Stomatologija. Baltic Dental and Maxillofacial Journal, 24: 3-12, 2022

A comparison of mechanic properties regarding complete removable dentures, which were made from polymethylmethacrilate (PMMA) during conventional and CAD/CAM processes. Systemic literature review

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SUMMARY

Background. It is not clear if complete removable dentures made during a CAD/CAM process can equate or surpass dentures created during the conventional process in regards of their mechanical properties.

Purpose. To compare mechanical properties of complete removable dentures made from polymethylmethacrilate (PMMA) during a process of CAD/CAM, which are used to help edentulous adult patients, with analogical dentures created from PMMA during the conventional process.

Material and methods. Data search was conducted regarding PRISMA criteria. According to chosen keywords, scientific articles, published from 2017 to 2022, were sampled from electronic databases such as PubMed, Science Direct, and Cohrane Library. Article search focused on studies that discussed mechanic properties of traditional and CAD/CAM complete removable dentures made from PMMA. The properties are: microhardness, nano hardness, the roughness of the surface, flexural strength and modulus, fracture toughness, flexural bond strength, mechanical compliance of the contact between the inner surface of the denture and the denture socket mucosa - adaptation of the prosthesis to the denture bearing, hydrophobicity, water sorption and solubility, dimensional stability, elasticity. Discussed measurements from the scientific studies, which are included into the systematic literature analysis, are assessed according to a synthesis method used for such data.

Results. The hardness, flexural strength, flexural modulus, and hydrophobicity of the conventional PMMA plastic blank, made during a process of CAD/CAM, were bigger and dimensional stability – better. Meanwhile, the roughness of the surface, fracture toughness, flexural bond strength, and elasticity of the blank were bigger than the ones made during the conventional process. Water sorption and solubility statistically did not differ among differently processed plastic polymethylmethacrilate blanks. Only one study was carried out in vivo, in which complete removable denture bases made from CAD/CAM prepolymerized PMMA plastic also showed better adaptation to the denture bearing tissue than those made by conventional polymerization.

Conclusions. The final plastic product from the pre-polymerized PMMA and the processed CAD / CAM is superior in many mechanical properties to the final plastic product made during the conventional PMMA polymerization process.

Keywords: CAD/CAM, complete denture, dentures, PMMA, comparison of mechanical properties.

INTRODUCTION

Complete removable dentures are manufactured and used for many years because they are the golden standard of edentulous patients' treatment (1). Traditionally, complete removable dentures are made from polymethylmethacrilate (PMMA) resin by polymerizing it with heat (2).

In the dental market, after the invention of dental prostheses, removable dentures were started being manufactured with a fixation on dental implants due to better prosthesis stabilization and fixation (3). Thus, it can be noted that the improvement of prosthetic structures used in the restoration of edentulous areas correlates with the emergence of innovations in dentistry.

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Over the last decade, with the rapid development of science and new technologies, the integration of digital methods into the work of dentists has become increasingly common. The production of dentures is no exception – a computer modelling and production method (CAD / CAM) and a 3D printer are becoming commonplaces in prosthetic dentistry (1).

Digital methods of denture modelling and manufacturing speed up the production process and reduce the number of clinical and laboratory stages and possible errors. PMMA is also used in this way to make complete removable dentures, but it is pre-polymerized under high temperature and pressure. The digital manufacturing process is thought to result in lower porosity of the prosthesis, which prevents various microorganisms from reproducing. It also causes better fracture toughness, smaller residual monomer emission, and polymerization shrinkage, in comparison with the conventional conventional polymerization production of complete removable dentures (1, 2, 4-6).

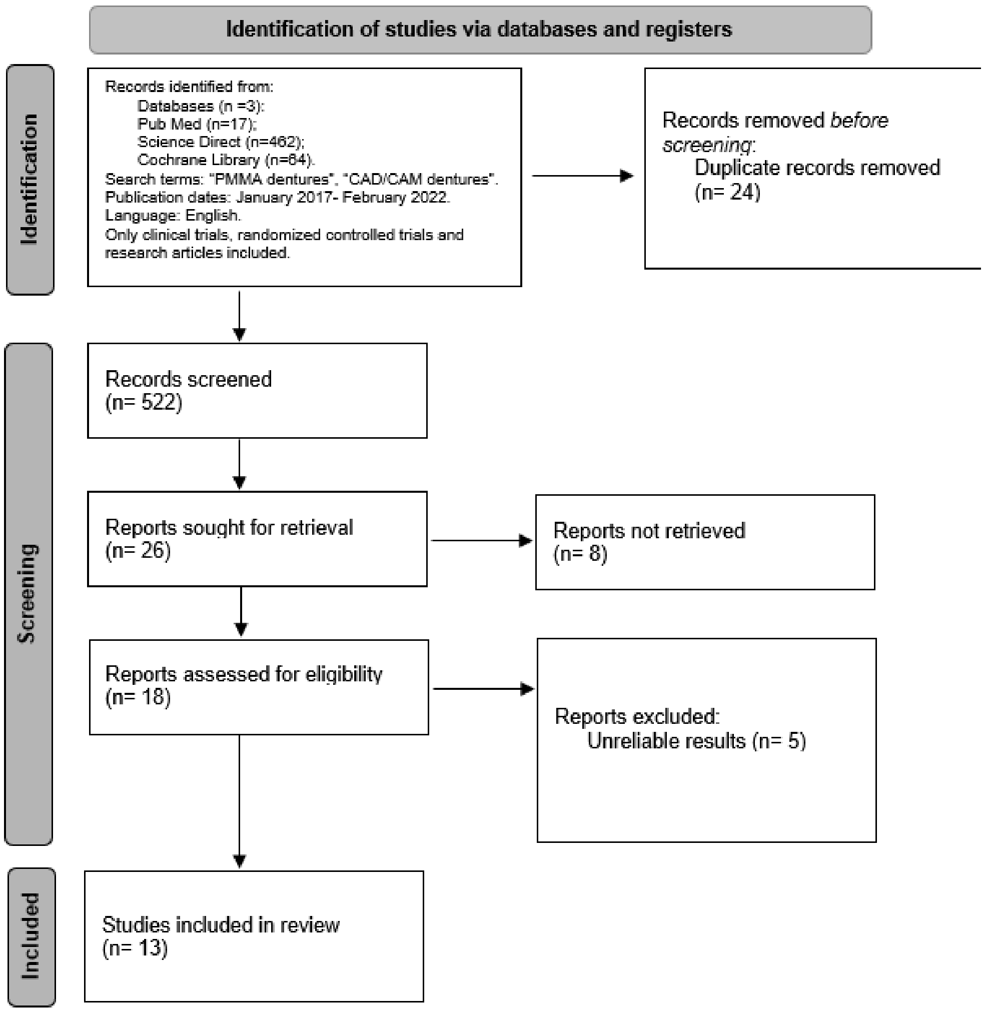

Fig 1. PRISMA selection criteria flow chart

However, a question arises as to whether complete removable dentures made by a computer can equal or outperform hot polymerized prostheses in terms of their mechanical properties.

The purpose of this systematic literature review is to determine whether the mechanical properties of a complete removable denture made from CAD/CAM prepolymerized polymethylmethacrylate are superior to the one made from hot polymerized polymethylmethacrylate.

MATERIAL AND METHODS

The study was conducted by two independent researchers who compared their data and opinions and summarized them by resolving the differences in the form of a discussion.

Focus question

The focus question was developed according to the population, intervention, comparison, and outcome (PICO) design (Table 1).

Table 1. The focus question development according to the PICOS study design

Component	Description
Population (P)	Edentulous adult patients
Intervention (I)	Edentulous spaces reconstruction with complete removable dentures
Comparison (C)	Heat-polymerizing PMMA and CAD CAM PMMA mechanic properties
Outcome (O)	Better PMMA mechanic properties
Study design (S)	Randomized and non-randomized controlled trial, retrospective, prospective, in vitro and in vivo studies
Focus question	Whether the mechanical properties of a complete removable denture made from CAD CAM prepolymerized polymethylmethacrylate are superior to the one made from hot polymerized polymethylmethacrylate

Data source and search strategies

Data search was conducted on February and March, 2022, by applying PRISMA criteria (7) (Figure 1) on articles published from 2017 to 2022 in electronic databases such as PubMed, Science Direct, and Cohrane Library. Last search entry was entered on March 11th, 2022. Terms of Medical Subject Headings (MeSH) were used in the search. Keywords of the search: *PMMA dentures, CAD/CAM dentures, CAD/CAM, complete denture, comparison of mechanical properties*.

Selection of studies

The focus of the search was scientific articles related to mechanical properties of traditional and CAD/CAM complete removable dentures made from PMMA. Mechanical properties include: microhardness, nano hardness, the roughness of the surface, flexural strength and modulus, fracture toughness, flexural bond strength, mechanical compliance of the contact between the inner surface of the denture and the denture socket mucosa - adaptation of the prosthesis to the denture bearing tissue, hydrophobicity, water sorption and solubility, dimensional stability, elasticity. After reviewing the titles and summaries of the selected articles, duplicate articles that did not meet the purpose of this study were rejected. The full texts of the remaining articles were reviewed and a study selection elegibility report was created. Articles that met the selection were considered appropriate for the research and were included into the current systematic literature review (Figure 1).

Inclusion criteria:

- Studies published in English.
- Studies that include information regarding mechanical properties of PMMA complete removable dentures made during conventional polymerization and in a process of CAD/CAM.
- Patients 18 years old and above.
- Studies no older than 5 years (2017-2022).
- Research with humans.

In vitro studies that research mechanical properties regarding conventional polymerization in PMMA and CAD/CAM PMMA laboratories.

Exclusion criteria:

- Studies with animals.
- Case reports.
- Meta-analyses.
- Systematic literature reviews.

Data extraction

Data were collected from full-text articles and covered the following areas:

- "Authors, publishing year" – the authors of the study and the year of publication of the article are indicated.
- "The sample of the study volume" – the volume of the study sample is indicated.
- "Research methods" – it is indicated which research methods were used to evaluate the mechanical properties of conventional polymerization and CAD / CAM prostheses made from PMMA.
- "Mechanical properties" – it is indicated which mechanical properties were investigated during the research and described in the article.
- "Results" – the advantages of conventional polymerization or CAD/CAM PMMA prostheses' mechanical properties are indicated.

Assessment of methodological quality

The quality of the included study protocols was assessed during the selection of the studies by reading the full texts of the articles. The Cochrane Collaboration's two-part tool was used to assess the risk of bias in a human clinical trial (8) – random sequence generation, concealment of the respective study group, blinding of subjects and staff, blinding of results evaluation, insufficient results data (9). The bias of *in vitro* studies was assessed using the bias risk assessment methods of the *in vitro* study (10). To assess the quality of the selected studies, the evaluation was based on the following criteria: simulation of different conditions, description of sample size calculation, the use of materials according to the manufacturers' instructions, manufacturer of the used materials, complete outcome data. If the authors reported the parameter, the article had a Y (yes) for that specific parameter; if it was not possible to find the information, the article received an N (no). The articles that reported 1–2 items were classified as high risk of bias, 3 as medium risk, and 4–5 as low risk.

Synthesis of results

A method of synthesis of these data was used to evaluate the data of the measurements described in the studies included in the systematic analysis of the scientific literature. Meta-analysis was not performed due to the heterogeneity of the studies that are included in the review. In the descriptive statistical analysis, the significance of the measurement data was based on the statistically significant difference in the results of the study between the groups, when the level of significance or statistical reliability of the statistical hypothesis is $P<0.05$. Data on areas of interest from the included full-text articles were collected and inserted into tables in the order indicated above (Figure 1).

Table 2. Data of interest

Study id	Authors, publication year	Sample size	Methods	Mechanical properties	Results
2	Al-Dwairi Z.N. *et al.*, 2019	45 25× 25×3 mm³ specimens (30 CAD/CAM PMMAand 15 conventional PMMA); *In vitro*	A digital contact profilometer was used for testing surface roughness (Ra); Vickers hardness number (VHN) was used for surface hardness testing.	Roughness, hardness	Conventional PMMA surface roughness > CAD/CAM PMMA; CAD/CAM VHN > conventional PMMA.
1	Prpić V. *et al.*, 2020	160 specimens; *In vitro*	The flexural strength was tested using a three-point flexure test on a universal testing machine; the surface hardness was determined using Brinell's method.	Flexural strength, surface hardness	CAD/CAM PMMA flexural strength > heat-polymerized PMMA; CAD/CAM PMMA surface hardness > conventional heat-polymerized PMMA (not significant).
4	Al-Dwairi Z.N. *et al.*, 2020	45 65×10× 3 mm³ specimens; *In vitro*	The three-point bending test was used to measure the flexural strength and the bending modulus; the Charpy impact test was used for testing impact strength.	Flexural strength, flexural modulus, impact strength	CAD/CAM PMMA flexural strength > heat-cured PMMA; CAD/CAM PMMA flexural modulus> heat-cured PMMA.
5	Alp G. *et al.*, 2019	75 25×2×2 mm³ specimens; *In vitro*	Three-point FS of the specimens was tested in a universal testing machine.	Flexural strength	CAD/CAM PMMA flexural strength > conventional PMMA.
14	Aguirre B.C. *et al.*, 2020	10 64×10×3.3 mm³ specimens; *In vitro*	Flexural strength and flexural modulus were obtained from a bench 3-point bend test by using a universal testing machine.	Flexural strength, flexural modulus	CAD/CAM flexural strength > conventional PMMA; CAD/CAM flexural modulus > conventional PMMA.
17	Choi J.J.E. *et al.*, 2020	120 25× 4 × 3 mm³ specimens; *in vitro*	All specimens were tested in four-point flexure; Fracture toughness was calculated using special equation; this study used the chevron notch beam method to determine fracture toughness and evaluate flexure bond strength.	Fracture toughness (K1C), flexural bond strength of denture teeth to denture base resins (DBR)	Conventional PMMA fracture toughness and bond strength > CAD/CAM; conventional PMMA significant fracture toughness and bond strength decrease with aging > CAD/CAM PMMA.
12	Arslan M. *et al.*, 2018	Twenty rectangular-shaped specimens (64×10×3.3 mm); *in vitro*	Flexural strength (FS; [MPa]) – a three-point bending test by a universal testing machine; surface roughness (Ra, μm) – three spots of each specimen by a profilometric contact surface measurement device; hydrophobicity – water contact angles (CA) by an automated contact angle measurement device.	Flexural strength, surface roughness and hydrophobicity.	CAD/CAM PMMA flexural strength > conventional PMMA; conventional heat-polymerized PMMA surface roughness > CAD/CAM PMMA (not significant); CAD/CAM PMMA contact angle values > conventional PMMA; CAD/CAM PMMA hydrophobic > conventional PMMA; thermal cycling: CAD/CAM PMMA hydrophobicity ↓; conventional PMMA hydrophobicity ↑.
8	Faty M.A. *et al.*, 2021	24 male patients 55-65 year	Adaptation – a 3-shape desktop scanner.	Adaptation	CAD/CAM adaptation > conventional PMMA
15	Hada T. *et al.*, 2021	Unspecified amount of specimens; *in vitro*	Flexural strength (FS, MPa) – a three-point bending test; flexural modulus (FM, GPa), water sorption, discoloration – calculated using special equation after measurements.	Flexural strength, flexural modulus, water sorption, solubility,	CAD/CAM PMMA flexural strength > conventional PMMA; CAD/CAM PMMA flexural moduli = conventional PMMA; CAD/CAM PMMA water sorption = conventional PMMA; CAD/CAM PMMA water solubility = conventional PMMA.
18	Einarsdottir E.R. *et al.*, 2020	45 specimens; *in vitro*	Denture bases were digitized and were measured by superimposing test bases with control base. 22 spherical indentations served as measurement points.	Dimensional stability	Denture bases fabricated by CAD/CAM dimensional deformation < denture bases fabricated by injection and compression dimensional deformation.
11	Perea-Lowery L. *et al.*, 2020	Eighty specimens (2×10×10 mm); *in vitro*	The flexural strength was determined with a static 3-point bend test in air. Dry-stored specimens were fractured after the 3-point bend test, they were repaired with methylmethacrylate liquid. Surface microhardness testing (VHN) was performed using a Vickers hardness testing machine. Nanohardness and modulus of elasticity of the tested materials was measured by nanoindentation.	Flexural strength, surface hardness, nanohardness, modulus of elasticity of dry and water-stored specimens	CAD/CAM PMMA flexural strength > conventional PMMA; CAD/CAM PMMA surface hardness < conventional PMMA; CAD/CAM PMMA nanohardness = conventional PMMA; CAD/CAM PMMA modulus of elasticity < conventional PMMA.
12	Klaiber D. *et al.*, 2021	120 specimens, *in vitro*	The surface roughness (Ra) – measured with a contact profilometer electron microscopy (SEM) was used to in order to determine the failure mode after the bond test.	Surface roughness	Conventional heat-polymerized PMMA surface roughness > CAD/CAM PMMA.
16	Angelara K. *et al.*, 2021	60 specimens, *in vitro*	The flexural strength was tested using a three-point flexure test on a universal testing machine (noncantilever group). As application of the 3-point flexural strength formula was not possible with the cantilever groups, only the mean failure load was calculated.	Flexural strength	CAD/CAM PMMA flexural strength > heat-processed PMMA.

	Random sequence generation (selection bias)	Allocation concealment (selection bias)	Blinding of Participants (performance bias)	Blinding of personnel (performance bias)	Blinding of outcome assessor (detection bias)	Incomplete outcome data (attrition bias)	Selective Reporting (reporting bias)
Faty MA et al., 2021	−	−	−	−	?	+	?

Fig 2. Risk of bias of the included study

	Simulation of different conditions	Sample size calculation	Materials used according to manufacturers' instructions	Manufacturer	Complete outcome data
Al-Dwairi ZN et al., 2019	N	N	Y	Y	Y
Prpić V et al., 2020	N	N	Y	Y	Y
Al-Dwairi ZN et al., 2020	Y	N	Y	Y	Y
Alp G et al., 2019	N	N	Y	Y	N
Aguirre BC et al., 2020	Y	N	Y	Y	Y
Choi JJE et al., 2020	Y	N	Y	Y	Y
Arslan M et al., 2018	N	N	Y	Y	N
Hada T et al., 2021	Y	N	Y	Y	Y
Einarsdottir ER et al., 2020	N	N	Y	Y	N
Perea-Lowery L et al., 2020	Y	N	Y	Y	N
Klaiber D et al., 2021	Y	N	Y	Y	Y
Angelara K et al., 2021	N	N	Y	Y	Y

Fig 3. Risk of bias of the included in vitro studies

RESULTS

Study selection

Using online search tools, a total of five hundred forty six references were identified that were less than five years old, analysed conventional and CAD/CAM complete removable dentures made of PMMA, and were performed on humans or in vitro. After excluding articles that were repetitive and had no data on the mechanical properties of these prostheses, eighteen articles were selected after reading their titles and abstracts. Based on the selection criteria, five articles were rejected for not presenting clear, accurate results of the studies, such as not stating statistical reliability, not presenting measurement values in the results and presenting graphs from which the exact measurement values cannot be determined. The current review used thirteen articles that met all the selection criteria for this study. Of these, twelve were in vitro studies and one was in vivo.

Study characteristics

The most relevant information from each selected article is summarised in Table 2. One clinical study was included in the review, in which patients had completely edentulous arches of maxillae and mandible, well-shaped alveolar processes with healthy mucosa, normal salivation, and an Angle class I maxillo-mandibular relationship (8). This study analysed the mechanical properties of patients' complete removable dentures made of PMMA and fabricated by conventional and CAD/CAM techniques. Using a 3Shape desktop scanner, the adaptation of the removable denture bases to the denture bearing tissue tissues was measured: the inner surface of the denture bases was scanned, the image of which was transferred to a computer and superimposition of the scans with the scanned images of the edentulous jawbones alginate impressions was performed using software. The studies included in the review evaluated the hardness (1, 2, 11), surface roughness (1, 12, 13), flexural strength and flexural modulus (2, 4, 5, 11, 12, 14-16), fracture toughness (17), flexural bond strength (17), adaptation of the prosthesis to the denture bearing tissue (8), hydrophobicity (12), water sorption and solubility (15), dimensional stability (18), elasticity (11) of PMMA processed by hot polymerization and CAD/CAM. In vitro studies have evaluated the mechanical properties of PMMA in hot-polymerized specimens and in prepolymerized and CAD/CAM-prepared specimens (1, 2, 4, 5, 11-18). These mechanical properties were evaluated by a universal testing apparatus designed to apply a load to the test workpieces, a profilometer, computer visualisation and using diameter and thickness measurements. The values obtained from the universal testing apparatus were used to calculate the flexural strength and flexural modulus, surface hardness and fracture toughness, using specific formulae for these mechanical properties, and the measurements of the diameter and thickness of the workpieces were used to calculate the water sorption and the solubility of the plastics, using specific formulae for these mechanical properties (1, 4, 5, 11, 12, 14-17) (Appendix, Formulas 1-6).

Methodological quality assessment of included studies

The Cochrane Collaboration's two-part tool (9) was used to assess the quality of the human clinical trial included in this review (8) (Figure 2). The study was assessed as being at high risk of bias because it did not meet the parameters of random sequence generation, concealment of allocation to the relevant treatment group, blinding of subjects and blinding of personnel. The quality of the other 12 articles could not be assessed by standard methods (bias assessment tool) because these studies were conducted in vitro (Figure 3). The bias of the in vitro studies was assessed using the risk of bias assessment methods of the in vitro study (10). The use of materials according to the manufacturers' instructions and the manufacturer of the materials parameters were met in all included in vitro studies, but the description of sample size calculation parameter was not met. Nevertheless, more than half (10 out of 12) of the included in vitro studies were at low or medium risk of bias.

Qualitative analysis

Based on two in vitro studies, no statistically significant difference was observed between the hardness of conventionally polymerized PMMA and CAD/CAM prepolymerized PMMA plastic specimens (1, 11). Nevertheless, the hardness of the PMMA samples produced by the different methods depended on the storage conditions: the samples had a higher hardness in dry storage compared with storage in a humid environment (11). According to the study by Al-Dwairi ZN *et al.*, 2019, it was observed that the hardness of the CAD/CAM prepolymerized PMMA plastic billets was higher than that of the conventionally polymerized PMMA on the Vickers hardness: the Vicker's hardness number (VHN) in the CAD/CAM group was 20.21±0.71 and in the conventional polymerization group it was 18.09±0.31VHN (2). One study also evaluated the nano-hardness (Gpa) of conventionally polymerized PMMA and CAD/CAM prepolymerized PMMA plastic specimens. No statistically significant difference between the nanohardness of the two specimen groups was observed ($p>0.05$) (11).

Faty MA *et al.*, in 2021 conducted a human clinical study (n=24; 55-65 years old males) assessing the adaptation of complete removable denture bases to the denture bearing tissue. The results of this study showed that removable denture bases made from CAD/CAM prepolymerized PMMA plastic had a statistically significantly better adaptation than denture bases made from conventionally polymerized PMMA plastic ($p=0.035$) (8).

The surface roughness of PMMA plastic specimens manufactured by different methods was measured in three studies. In all studies, it was observed that the surface roughness of the conventionally polymerized PMMA workpieces was higher than that of the CAD/CAM prepolymerized PMMA workpieces (2, 12, 13). It should be noted that Al-Dwairi ZN *et al.*, 2019, and Klaiber D *et al.*, 2021, in their studies reported a statistically significant difference in surface roughness ($p<0.05$) between the conventionally polymerized and CAD/CAM prepolymerized PMMA workpieces (2, 13). On the other hand, Arslan M *et al.*, 2018, reported no statistically significant difference (12).

In eight studies, the flexural strength of differently processed PMMA plastic billets was analysed (2, 4, 5, 11, 12, 14-16). The results of these studies show a higher flexural strength of CAD/CAM prepolymerized PMMA plastic workpieces compared to conventionally polymerized PMMA workpieces. Nevertheless, according to Perea-Lowery L *et al.*, 2020, the flexural strength of CAD/CAM and conventionally polymerized PMMA plastic workpieces is dependent on whether the workpiece has undergone a repair, i.e. whether the workpiece has been fractured and a fracture repair has been performed. The flexural strength of the workpieces without fracture repair was higher compared to those with fracture repair ($p<0.001$) (11). Three of these eight studies also assessed the flexural modulus (4, 14, 15). In two of these three studies, a higher flexural modulus was observed for CAD/CAM prepolymerized PMMA than for conventionally polymerized PMMA (4, 14). However, Hada T *et al.*, 2021, in their study, observed that there was no difference in the flexural modulus measurements between CAD/CAM and conventionally polymerized PMMA plastic workpieces (15).

According to an in vitro study by Choi JJE *et al.*, 2020, which analysed the fracture toughness and flexural bond strength of CAD/CAM and conventionally polymerized PMMA plastic specimens, it was observed that the conventionally polymerized PMMA plastic specimens exhibited these features better compared with CAD/CAM prepolymerized PMMA specimens. It should also be mentioned that the ageing of the CAD/CAM-treated PMMA plastic billets did not affect their fracture toughness and flexural bond strength. On the other hand, the ageing of PMMA workpieces produced by conventional polymerization had a statistically significant effect on these features (p<0.01) (17).

In a study by Arslan M *et al.*, 2018, the hydrophobicity of CAD/CAM and conventionally polymerized PMMA plastic workpieces was assessed. It was observed that the hydrophobicity of CAD/CAM prepolymerized PMMA plastic workpieces was higher compared to conventionally polymerized PMMA. The thermal treatment of the workpieces was also carried out in this study. This treatment resulted in a decrease in the hydrophobicity of the CAD/CAM prepolymerized PMMA plastic blanks and an increase in the hydrophobicity of the conventionally polymerized PMMA plastic specimens (12).

Hada T *et al.*, 2021, conducted an in vitro study analysing the water sorption and solubility of CAD/CAM and conventionally polymerized PMMA plastic specimens. The study showed that there was no statistically significant difference between the water sorption of conventionally polymerized PMMA and CAD/CAM prepolymerized PMMA plastic specimens (p=0.085). No statistically significant difference was also observed when comparing the water solubility of the specimens (p=0.307) (15).

According to a study by Einarsdottir ER *et al.*, 2020, which analysed the dimensional stability of CAD/CAM and conventionally polymerized PMMA using double processing method, it was observed that the dimensional deformation of CAD/CAM prepolymerized PMMA was lower than that of conventionally polymerized PMMA (p<0.05) (18).

Perea-Lowery L *et al.*, 2020, analysed the elasticity of CAD/CAM and conventionally polymerized PMMA plastic workpieces in in vitro study. The results of this study indicate that the elasticity of conventionally polymerized PMMA plastic workpieces was higher than that of CAD/CAM prepolymerized PMMA plastic workpieces (p<0.01) (11).

DISCUSSION

This systematic review showed that CAD/CAM-prepared PMMA was superior to conventionally polymerized PMMA in that it had better mechanical properties, i.e. in terms of hardness, flexural strength and flexural modulus, hydrophobicity, dimensional stability, and adaptation, (1, 2, 4, 5, 8, 11, 12, 14-16, 18). On the other hand, some mechanical properties of the conventionally polymerized PMMA were better than those of the CAD/CAM-prepared PMMA, such as surface roughness, fracture toughness, flexural bond strength and elasticity (2, 11-13, 17). Also, both CAD/CAM prepolymerized PMMA and conventionaly polymerized PMMA plastic have the same water absorption and solubility (15).

According to a study by Al-Dwairi ZN *et al.* in 2019, the CAD/CAM PMMA group outperformed the conventional polymerization group in terms of hardness. According to the authors, this could be due to the lower content of residual monomer with plasticising effect in the CAD/CAM PMMA plastic. In addition, the authors suggest that the choice between these two different manufacturing processes for the same material is ultimately determined by the processing time and cost (2). Unfortunately, Perea-Lowery L *et al.*, 2020, in their study do not report a significant difference between the hardness of differently manufactured PMMA plastics. On the other hand, in the study, the highest average dry and wet hardness values were observed in conventionally polymerized PMMA specimens. The paper suggests that this may be due to partial cross-combination between the dimethyl methacrylate monomers as a result of the heat-induced free radical polymerization process. According to the authors, it is not known whether this process occurs during the polymerization of CAD/CAM plastics (11). Prpić V *et al.*, 2020, support the results of the above mentioned study, but claim that the differences between the results may not be solely due to different polymerization technologies (1).

Al-Dwairi ZN *et al.* (2) and Klaiber D *et al.* (13) reported in their studies that the surface roughness of conventionally polymerized PMMA workpieces was higher than that of CAD/CAM prepolymerized PMMA workpieces (2, 13). Al-Dwairi ZN *et al.* reported in their paper that CAD/CAM PMMA has better surface properties because it has fewer pores, which results in fewer microbes on this surface and surface roughness alteration. The aforementioned authors believe this is due to the lower residual monomer content of CAD/CAM PMMA and the polymerization method (2). Nevertheless, Arslan M *et al.*, 2018, state that there is no significant difference in surface roughness between differently processed PMMA. Authors believe this heterogeneity between the results of the different studies could be influenced by the different water solubility, hardness, microstructure and chemical configuration of the plastics studied (12).

A group of 8 different studies unanimously reported that the flexural strength of CAD/CAM prepolymerized PMMA was higher than that of conventionally polymerized PMMA (2, 4, 5, 11, 12, 14-16). The researchers suggested in their papers that this could be due to the processing conditions of CAD/CAM PMMA (high heat and pressure), the homogeneity of the structure and the high number of cross-links, minimal shrinkage, and the low number of pores and loose monomers (1, 4, 5, 11). In addition, Prpić V *et al.* reported that the difference in flexural strength of differently processed PMMA may have been influenced by the use of materials from different manufacturers in different studies (1).

Choi JJE *et al.*, 2020, reported that conventionally polymerized PMMA had higher fracture toughness and flexural bond strength than CAD/CAM PMMA. These results were influenced by the amount of monomer in the PMMA plastic: the higher the monomer amount, the better the mechanical properties mentioned above. Also in the study, ageing of the PMMA had a lesser effect on fracture toughness and flexural bond strength in the CAD/CAM group due to the lower swelling and deterioration of the crosslinked matrix and the leaching of components due to interface hydrolysis. In other words, the reduced ageing was due to a lower water absorption and thermal expansion ratio difference between the denture base and the artificial teeth (17).

Faty *et al.*, in an in vivo study published in 2021 concluded that removable denture bases made from CAD/CAM prepolymerized PMMA showed better adaptation to the denture bearing tissue than those made from conventionally polymerized PMMA. This is due to the lower dimensional changes during polymerization when denture bases are made from prepolymerized PMMA. CAD/CAM PMMA also has better retention properties due to lower polymerization shrinkage. On the other hand, the authors point out the disadvantages of CAD/CAM-manufactured PMMA prostheses, which are more costly, wasteful and energy intensive. In addition, the study discusses the disadvantages of manufacturing denture bases from conventionally polymerized PMMA, such as processing complexity, time-consuming manufacturing and deformation (8).

Arslan M *et al.*, 2018, reported in their study that the hydrophobicity of CAD/CAM prepolymerized PMMA was higher than that of conventionally polymerized PMMA due to the lower residual monomer content in the plastic. According to the authors, this is due to the CAD/CAM processing of PMMA polymers at high pressure and temperature and the polarity of the molecules in the polymer matrix. The paper also highlights the effect of thermal cycling on plastics: heat treatment reduces the amount of residual unpolymerized components in conventionally polymerized PMMA, resulting in an increase in their hydrophobicity; the reverse is true for CAD/CAM PMMA (12).

Hada T *et al.*, 2021, reported in an in vitro study that there is no difference in water sorption and water solubility, which impair the mechanical properties of prostheses: causing cracks in the prostheses, which can lead to fracture, between conventionally polymerized PMMA and CAD/CAM prepolymerized PMMA. There is also a causal relationship between water sorption and water solubility and the degree of polymerization and the amount of residual monomer: the lower the degree of polymerization and the higher the amount of residual monomer, the higher the water sorption and water solubility of the denture (15).

Einarsdottir ER *et al.*, 2020, observed that CAD/CAM prepolymerized PMMA denture bases exhibit less dimensional deformation during polymerization compared to conventionally polymerized PMMA bases, but that, regardless of the method of PMMA production, the most significant changes in the dimensional stability of the denture base are observed during the first processing cycle (18).

Table 2 shows that the vast majority of the studies analysed in this systematic literature review were in vitro and only one was clinical. For in vitro studies, there is not yet a widely used tool for assessing the risk of bias, which may have influenced the assessment of the reliability of the articles. The low number of in vivo sources included in the review may have been due to the novelty of the topic, the lack of knowledge of dentists about the potential of CAD/CAM for removable dentures and the high cost of CAD/CAM technology. The in vitro studies of the articles used in the review detail the mechanical properties and the advantages and disadvantages of conventionally polymerized PMMA and CAD/CAM prepolymerized PMMA and clearly show that digitally manufactured PMMA is superior to conventionally manufactured PMMA in terms of the stronger mechanical properties. On the other hand, based on the results of the in vitro studies, it is not known whether the mechanical properties of conventionally polymerized PMMA and CAD/CAM prepolymerized PMMA would remain the same in human clinical trials. Although clinical studies provide more relevant results and conclusions, the in vitro studies of high methodological value (4, 14-15, 17) in the review may also be of considerable clinical relevance. The studies evaluating the flexural strength, flexural modulus and surface roughness of CAD/CAM-prepolymerized PMMA and conventionally polymerized PMMA plastics used identical test methods. However, different test methods were used to analyse the hardness and hydrophobicity of the differently manufactured PMMA. Other mechanical properties were described only by individual authors and it was not possible to compare their chosen test methods and the analysed mechanical properties of PMMA with other studies. The studies used different testing methodologies: different manufacturers of PMMA, different lengths, widths and heights of the test pieces, different samples of the test material, different manufacturers of the plaster material, different software to process the scans, different treatments of the test material before the measurements. This led to heterogeneity in the papers, and prevented accurate comparison of measurement results and develop meta-analysis. For these reasons, the results presented in the systematic literature review should be viewed critically. In clinical dental practice, there are many requirements for denture materials, the priorities for which may change depending on the clinical situation. There are some cases where it is necessary to choose a harder material and in other cases a more flexible structural material. A systematic literature review revealed detailed differences in the mechanical properties of PMMA depending on the choice of manufacturing technology, conventional polymerization and modern digital CAD/CAM, and provided greater clarity for dentists in the choice of PMMA denture technique for a given case. There is no doubt that PMMAs are widely used in clinical dental practice and their mechanical properties are relevant to the functional performance, comfort, aesthetics, body response, microbial contamination, repairability, durability, maintenance and manufacturing costs of dentures. The systematic literature review carried out revealed a lack of clinical research on these topics that is relevant to the dental market and may encourage more research.

CONCLUSIONS

The hardness, flexural strength, flexural modulus and hydrophobicity were higher and the dimensional stability was better of the prepolymerized PMMA billets than that of the conventionally polymerized PMMA billets. Only one study was performed in vivo, in which complete removable denture bases made from CAD/CAM prepolymerized PMMA showed better adaptation to the denture bearing tissue than those made by conventional polymerization.

The surface roughness, fracture toughness and flexural bond strength and elasticity of the conventionally polymerized PMMA workpieces were higher than those of the CAD/CAM prepolymerized PMMA workpieces.

No statistically significant difference was observed in water sorption and solubility between the CAD/CAM prepolymerized PMMA specimens and the conventionally polymerized PMMA specimens.

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APPENDIX

Formula 1. Flexural strength

$$FS = 3FL/2bh^2$$

FS - flexural strength (MPa)

F - maximum force applied to a specimen (N)

L – distance between the specimen carrier (mm)

b - specimen width (mm)

h - specimen height (mm).

Formula 2. Flexural modulus

$$FM = F_1 l^3 / 4bh^3 d,$$

FM - flexural moduli (GPa)

F1 – load (N) at a point in the straight – line portion of the flexural load – deflection curve and the deflection (mm) at load F1, respectively

l - distance between the specimen carrier (mm)

b - specimen width (mm)

h - specimen height (mm)

d - load (N) at a point in the straight – line portion of the flexural load – deflection curve and the deflection (mm) at load F1, respectively

Formula 3. Surface hardness

$$\mathbf{HB} = F/\pi D h_k$$

HB - the Brinell hardness (MPa)

F - force applied to the specimen (N)

D - the ball diameter (mm)

H - the depth of penetration (mm)

Formula 4. Fracture toughness

$$K_{1C} = Y\left[\frac{P_{Crit}(S_o - S_i) \times 10^{-6}}{BW^{1.5}}\right]$$

$$Y = \frac{0.3874 - 3.0919(a_o/W) + 4.2017(a_1/W) - 2.3127(a_1/W)^2 + 0.6379(a_1/W)^3}{1.000 - 2.9686(a_o/W) + 3.5056(a_o/W)^2 - 2.3174(a_o/W)^3 + 0.0130(a_1/W)}$$

K1C - fracture toughness (MPa m1/2)

Pcrit - critical load (N)

So and Si - the outer and inner spans (m)

B and W - thickness and height (m)

Y - stress intensity factor coefficient

ao - initial crack length (W – CL)

a1 - equal to (W+W)/2

Formula 5. Water sorption

$$W_{sp} = (m2 - m3) / V,$$

Wsp – water sorption (μg/mm³)

m2 – sample mass that became constant within 0.2 mg and was immersed in water at 37 ± 1 ◦C for 7 days, wiped with a Kimwipe shaken in air for 15 s, and weighed for 60 s after removal from the water

m3 – mass of the desiccator in a constant temperature bath at 37 ± 1◦C

Formula 6. Solubility

$$W_{sl} = (m1 - m3) / V.$$

Wsl – solubility (μg/mm³)

m1 – test piece mass after storage in the desiccator at 23 ± 1 ◦C for 60 min that was previously in a constant temperature at 37 ± 1 ◦C for 24 h and was weighed using standard-level analytical balances

m3 – mass of the desiccator in a constant temperature bath at 37 ± 1◦C

Received: 15 05 2021
Accepted for publishing: 21 03 2022