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Properties of Acrylic Resin For CAD/CAM: A Systematic Review and Meta-Analysis of In Vitro Studies

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Abstract

Purpose: This systematic review and meta-analysis of in vitro studies compared the prepolymerized acrylic resin used for CAD/CAM complete denture manufacturing versus the heat-polymerized acrylic resin for conventional complete dentures in terms of surface roughness, wettability, hardness and flexural strength.
Materials and Methods: An electronic search was performed in the PubMed, Embase, LILACS and Web of Science databases, without language or date restrictions. Gray literature and manual search tools were also used. The systematic review was carried out by two researchers independently, following the inclusion criteria: in vitro studies testing the CAD/CAM acrylic resin with a control group of heat-polymerized acrylic resin which compared at least one of the four material properties above. The meta-analysis was performed separately for each property, using a random effect model.
Results: Of the 914 studies found by means of search strategies, 698 were selected for the systematic review. After applying the eligibility criteria, only 17 articles were selected for the qualitative analysis in the systematic review; among these, 14 were included in the quantitative meta-analysis. The CAD/CAM prepolymerized acrylic resin in blocks had similar properties when compared to heat-polymerized acrylic resin in almost all outcome measures, with the exception of a statistically significant reduction in surface roughness.
Conclusions: Based on the findings of this systematic review and meta-analysis, equally satisfactory results can be expected from dental prosthesis manufactured by the CAD/CAM system when compared to conventional ones, with the additional potential of reducing the pigmentation and attached microorganisms due to the reduced surface roughness of the prepolymerized resin.

The poly(methylmethacrylate) (PMMA) based heat-polymerized acrylic resin has become the material of choice for manufacturing complete dentures (CDs) since its introduction in the dental market. Due to its favorable properties, its use is widespread and popular in complete oral rehabilitations.[1,2]

Properties like wettability and surface roughness can impact the esthetic results and quality of life for wearers of CDs. Esthetics can be compromised by the impregnation of pigments to the prosthesis acrylic base, when the material properties are not adequate. In addition, these acrylic resin properties play a major role in the accumulation and colonization of microorganisms that may lead to denture stomatitis and halitosis.[2,3]

During mastication, dentures are subjected to flexural or bending forces, which induce stress in the acrylic base and results in internal tensions or even small cracks. The propagation of these cracks over time might lead to the prosthesis fracture. The predisposition to fracture is also determined by alterations in the prosthesis base, wearing of the teeth, and change in the supporting tissues.[4,5] For this reason, it is important for the material to have an adequate flexural strength, considering that the alveolar resorption is a process that occurs gradually and irregularly, which might lead to an imbalance and mismatch in the prosthesis support by the hard and soft tissues.[6] The denture's resistance to grinding is determined by the hardness of the acrylic resin material.[7,8]

The CAD/CAM technology was introduced in the manufacturing of CDs by Maeda et al.[9] The objective of this digital approach is: to reduce the number of consultations to two or three appointments, to facilitate the duplication of existing prosthesis, to optimize the prosthesis precision and to improve its mechanical properties.[10] The prosthetic bases are milled from blocks of preheated acrylic resin, where the polymerization process occurs under standardized conditions, which in turn reduces the possibility of operatory interferences. The lack of control over the polymerization rate as well as the incorporation of cracks and porosities during the conventional heated acrylic polymerization may worsen mechanical properties.[4] Regarding the industrial processing, the formation of polymer chains and the degree of conversion from monomers to polymers are higher, resulting in lower levels of residual monomers and polymerization contraction.[7,11,12]

Taking into consideration that the manufacturing of removable CDs is still a common practice, and that the long-term performance is directly related to the material properties, a review of the literature might help health professionals to inform their choices regarding materials and techniques. Thus, this in vitro systematic review and meta-analysis has the objective of comparing the prepolymerized acrylic resin for CAD/CAM CDs versus the heat-polymerized acrylic resin for conventional CDs in terms of surface roughness, wettability, hardness and flexural strength. The null hypothesis tested was that there is no difference between CAD/CAM acrylic resin and heat-polymerized acrylic resin.

Materials and methods

This systematic review and meta-analysis was based on the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) guidelines and the research protocol is registered in the PROSPERO database (ID CRD42020157053).[13] The research question: "Does the CAD/CAM acrylic resin possess similar properties to the heat-polymerized acrylic resin?", was formulated according to the PICOS model, where "P" is the population (i.e., removable partial denture), "I" is the intervention group (i.e., acrylic resin for CAD/CAM prosthesis), "C" is the comparison group (i.e., heat-polymerized acrylic resin for conventional prosthesis), "O" is the outcome (i.e., surface roughness, wettability, hardness and flexural strength); and "S" is the study design (i.e., in vitro studies).[14]

The search strategy used controlled and non-controlled descriptors as well as Boolean terms (OR, AND). The search in PubMed, Embase, LILACS and Web of Science databases was performed without language or year restrictions. The articles were searched in PubMed/MEDLINE using the following terms: ("Denture, Complete" [mesh] OR "Complete Denture" OR "Complete Dentures" OR "Dentures Complete") AND ("Computer-Aided Design" [mesh] OR "Computer Aided Design" OR "Computer-Aided Designs" OR "Design, Computer-Aided" OR "Designs, Computer-Aided" OR "Computer-Assisted Design" OR "Computer Assisted Design" OR "Computer-Assisted Designs" OR "Design, Computer-Assisted" OR "Designs, Computer-Assisted" OR "Computer-Aided Manufacturing" OR "Computer Aided Manufacturing" OR "Manufacturing, Computer-Aided" OR "Computer-Assisted Manufacturing" OR "Computer Assisted Manufacturing" OR "Manufacturing, Computer-Assisted" OR "CAD-CAM").

Literature search was also performed in the gray literature using the Brazilian Digital Library of Thesis and Dissertations (BDTD), Google Scholar, and OpenGrey. In addition, the references of selected studies were also manually searched and included when applicable. Finally, specialized journals from the field of interest were searched from 1994 until the present time (*Journal of Prosthodontics*, *Dental Materials*, *International Journal of Prosthodontics*, and *Journal of Prosthetic Dentistry*).

The results of the database search were exported to the EndNote web program (Clarivate Analytics, PA), where the exclusion of duplicated articles was performed. After the study selection, a two-phase selection was carried out by two independent researchers (one master and one doctoral student). The first phase was characterized by reading of titles and abstracts, where the article was included by at least one researcher. The second phase was characterized by full text reading, and the articles inclusion or exclusion had to be agreed to by both researchers. In case of disagreement, a third evaluator was consulted to make the final decision (graduate students' supervisor).

The inclusion criteria were: in vitro studies testing the CAD/CAM acrylic resin versus the conventional heat-polymerized acrylic resin control group, evaluating at least one of the four properties of this study (i.e., surface roughness, wettability, hardness and flexural strength). Other acrylic resin properties which were not part of the inclusion criteria were considered part of the exclusion criteria (e.g., non in vitro studies or in vitro studies without a control group). For data extraction, a standardized Excel software spreadsheet was created and completed by the researchers.

The evaluation of the methodological quality of the studies, carried out by two independent researchers, was based in the items set forth by the Consolidated Standards of Reporting Trials (CONSORT).[15]

The statistical program used for data analysis and graphic production was the RStudio version 1.2.5019 (Meta package version 4.11-0).[16] The heterogeneity was assessed by means of the I^2 inconsistency test, which attributed a value from 0% to 100%, which shows how much the magnitude of difference among studies can be explained by heterogeneity, and not by chance. From 0 to 25% was considered a low heterogeneity; from 25% to 75%, intermediate heterogeneity; and from 75% or higher, high heterogeneity.[17]

If the comparison among the selected studies was possible, the data were analyzed quantitatively in a meta-analysis using forest plot graphs. Considering that the outcomes are continuous variables, the measure of effect was analyzed using mean deviations. Depending on the heterogeneity, either the random effect model (REM) or the fixed effect model (FEM), or both, were used at a 5% statistical significance.[18]

Results

The fluxogram including the identification and selection of the studies as well as the reasons for the exclusion are shown in Figure 1. The electronic search yielded 914 articles, and after

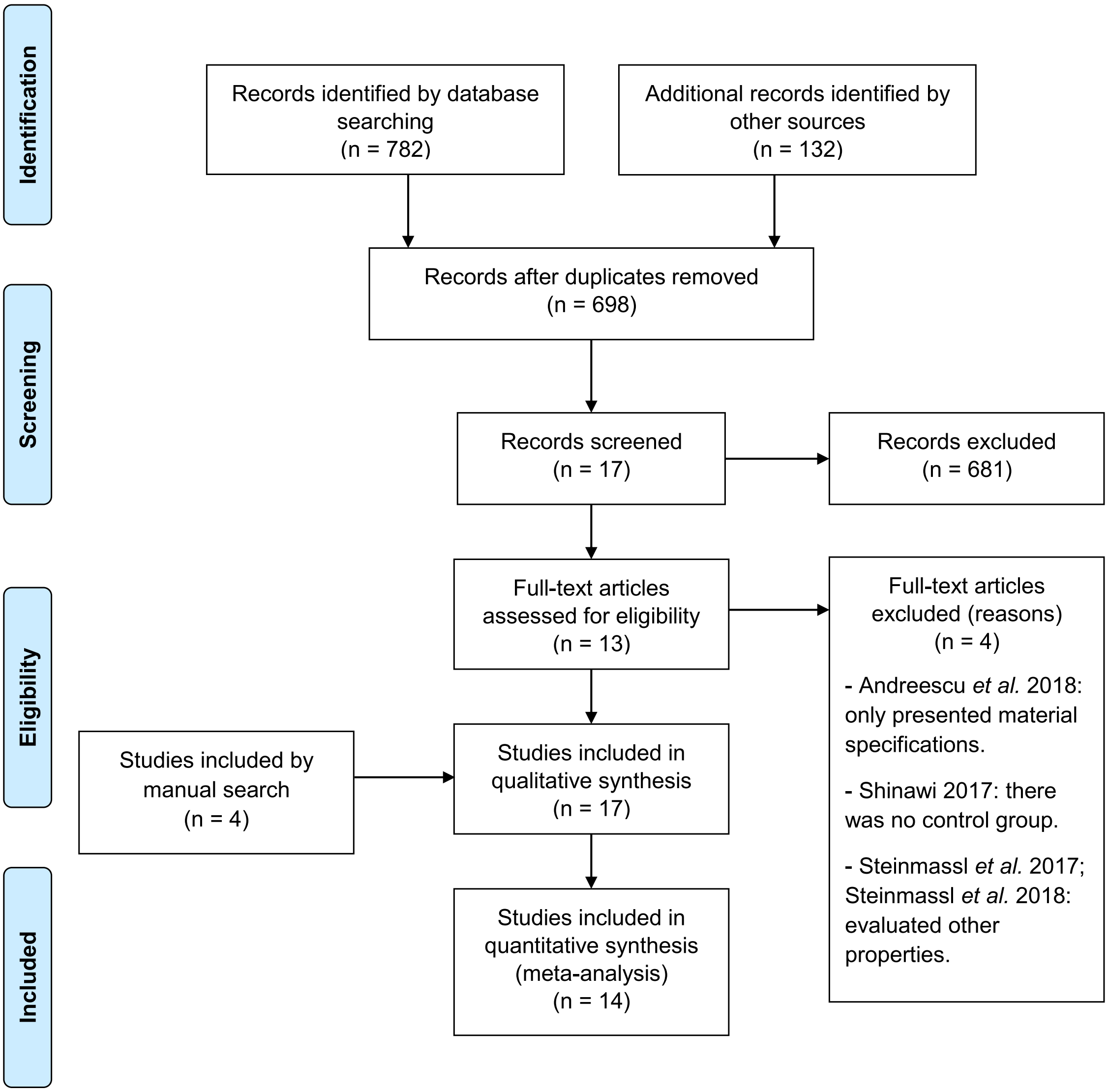

Figure 1 PRISMA Flow diagram of article selection.

the removal of duplications, 698 articles were selected for further analysis. After title and abstract reading, 17 articles were selected for full-text reading, four of which were excluded and 13 remained (Fig 1). On the other hand, four new articles were added by means of manual search, resulting in 17 articles to be included in the qualitative analysis (i.e., systematic review). The study description of each article is shown in Table 1 (i.e., authorship, year of publication, material properties evaluated, tests used, sample size, etc.). As there were no language restrictions, articles written in Turkish[29] and Portuguese[30] were included.

Out of the 17 articles selected for the systematic review, only 14 were selected for the meta-analysis for presenting comparable values and methodologies. Therefore, the following studies were excluded from the quantitative analysis: Alp et al[20] and Murat et al,[21] who showed the test results only after thermal cycling; and Al-Fouzan et al,[25] who showed surface roughness in terms of area values (Sa), which could not be compared with the other studies that displayed surface roughness using mean values (Ra). The three excluded studies were only analyzed qualitatively (Table 1).

The qualitative analysis of the studies is described in Table 2. Considering that CONSORT[15] items 6, 7, 8, and 14 do not apply to in vitro studies and considering that they were designed for randomized clinical trials (RCT), only the remaining items were taken into consideration in the evaluation (i.e., 11 items). In general, all studies showed satisfactory quality, fulfilling at least 7[7,23] to a maximum of 10[27] out of 11 analyzed items.

In the meta-analysis, only studies which showed mean and standard deviation for both experimental and control groups and which used the same units of comparison for the four material properties considered in the present study were

Table 1 General description of the selected studies for the systematic review (qualitative analysis)

First author and year	Evaluated properties	Tests	Sample size (n)	Dimensions	Storage	ISO	Unit
Aguirre, 2020[19]	Flexural strength	Three-point bending test	10	63×10×3.3 mm	Distilled water at 37°C for 7 days	20795-1	MPa
Alp, 2019[20]	Flexural strength	Three-point bending test	15	25×2×2 mm	Distilled water at 37°C for 24 hours	10477: 2004	MPa
Murat, 2019[21]	Surface roughness Wettability	Contact profilometer Contact angle measurement	10	10×2 mm	Distilled water for 6 days	NR	μm degree
Pacquet, 2019[12]	Hardness Flexural strength	Vickers hardness Three-point bending test	10 (H) 25 (FS)	65×10×2.5 mm	Distilled water at 37°C for 24 hours	20795-1	HV MPa
Alammari, 2017[22]	Surface roughness Wettability	Profilometer Contact angle measurement	10	30×15×3 mm	Distilled water at room temperature for 24 hours	NR	μm degree
Al-Dwairi, 2020[4]	Flexural strength	Three-point bending test	15	65×10×3 mm	Distilled water at 37°C for 7 days	1567	MPa
Ayman, 2017[7]	Flexural strength	Three-point bending test	10	65×10×3 mm	Distilled water at 37°C for 24 hours	NR	MPa
Perea-Lowery, 2020[23]	Hardness Flexural strength	Vickers hardness Three-point bending test	8	10×10×2 mm (H) 65×10×3.2 mm (FS)	Distilled water at 37°C for 30 days	1567	HV MPa
Srinivasan, 2018[24]	Surface roughness	Non-contact profilometer	5	20×20×1.5 mm	70% ethanol solution for 5 minutes and drying with sterile cotton	11562	μm
Al-Dwairi, 2019[2]	Surface roughness Wettability Hardness	Contact profilometer Contact angle measurement Vickers hardness	15	25×25×3 mm	Distilled water for 48 hours	NR	μm degree HV
Al-Fouzan, 2017[25]	Surface roughness	Non-contact profilometer	10	10×3 mm	NR	NR	μm
Alp, 2019[26]	Surface roughness	Contact profilometer	6	10×2×2 mm	Ultrasound cleaning in distilled water for 10 minutes and drying with paper towel	NR	μm
Arslan, 2018[6]	Surface roughness Wettability Flexural strength	Contact profilometer Contact angle measurement Three-point bending test	10	64×10×3.3 mm	Water at 37°C for 48 hours	20795-1	μm degree MPa
Bedrossian, 2019[27]	Flexural strength	Three-point bending test	16	32×10×3 mm	Water at 37°C for 50 hours	20795-1	MPa
Steinmassl, 2018[28]	Surface roughness Wettability	Contact profilometer Contact angle measurement	10	39×8×4 mm	Deionized water at 21°C for 7 days in darkness	3274	μm degree
Dayan, 2019[29]	Hardness	Vickers hardness	8	15×2 mm	Distilled water at 37°C for 24 hours	NR	HV
Costa, 2018[30]	Surface roughness	Contact profilometer	10	12×12×3 mm	Deionized water at 37°C for 24 hours	NR	μm

NR = not reported.

Table 2 Risk of bias of the selected studies from the databases and gray literature for the meta-analysis

Author (year)	1	2a	2b	3	4	5	6	7	8	9	10	11	12	13	14
Aguirre et al, 2020[19]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	No	No
Pacquet et al, 2019[12]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	No	Yes	No
Alammari, 2017[22]	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	No	No	No
Al-Dwairi et al, 2020[4]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	Yes	No
Ayman, 2017[7]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	No	No	No
Perea-Lowery et al, 2020[23]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	No	No	No
Srinivasan et al, 2018[24]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	Yes	No
Al-Dwairi et al, 2019[2]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	No	Yes	No
Alp et al, 2019[26]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	Yes	No
Arslan et al, 2018[6]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	No	No
Bedrossian et al, 2019[27]	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	No
Steinmassl et al, 2018[28]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	No	Yes	No
Dayan, 2019[29]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	No	No
Costa, 2018[30]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	Yes	No

(1) Structured summary of trial design, methods, results, and conclusions; (2a) Scientific background and explanation of rationale; (2b) Specific objectives and/or hypotheses; (3) The intervention for each group, including how and when it was administered, with sufficient detail to enable replication; (4) Completely defined, pre-specified primary and secondary measures of outcome, including how and when they were assessed; (5) How sample size was determined; (6) Method used to generate the random allocation sequence; (7) Mechanism used to implement the random allocation sequence; (8) Who generated the random allocation sequence; (9) If done, who was blinded after assignment to intervention; (10) Statistical methods used to compare groups; (11) Results for each group, and the estimated size of the effect and its precision (for example, 95% confidence interval); (12) Trial limitations, addressing sources of potential bias, imprecision, and, if relevant, multiplicity of analyses; (13) Sources of funding and other support; (14) Where the full trial protocol can be accessed, if available.

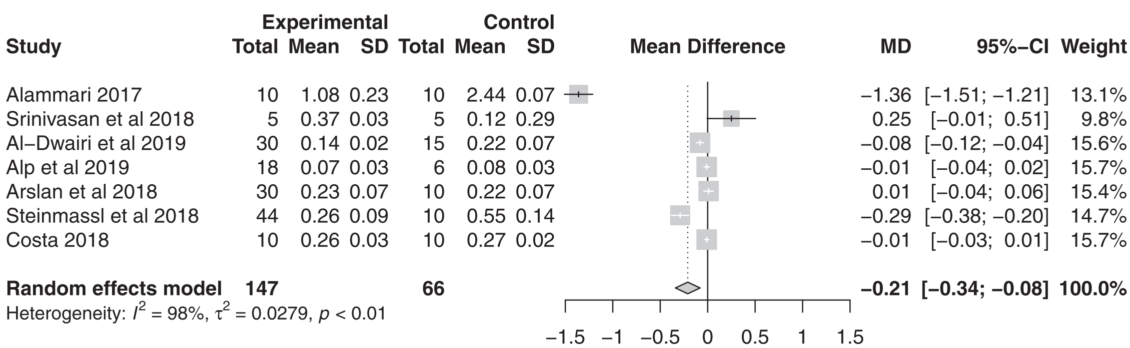

Figure 2 Forest plot: surface roughness, experimental (CAD/CAM) and control (heat-polymerized) acrylic resin groups. SD = standard deviation; CI = confidence interval.

included. Quantitative analysis was divided according to each material property evaluated: surface roughness (Fig 2), wettability (Fig 3), hardness (Fig 4) and flexural strength (Fig 5).

Figure 2 shows the forest plot graph of the meta-analysis among the studies[2,6,22,24,26,28,30] which evaluated the materials surface roughness by means of a profilometer. The analysis resulted in a statistically significant reduction of the surface roughness of CAD/CAM acrylic resin ($p < 0.001$) in comparison to the heat-polymerized acrylic resin for conventional CDs.

Wettability

Figure 3 shows the forest plot graph of the meta-analysis among the studies[2,6,22,28] which evaluated the acrylic resin wettability of both materials, with the measurement of contact angle of the drop with the acrylic resin surface. The analysis showed no statistically significant difference ($p = 0.861$) between the experimental and control materials studied.

Hardness

Figure 4 shows the forest plot graph generated by the meta-analysis among the studies[2,12,23,29] which evaluated the acrylic resin hardness between the two materials by means of the Vickers hardness test. No statistically significant difference ($p = 0.615$) was found between the CAD/CAM versus conventional acrylic resin.

Flexural strength

Figure 5 displays the forest plot graph from the meta-analysis among the studies[4,6,7,12,19,23,27] which compared both acrylic resin flexural strength by using a 3-point bend test. No

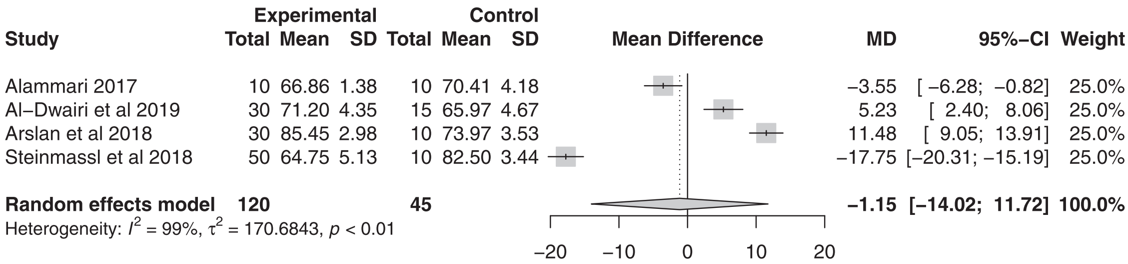

Figure 3 Forest plot: wettability, experimental (CAD/CAM) and control (heat-polymerized) acrylic resin groups. SD = standard deviation; CI = confidence interval.

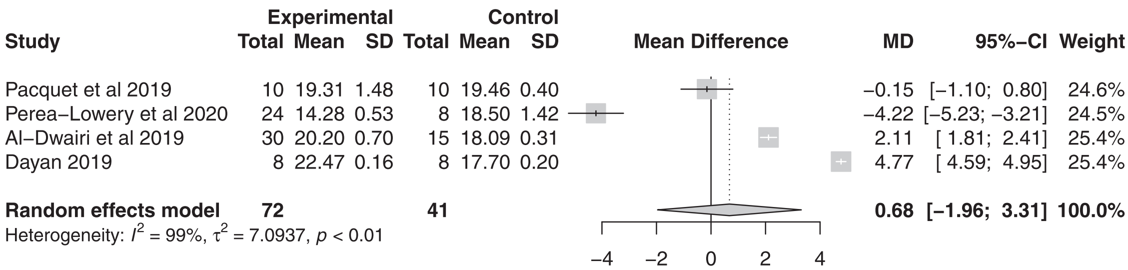

Figure 4 Forest plot: hardness, experimental (CAD/CAM) and control (heat-polymerized) acrylic resin groups. SD = standard deviation; CI = confidence interval.

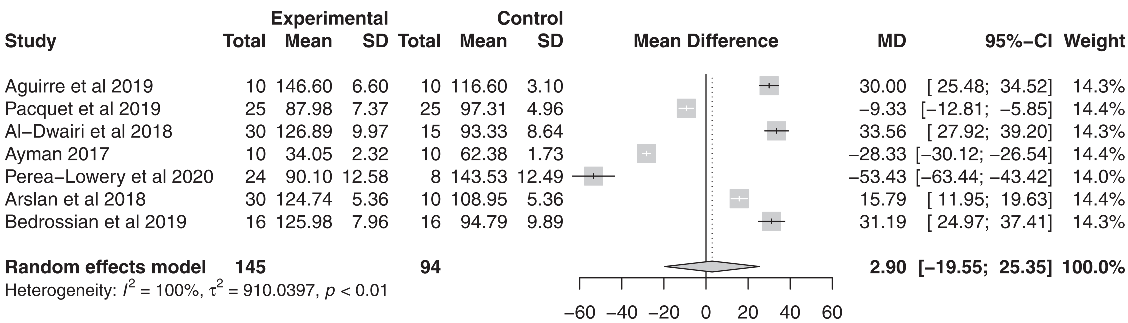

Figure 5 Forest plot: flexural strength, experimental (CAD/CAM) and control (heat-polymerized) acrylic resin groups. SD = standard deviation; CI = confidence interval.

statistically significant difference ($p = 0.800$) was found between the two materials analyzed.

Discussion

The acrylic resin blocks used in the CAD/CAM systems are prepolymerized under specific and standardized conditions; and because of that, it is believed that it has improved material properties when compared to the heat-polymerized acrylic resin for conventional CDs.[2,4] In this study, no statistically significant differences were found in wettability, hardness and flexural strength between the two acrylic resins assessed. Only surface roughness was significantly better in the CAD/CAM prepolymerized acrylic resin. Thus, the null hypothesis of this study was partially accepted.

Regarding the methodological characteristics of the studies included in this systematic review, it was verified that most authors reported the ISO norms in which they based the manufacturing of their test samples and protocols. The test norms and protocols are specific for prosthesis base polymers. It is important to point out that the ISO 1567 norm[31] has not been valid since 2008, and it was later replaced by the current 20795-1 norm[32]; however, some authors still refer to the outdated norm.[4,23] The ISO 11562[33] and 3274[34] norms deal with geometric specifications, specifically the material's surface texture. It could be observed also that the selected studies keep, in general, a standard regarding sample size, where the majority of them had 10 samples per group (range = 5 to 25).

The microbial adhesion is determined by surface roughness, where the increase in roughness between 0.1 and 0.4 μm implies an increase in the colonization of microorganisms.[28] A threshold surface roughness of 0.2 μm (Ra) indicates a maximum acceptable value,[35] below which no further reduction in bacterial accumulation could be expected. The adoption of an effective protocol of finishing and polishing of the prosthesis surface is essential and contributes to the increase in surface smoothness. However, the finishing and refined polishing is only indicated in the external surface of the CDs, because the internal surface must be preserved to remain in the closest possible contact to the remaining tissues.

All authors used some form of mechanical polishing of the samples before the tests, mimicking the protocol that occurs in daily clinic.[22] In this stage, authors used grinding points and silicon carbide papers, which varied from 120 to 1,200 grits.

Physical properties of conventional heat-polymerized acrylic resins are influenced by different factors, such as: size of the polymer spheres in the resin powder, type of initiator and accelerator,[36] and aspects related to the prosthesis technician who performs the acrylic processing (i.e., powder/liquid proportion and thermal cycle).[22] Despite the fact that the chemical composition seems to have an important role in the determination of the material properties, the processing protocol is the main determinant of the surface roughness.[28] The improved surface roughness of the prepolymerized CAD/CAM acrylic resin might be attributed to the manufacturing process exclusive of these materials.

The wettability is the indicator of the saliva and other fluids capacity to spread over a surface. The contact angle is considered the result of the balance between the interfacial and surface forces.[2] Small contact angles represent a greater hydrophilicity, which is fundamental in the retention of removable prosthesis, but also favors the staining and adhesion of microorganisms[2] as well as the composition of the biofilm.[28]

Al-Dwairi et al[2] and Arslan et al[6] found a greater hydrophobicity in the CAD/CAM acrylic resin, while Alammari[22] and Steinmassl et al[28] found more hydrophilicity for CAD/CAM resins. The results of this study showed no statistical difference regarding the wettability of either acrylic resins. We can expect prosthesis manufactured with the CAD/CAM system to have an adequate retention, due to the formation of a saliva film over the prosthesis, with the potential of reducing the pigmentation and attached microorganisms due to the reduced surface roughness.

The hardness refers to the material density as well as its resistance to wearing and/or abrasion. This property affects the mechanical behavior and durability of the prosthesis during function, parafunction, and cleaning methods used over time.[7] It is also considered an indirect method to evaluate the degree of monomeric conversion obtained, and as a result, the quality of the polymerization reaction. Higher hardness values indicate better polymerization with higher degree of monomeric conversion of acrylic resins.[37]

The association of higher-pressure values and temperature yield an increase in the degree of monomeric conversion of acrylic resins, reducing the concentration of residual monomer and forming polymers with higher molecular weight and longer chains.[23] In this manner, with closer chains among themselves, the material becomes denser. The hardness test also helps to predict the mechanical behavior of base resins for prosthesis, correlating with the flexural properties that the material presents.[38]

The flexural strength can be considered one of the most important mechanical properties of the acrylic prosthesis. Testing the materials to flexural strength by using a 3-point bend test simulates its capacity to resist to high functional loads during mastication or parafunction.[19,27] According to the specifications of ISO 20795-1 norm[32] for prosthesis base polymers, the value of flexure strength obtained in acrylic resins type 1 should not be less than 65MPa. In the included studies, it was verified that in most of the acrylic resins, both prepolymerized acrylic resin for fabricating CAD/CAM CDs and the heat-polymerized acrylic resin for conventional CDs, fulfill this requirement. Clinically, the use of material for prosthesis base with higher flexural strength makes the prosthesis less prone to fracture.[19]

Alp et al[20] and Murat et al[21] were not included in the meta-analysis, because they only showed data after the thermal cycling. Both authors performed 10,000 thermal cycles in their samples in order to simulate one year of physiological aging. These authors described statistically significant differences between CAD/CAM versus conventional acrylic resins in flexural strength, with superior values in the prepolymerized resin (i.e., CAD/CAM). Besides a smaller surface roughness and contact angle in the CAD/CAM samples, they also reported a greater adhesion of *Candida albicans* in the thermopolymerized acrylic resins. Studies which adopted the aging methodology are of great importance, because they indicate that the good mechanical behavior of prepolymerized acrylic resins remain effective over time in oral conditions. This is paramount when patients use removable prosthesis for long periods of time.

The lack of meta-analysis of samples aged in the laboratory can be considered a limitation of this study. It is due to the absence of a greater number of studies which tested this methodology before and after the use of thermocycling, which allows a more reliable comparison and estimation of the behavior of theses samples over time. Therefore, future studies should include aged samples in their experiments. Also, the high heterogeneity observed in all analysis can be considered an intrinsic limitation of in vitro studies; these studies are very precise and show a very small standard deviation, making the heterogeneity more easily identified.

The inclusion of digital technologies in the dental practice is a trend worldwide. The replacement of analogic for digital processing has been taking place in a gradual manner, and despite being in its initial stage, the milling of CAD/CAM CDs show promising results. Studies have shown retention[39,40] and precision[41] results significantly better in CAD/CAM CDs than in conventional ones, with good levels of patient satisfaction,[42] esthetics and phonetics. [43]

Conclusion

The prepolymerized acrylic resin in blocks for CAD/CAM show similar properties to thermoheated ones, with additional reduction in surface roughness, and it can be considered a potential alternative to conventional CDs.

Conflict of interest statement

The authors report no conflicts of interest.

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