CAD/CAM technologies and their comparison to conventionally made complete dentures. Whilst the evidence presented in this review does not allow an overall assessment of the superiority of one technique over another to be made, analysis regarding the individual requirements of ISO standard 20795-1:2013 can be achieved.

Biocompatibility is a material property defined as the ability of a material or device to be tolerated by a tissue.(31) For protheses such as complete dentures this tissue tolerance is of vital clinical importance, due to the risk of adverse reactions associated with their close contact to the oral mucosa; adverse reactions linked with acrylic denture resins include: hypersensitivity reactions, pain and burning mouth sensations.(21, 32) Although the biocompatibility of medical devices is highly regulated by international standards, such as ISO 7405, the approach to biocompatibility testing varies immensely; this variation undoubtedly stems from the in-depth test selection procedure required, which is based upon the careful consideration of factors including: the intended use of the device, the tissues contacted and the duration of contact.(33) In the reviewed paper by Srinivasan et al.,(18) cell culture assays (with DMEM medium) of human primary osteoblasts and embryological mouse fibroblasts are used to demonstrate the equal biocompatibility of conventional and milled DBRs. Similarly, zebrafish embryo bioassays were performed by Alifui-Segbaya et al.(34) to assess the toxicology of the 3-D printed DBR material, E-Denture. Within these bioassays (with E3 medium), considerable variation in the toxicology was observed between non-ethanol and ethanol treated samples, with embryo mortality reported at 100% and 0% respectively at 120 hours.(34) This extreme polarisation of results can likely be explained by the presence of residual monomer – a cytotoxic component left due to the non-reaction of methacrylate monomers within the polymerisation (curing) process.(35) Although the residual monomer content was not directly measured by Alifui-Segbaya et al.(34), their results regarding the degree of double-bond conversion do offer some insight, due to the indirect correlation that exists between these variables. Within these results, ethanol-treated samples noted a 4.77% increase in double-bond conversion rate, compared to the non-ethanol treated samples; as such it can be inferred that the ethanol-treated samples contain a lower level of residual monomer, therefore explaining the decreased cytotoxicity.(34) This theory is supported by the observed and well-evidenced detoxifying effect of ethanol on acrylic polymers used in dentistry.(34, 36, 37) Correspondingly, the similar levels of residual monomer released by conventional and milled DBRs, evidenced by Steinmassl et al.(21), can be used to explain the observed non-significant difference in biocompatibility. However, this picture is complicated by the Candida albicans adhesion assays performed by Murat et al.(26), which demonstrate milled DBRs to show significantly increased resistance to microbial adhesion compared to the conventional DBR, Promolux. This finding highlights the complex nature of determining biocompatibility and the need for further biocompatibility tests to investigate both the toxicology and microbial resistance of DBRs. Overall, all three of the manufacture techniques are presented to have the potential to produce biocompatible denture bases, with milled DBRs suggested to offer advantages in terms of microbial resistance; however further biocompatibility tests are required in order to substantiate this claim.

The bonding of synthetic polymer teeth to DBRs is an important property within complete denture manufacture, with the debonding of denture teeth considered a major issue.(38) Despite this, tooth de-bonding remains highly prevalent, estimated to be involved in 22-30% of denture repairs – especially those in anterior regions.(38) These repairs can be time-consuming and costly for patients, with the vulnerability of the anterior region causing potential for aesthetic problems.(19) Within the regulatory standards for denture base polymers and artificial teeth (ISO 20795-1 & ISO 22112 respectively), a method of testing is outlined whereby tensile-testing apparatus is used to apply a labially-directed force to the incisal edge of bonded artificial teeth, until failure.(15, 39) The bond is deemed satisfactory if the fracture mode is cohesive; this is determined by examining the fracture site for artificial teeth remnants remaining bonded to the denture base, or vice versa.(15, 39)

Meanwhile, an alternative method involving a 4-point bend test of chevron-notched beam prepared specimens, is implemented in the reviewed study by Choi et al.[19] Through this method, synthetic teeth bonded to conventional DBRs were demonstrated to have significantly higher flexure bond strength and fracture toughness than both the milled and the 3-D printed DBRs.[19] However, upon simulation of intraoral ageing – via thermal cycling – these values were found to significantly decrease in conventional resin, whilst no significant effects where observed in either of the CAD/CAM DBRs.[19] Despite this, the conventional resin retained the highest values across all time intervals, whilst the 3-D printed resin maintained the lowest.[19] With regards to bond strength, it is stated that the greater the availability of free monomers during processing, the higher the quality of the resulting bond.[40] Thus, the significant differences between the groups can be explained by examining the differing processing techniques. Conventional DBRs are heat-cured with the teeth in-situ, therefore exposing the synthetic teeth to high quantity of free monomer, enabling a greater degree of cross-linking to form between the polymerising denture base and polymerised teeth.[41] In contrast, milled DBRs are pre-polymerised and as such require a bonding-agent to fix the synthetic teeth in place. As highlighted in the reviewed study the polymer-monomer ratio for the bonding agent used is 1.75:1.9 compared to the conventional resin's ratio of 2.3:1; consequently, a 2.5 times lower free monomer content is indicated in the bonding-agent, which correlates with the observed significant difference in flexure bond strength and fracture toughness.[19] Meanwhile, in 3-D printed DBRs the denture base and teeth are printed and light-cured (polymerised) together, therefore a high bond strength would be expected due the availability of free monomer – however this is not the case, with these resins actually demonstrating the lowest bond strength.[19] Explanation of this phenomenon is gleaned by the greater pigmentation of the resins required to produce aesthetic denture teeth; which, as evidenced by Monson et al.[42] reduces the penetration of UV light, thereby preventing polymerisation. The tooth/denture interface is therefore significantly weakened by unpolymerized material due to its depth, hence explaining the significantly reduced values of bond strength and fracture toughness. Together these findings present the picture of conventional DBRs being the superior material choice for bonding synthetic teeth, despite the adverse effect of intra-oral aging on these resins. The results of Goodacre et al.[43] complicate the situation however, as compressive processing techniques (pack-and-press) are demonstrated to cause positive occlusal tooth movement which can lead to potential clinical implications, such as an increase in the occlusal-vertical dimension. A solution to this quandary may be found through the recent introduction of the monolithic milling technique, through which the risk of occlusal tooth movement is negated due to its subtractive nature.[43] Further to this, superior bond strength values may be offered by this technique as the denture base and teeth are milled together from a single pre-polymerised puck, therefore removing the previous limiting factor of bonding agent – however further testing is required to validate this hypothesis.

Colour stability is an important property in denture bases, with colour changes acting as an indicator of aging and material wear, as well as causing potential aesthetic problems which may necessitate denture replacement.[20] For this reason, a denture base must not demonstrate more than a slight change in colour to be deemed satisfactory.[15] In the reviewed study by Alp et al.[20], colour stability was investigated through comparison of Commission Internationale De L'éclairage (CIE) colour parameters – calculated from spectral radiance measurements – before and after coffee thermal cycling. Coffee thermal cycling (CTC) is considered an appropriate method of simulating intra-oral aging, with coffee reported to have a significant staining potential; this staining potential results from both the surface adsorption and absorption of yellow colourants, with tannic acid considered the primary staining component.[20, 44] In the present study, 6-months of coffee consumption was simulated through 5000 CTC cycles.[20] The results of this simulation demonstrate the fabrication method to have no significant effect on the colour difference value (CIEDE2000 units) with both conventional and milled DBRs also observing no perceptible colour change upon completion of CTC.[20] Al-Qarni et al.[44] similarly report conventional and milled denture bases to display no significant difference in stainability (colour stability); however coffee immersion was found to produce a significant colour change in all resins, although remaining beneath the pre-determined acceptability threshold. These differing impacts of coffee may be due to several factors including the concentration and brand of the coffee used. A further finding of note was the increased stain resistance of milled DBRs at the tooth-denture base interface.[44] This observation likely arises from the occurrence of polymerisation shrinkage in conventional fabrication techniques, which may lead to void creation at the interface through which stains can penetrate.[44] Interestingly, fully-milled (monolithic) dentures were noted to harbour no stain at the tooth-denture base interface.[44] Overall, these studies demonstrate both milled and conventional techniques to produce acceptable colour stability, with potential advantages suggested for milled fabrication techniques – especially monolithic – in terms of stain resistance at the tooth-denture base interface. However, as of yet no studies have been published reporting the colour stability of 3-D printed dentures, therefore further research is required to investigate these materials.

Residual monomer is undesired in denture bases due to its negative impact on both biocompatibility and mechanical properties.[21, 22] As aforementioned, residual methacrylate monomer is responsible for the cytotoxic potential of denture bases, with leaching of the monomer into the surrounding tissue and saliva causing several adverse reactions.[21, 32, 35] For these reasons a residual monomer content of zero would be optimum, however unfortunately this is unachievable due to the monomer-polymer equilibrium necessary for free radical polymerisation.[45] As such the ISO standard for denture base polymers states residual methacrylate monomer must not exceed 2.2% mass fraction for a DBR to be deemed acceptable.[15] Within the reviewed studies by Ayman[22] and Steinmassl et al.[21], the recommended method of chromatographic analysis was implemented;[15] however the form of chromatography differs between these studies, with gas and liquid chromatography used respectively. Ayman[22], demonstrates a milled DBR (Polident) to release significantly reduced residual monomer compared to the conventional resin (Vertex RS). This result supports the current hypothesis in which the high temperatures and pressures associated with milled fabrication techniques are thought to enhance the degree of monomer conversion through the formation of longer polymer chains.[21, 46] Contrary to this, Steinmassl et al.[21] find both conventional and milled DBRs to release statistically similar levels of residual methacrylate monomer. These contrasting results are likely caused by the respective preparation of samples in which synthetic teeth are either present or absent. Within the Steinmassl et al.[21] study, denture base samples are prepared bearing synthetic teeth and therefore the tested milled DBRs (bar Baltic denture system) incorporated methacrylate-based bonging agents. Subsequently, these bonding agents act as an additional source of methacrylate monomer, which therefore raises the residual monomer content to match the levels leached by conventional DBRs.[21] Meanwhile, a further finding of note was the significant difference evidenced amongst the DBRs investigated; therefore it must be considered that whilst the fabrication technique may offer some standardisation of residual monomer release, the varying processing steps of different resins are another influential factor.[21] Overall, whilst milled denture bases themselves are cited to offer potential advantages in terms of monomer release it is important to view the fabrication process as a whole, considering the influence of bonding agents as well as any material specific processing methods.[21, 22] Regarding 3-D printed DBRs no studies have currently been published on this topic; thus, research is required to explore the residual monomer release within these materials.

Hardness is defined as a measure of the resistance to localised plastic deformation induced by either mechanical indentation or abrasion.[23] Abrasive forces are routinely applied to denture bases due to the role of mechanical brushing in denture care, therefore a high surface hardness is required to prevent wear, which could lead to pigmentation, plaque retention and a reduced life-span of the denture.[22, 23] Within the ISO standard for denture base polymers no quantitative testing procedure is outlined for surface hardness, instead an assessment is only required through visual inspection.[15] Contrary to this, the reviewed studies perform a variety of quantitative methods to assess this property, including: Brinell's method, Vickers hardness and nano-indentation testing.[18, 22-25] Through these testing procedures Prpić[23], Al-Dwairi[24] and Ayman et al.[22] demonstrate milled

DBRs to show significantly higher values of surface hardness, compared to conventional DBRs. This result can be attributed to the high temperature and pressure conditions used in milled DBR polymerisation; these conditions are hypothesised to restrict dimensional polymerisation shrinkage as well as increase the level of double-bond conversion, limiting the plasticising effect.[21-24] However, significant intra-group differences are noted by Prpić et al.[23], correlating with the findings of both Al-Dwairi[24] and Perea-Lowery et al.[25] Thus, it must be concluded that fabrication technique is not the only influencing factor in determining surface hardness. With regards to 3-D printed DBRs, Prpić et al.[23] observed significantly lower surface hardness values than all the other tested resins, with the exception of Ivobase – a milled DBR demonstrating severe intra-group variation. Explanation of this outcome is found through the low double-bond conversion rate evidenced in 3-D printed resins;[23] as such the plasticising effect is enhanced due to the increased levels of residual methacrylate monomer, which act as a plasticizer.[21, 22, 24] Meanwhile, the results of Srinivasan et al.[18] contest those of Prpić[23], Al-Dwairi[24] and Ayman et al.[22], with conventional and milled DBRs instead observed to have statistically similar surface hardness. On balance, the results of these studies present milled DBRs to offer potentially increased values of surface hardness and therefore greater wear-resistance. Conversely, 3-D printed DBRs appear to display decreased surface hardness and as such reduced wear-resistance; although as no studies are yet available for comparison, further research is required to confirm or dispute this finding. Despite these observed trends, it is emphasised that materials should be considered on an individual basis, rather than by manufacture process alone, due to the importance of material composition in determining mechanical properties.

Surface roughness is a component of surface texture described as the indentations or irregularities characterizing the surface of a material.[24] Within denture bases, surface roughness is cited to influence wettability, microbial adhesion and stain retention.[24, 28] As microbial adhesion is more commonplace on non-shedding surfaces, denture bases are especially vulnerable;[24] therefore, a threshold roughness level of 0.2µm is recommended to prevent excess accumulation and colonisation of microorganisms.[20, 24, 26, 27] Despite this, the ISO standard for denture base polymers only states a requirement of smoothness, which is to be determined through visual inspection.[15] Rather than this arbitrary assessment, all the reviewed studies chose to measure the roughness average (R_a) value via profilometry. Through this quantitative measurement of surface roughness, Al-Dwairi[24], Murat[26] and Steinmassl et al.[27] observe milled DBRs to have significantly lower R_a values than conventional resins. Further support for this finding is gained by the scanning electron microscope (SEM) investigations of Murat[26] and Arslan et al.[28], in which conventional DBRs were observed to exhibit a more porous surface with multi-dots and surface irregularities than milled DBRs. These observations may once again be explained by the high temperatures and pressures associated with the polymerisation of milled DBRs, with the corresponding reduction in residual monomer reported to contribute to surface roughness alteration.[24] Interestingly, despite the SEM observations of increased porosity within conventional DBRs, the results of Arslan et al.[28] demonstrate statistically similar R_a values in conventional and milled resins. Alp et al.[20] also report a similar non-significant difference between conventional and milled DBRs; thus, it must be considered that surface roughness is not solely influenced by the fabrication technique, with factors such as the material composition and polishing process having an influential effect.[20, 24, 47] On the other hand, Srinivasan et al.[18] present a reversal of the previously stated trend, reporting conventional DBRs to provide lower R_a values compared to milled DBRs. However, this controversial result is likely to be caused by the differing approach to specimen preparation, in which manual table saws were implemented in place of a milling system to machine (mill) the milled denture bases. Additionally, the alternative use of non-contact laser profilometry within this study may have had an effect. Overall, these studies portray fabrication techniques to have some impact on surface roughness, with milled fabrication cited to offer a potential reduction in porosity, surface irregularities and R_a values.[24, 26-28] However clinically whilst this may be a useful guide, the need to assess potential materials individually is emphasised, due to the influence of material composition.[24] Further to this, it is noted that optimum surface roughness will only be achieved when suitable polishing procedures are performed.[24, 47] Regarding 3-D printed DBRs the lack of studies on surface roughness necessitates the need for additional research on this topic.

Translucency is desired within denture bases to maintain compatibility with the colour and appearance of the underlying mucosa.[20] For this reason, the ISO standard for denture base polymers requires all coloured DBRs to be translucent.[15] To determine translucency, Alp et al.[20] perform a method involving the use of the CIEDE2000 formula to determine the relative translucency parameter (RTP), from observation of the colour difference between an opaque black backing and a white backing. The results of this study show translucency to be unaffected by fabrication technique with conventional and milled DBRs displaying similar RTP values.[20] However, significant differences were observed amongst the DBRs investigated, with Merz M-PM reported to have significantly lower RTP values than all other resins.[20] It is therefore indicated that translucency depends on material composition rather than fabrication; hence, the importance of considering materials on an individual basis is emphasised. Currently, the study by Alp et al.[20] is the only published study investigating this material property; therefore, further research is required to enable comparison of results as well as to investigate the translucency of 3-D printed DBRs.

Ultimate flexural strength, also known as bend strength, can be defined as the stress within a material just before it yields in a flexure test.[23] Similarly, flexural modulus – or bending modulus – is formulated as the ratio of stress to strain during flexural deformation, therefore representing the ability of a material to resist bending, otherwise known as rigidity.[29, 30] Due to the inherent involvement of bending within these properties, the ISO standard for denture base polymers requires a three-point flexure test to be performed.[15] A DBR is deemed to be satisfactory if, the three-point flexure test results in an ultimate flexural strength of at least 65MPa and a flexural modulus of at least 2,000MPa.[15] The ISO requirement of these high flexural strength and modulus values is essential due to the uneven force distributions (or flexural stresses) that denture bases are subjected to throughout their function.[28, 30] These flexural stresses are a particular concern due to their potential to cause cyclic deformation, crack propagation and eventually fracture of the denture.[28-30] Further to this, intraoral factors such as frenal notches, tori, and alveolar bone resorption can heighten these flexural stresses through the creation of uneven denture support;[28, 30] thus, it is imperative that DBRs are manufactured to ensure these high flexural stresses can be endured – hence the requirement of high flexural strength and modulus. With regards to ultimate flexural strength the reviewed studies offered a varied set of results. Ayman[22], demonstrates conventional resins to exhibit significantly higher flexural strength whilst most of the remaining reviewed studies observe the opposite, whereby milled DBRs express significantly higher flexural strength.[18, 23, 28-30] Meanwhile, Perea-Lowery et al.[25] present a mixed set of results in which different milled DBRs show higher, lower, or similar flexural strength to the two conventional resins investigated. The higher flexural strength seen in milled DBRs can be explained by the high temperature and pressure conditions involved in their processing, which thereby produces condensed acrylic resins with minimal porosity, shrinkage, and residual methacrylate monomer.[22, 23, 25, 28-30] Furthermore, these processing conditions have been reported to reduce the intermolecular distances within the polymer matrix, reducing the free volume.[22, 25] However, as demonstrated through the results of Perea-lowery et al.[25] the method of fabrication is not the sole determinant of flexural strength, therefore it must be noted that the differences observed amongst the studies may be caused by the use of different resin materials. Meanwhile, 3-D printed DBRs are shown by Prpić et al.[23] to offer the significantly lower flexural strength than both conventional and milled DBRs; although, the flexural strength was found to meet the ISO requirement of 65MPa. Regarding flexural modulus, the reviewed studies of Aguirre[30], Al-Dwairi[29], and Ayman[22] report milled DBRs to provide significantly higher flexural modulus compared to conventional acrylic resins. Srinivasan et al.[18] opposes this finding however, stating no significant difference in flexural modulus between conventional and milled DBRs. These differences may once again be attributed to the high temperature and pressures involved in milled DBR fabrication, with the reduction in residual methacrylate monomer thought to reduce the plasticising effect and therefore enhance the flexural properties.[22, 29] Currently, no studies have yet investigated the flexural modulus expressed by 3-D printed DBRs, therefore necessitating the need for further research in this area. Overall, milled DBRs are presented to offer better flexural properties in terms of both ultimate flexural strength and flexural modulus; this may translate to clinical advantages such as improved speech and patient comfort, due to the enabling of thinner denture bases.[18] However, it must be noted that all commercially available DBRs must adhere to the requirements set by the ISO and therefore are suitable for use.

Table 3: Fields Requiring Further Research

FURTHER RESEARCH REQUIRED:

- Biocompatibility
    - Further assessment of the microbial resistance & toxicology of DBR materials
- Bond Strength to Synthetic Polymer Teeth
    - Investigation into the bond strength provided by monolithic milled dentures
- Colour Stability
    - Investigation into the colour stability of 3-D printed dentures
- Residual Monomer Release
    - Investigation into the residual monomer release of 3-D printed dentures
- Surface Hardness
    - Further research into the hardness of 3-D printed dentures
- Surface Roughness
    - Investigation into the roughness of 3-D printed dentures
- Translucency
    - Further research into the translucency of DBR materials
- Ultimate Flexural Strength
    - Further research into the flexural strength of 3-D printed dentures
- Flexural Modulus
    - Investigation into the flexural modulus of 3-D printed dentures

CONCLUSION:

The literature search performed within this critical review revealed several relevant studies, all of which addressed varying ISO requirements for denture base polymers. The conclusions of this review are therefore an amalgamation of the findings presented in these studies and as such must be viewed with some caution. Additionally, it must be noted that all commercially available DBRs must adhere to the regulations imposed by ISO standard 20795-1:2013 and as such are suitable for clinical use. Clinically, the importance of considering DBR materials individually must therefore be emphasised, however the conclusions of this review can be used as a general guide for the expected material properties.

Within the confines of this study the following conclusions were drawn:

1) Conventional DBRs offer significantly higher flexure bond strength and fracture toughness to synthetic polymer teeth than both milled and 3-D printed DBRs.
2) Milled fabrication techniques are associated with significant improvements in residual methacrylate monomer release, surface characteristics and flexural properties, compared to conventional fabrication.
3) Monolithic milled techniques may enhance the milled fabrication process, improving the bond strength to synthetic polymer teeth, colour stability and residual monomer release.

4) Current 3-D printed DBR materials display significantly lower outcomes compared to both milled and conventional DBRs with regards to: bond strength and fracture toughness to synthetic polymer teeth; surface hardness and ultimate flexural strength.
5) Further research surrounding the requirements outlined in ISO standard 20795-1:2013 is required, especially regarding recent CAD/CAM techniques such as 3-D printed and monolithic milled DBRs.

REFERENCES:

1. 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.
2. Bilgin MS, Baytaroğlu EN, Erdem A, Dilber E. A review of computer-aided design/computer-aided manufacture techniques for removable denture fabrication. Eur J Dent. 2016;10(2):286-91.
3. Maeda Y, Minoura M, Tsutsumi S, Okada M, Nokubi T. A CAD/CAM system for removable denture. Part I: Fabrication of complete dentures. Int J Prosthodont. 1994;7(1):17-21.
4. Kawahata N, Ono H, Nishi Y, Hamano T, Nagaoka E. Trial of duplication procedure for complete dentures by CAD/CAM. J Oral Rehabil. 1997;24(7):540-8.
5. Fernandez MA, Nimmo A, Behar-Horenstein LS. Digital Denture Fabrication in Pre- and Postdoctoral Education: A Survey of U.S. Dental Schools. J Prosthodont. 2016;25(1):83-90.
6. Bilgin MS, Erdem A, Aglarci OS, Dilber E. Fabricating Complete Dentures with CAD/CAM and RP Technologies. J Prosthodont. 2015;24(7):576-9.
7. Infante L, Yilmaz B, McGlumphy E, Finger I. Fabricating complete dentures with CAD/CAM technology. J Prosthet Dent. 2014;111(5):351-5.
8. Kattadiyil MT, AlHelal A. An update on computer-engineered complete dentures: A systematic review on clinical outcomes. J Prosthet Dent. 2017;117(4):478-85.
9. 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.
10. Hwang HJ, Lee SJ, Park EJ, Yoon HI. Assessment of the trueness and tissue surface adaptation of CAD-CAM maxillary denture bases manufactured using digital light processing. J Prosthet Dent. 2019;121(1):110-7.
11. Steinmassl O, Dumfahrt H, Grunert I, Steinmassl PA. CAD/CAM produces dentures with improved fit. Clin Oral Investig. 2018;22(8):2829-35.
12. Tasaka A, Matsunaga S, Odaka K, Ishizaki K, Ueda T, Abe S, et al. Accuracy and retention of denture base fabricated by heat curing and additive manufacturing. J Prosthodont Res. 2019;63(1):85-9.
13. 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.
14. 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.
15. International Organization for Standardization. Dentistry - Base polymers - Part 1: Denture Base Polymers. ISO 20795-1:2013: ISO; 2013.
16. Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: the PRISMA statement. Journal of Clinical Epidemology. 2009;62(10):1006-12.
17. 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):1498-502.

18. 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;37(4):526-33.
19. Choi JJE, Uy CE, Plaksina P, Ramani RS, Ganjigatti R, Waddell JN. Bond Strength of Denture Teeth to Heat-Cured, CAD/CAM and 3D Printed Denture Acrylics. J Prosthodont. 2020;29(5):415-21.
20. Alp G, Johnston WM, Yilmaz B. Optical properties and surface roughness of prepolymerized poly(methyl methacrylate) denture base materials. J Prosthet Dent. 2019;121(2):347-52.
21. Steinmassl PA, Wiedemair V, Huck C, Klaunzer F, Steinmassl O, Grunert I, et al. Do CAD/CAM dentures really release less monomer than conventional dentures? Clin Oral Investig. 2017;21(5):1697-705.
22. Ayman AD. The residual monomer content and mechanical properties of CAD\CAM resins used in the fabrication of complete dentures as compared to heat cured resins. Electron Physician. 2017;9(7):4766-72.
23. Prpić V, Schauperl Z, Ćatić A, Dulčić N, Čimić S. Comparison of Mechanical Properties of 3D-Printed, CAD/CAM, and Conventional Denture Base Materials. J Prosthodont. 2020.
24. Al-Dwairi ZN, Tahboub KY, Baba NZ, Goodacre CJ, Ozcan M. A Comparison of the Surface Properties of CAD/CAM and Conventional Polymethylmethacrylate (PMMA). J Prosthodont. 2019;28(4):452-7.
25. Perea-Lowery L, Minja IK, Lassila L, Ramakrishnaiah R, Vallittu PK. Assessment of CAD-CAM polymers for digitally fabricated complete dentures. J Prosthet Dent. 2020.
26. Murat S, Alp G, Alatali C, Uzun M. In Vitro Evaluation of Adhesion of Candida albicans on CAD/CAM PMMA-Based Polymers. J Prosthodont. 2019;28(2):e873-e9.
27. Steinmassl O, Dumfahrt H, Grunert I, Steinmassl PA. Influence of CAD/CAM fabrication on denture surface properties. J Oral Rehabil. 2018;45(5):406-13.
28. Arslan M, Murat S, Alp G, Zaimoglu A. Evaluation of flexural strength and surface properties of prepolymerized CAD/CAM PMMA-based polymers used for digital 3D complete dentures. Int J Comput Dent. 2018;21(1):31-40.
29. Al-Dwairi ZN, Tahboub KY, Baba NZ, Goodacre CJ. A Comparison of the Flexural and Impact Strengths and Flexural Modulus of CAD/CAM and Conventional Heat-Cured Polymethyl Methacrylate (PMMA). J Prosthodont. 2020;29(4):341-9.
30. Aguirre BC, Chen JH, Kontogiorgos ED, Murchison DF, Nagy WW. Flexural strength of denture base acrylic resins processed by conventional and CAD-CAM methods. J Prosthet Dent. 2020;123(4):641-6.
31. Oxford Medical Dictionary. 9th ed. New York: Oxford University Press; 2015. Oxford Concise Medical Dictionary.
32. Kostic M, Pejcic A, Igic M, Gligorijevic N. Adverse reactions to denture resin materials. Eur Rev Med Pharmacol Sci. 2017;21(23):5298-305.
33. International Organization for Standardization. Dentistry - Evaluation of biocompatibility of medical devices used in dentistry. ISO 7405:2018: ISO; 2018.
34. Alifui-Segbaya F, Bowman J, White AR, Varma S, Lieschke GJ, George R. Toxicological assessment of additively manufactured methacrylates for medical devices in dentistry. Acta Biomater. 2018;78:64-77.
35. Chaves CA, Machado AL, Vergani CE, de Souza RF, Giampaolo ET. Cytotoxicity of denture base and hard chairside reline materials: a systematic review. J Prosthet Dent. 2012;107(2):114-27.
36. Neves CB, Lopes LP, Ferrão HF, Miranda JP, Castro MF, Bettencourt AF. Ethanol postpolymerization treatment for improving the biocompatibility of acrylic reline resins. Biomed Res Int. 2013;2013:485246.
37. Boeckler AF, Morton D, Poser S, Dette KE. Release of dibenzoyl peroxide from polymethyl methacrylate denture base resins: an in vitro evaluation. Dent Mater. 2008;24(12):1602-7.
38. Patil SB, Naveen BH, Patil NP. Bonding acrylic teeth to acrylic resin denture bases: a review. Gerodontology. 2006;23(3):131-9.

39. International Organisation for Standardization. Dentistry - Artifical teeth for dental prostheses. ISO 22112:2017: ISO; 2017.
40. Robison NE, Tantbirojn D, Versluis A, Cagna DR. Failure strengths of denture teeth fabricated on injection molded or compression molded denture base resins. J Prosthet Dent. 2016;116(2):292-9.
41. Cunningham JL. Bond strength of denture teeth to acrylic bases. J Dent. 1993;21(5):274-80.
42. Monzón M, Ortega Z, Hernández A, Paz R, Ortega F. Anisotropy of Photopolymer Parts Made by Digital Light Processing. Materials (Basel). 2017;10(1).
43. Goodacre BJ, Goodacre CJ, Baba NZ, Kattadiyil MT. Comparison of denture tooth movement between CAD-CAM and conventional fabrication techniques. J Prosthet Dent. 2018;119(1):108-15.
44. 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):880-7.
45. Lung CY, Darvell BW. Minimization of the inevitable residual monomer in denture base acrylic. Dent Mater. 2005;21(12):1119-28.
46. Murakami N, Wakabayashi N, Matsushima R, Kishida A, Igarashi Y. Effect of high-pressure polymerization on mechanical properties of PMMA denture base resin. J Mech Behav Biomed Mater. 2013;20:98-104.
47. Gungor H, Gundogdu M, Yesil Duymus Z. Investigation of the effect of different polishing techniques on the surface roughness of denture base and repair materials. J Prosthet Dent. 2014;112(5):1271-7.