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The Effect of Curing Time on the Impact Strength of Resin Denture Bases Made by 3D Printing Techniques

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ABSTRACT

Advances in additive manufacturing have enabled the fabrication of denture bases using three-dimensional (3D) printing technology; however, the mechanical properties of the resulting materials, particularly impact strength, are highly influenced by post-processing parameters such as curing time. This experimental laboratory study aimed to evaluate the effect of different curing time variations on the impact strength of 3D-printed denture base resin and to compare its performance with that of heat-polymerized acrylic resin (HPAR). A post-test only control group design was employed, in which specimens were divided into four groups consisting of 3D-printed resin with curing times of 4.5, 5.0, and 5.5 seconds, and a control group fabricated from HPAR. The results demonstrated that the 3D-printed resin cured for 5.0 seconds exhibited the highest mean impact strength (1.56 ± 0.14 kJ/m^2), followed by the 4.5-second group (1.47 ± 0.09 kJ/m^2), while the lowest value was observed in the 5.5-second curing group (1.28 ± 0.23 kJ/m^2). In contrast, the HPAR group showed substantially higher impact strength than all 3D-printed resin groups, with a mean value of 2.99 ± 0.97 kJ/m^2. These findings indicate that curing time optimization significantly affects the impact strength of 3D-printed denture base resin; nevertheless, heat-polymerized acrylic resin remains superior in terms of mechanical toughness for denture base applications.

Keywords: 3D printing, curing time, impact strength, denture base

INTRODUCTION

Teeth are a vital component of the human body that play a crucial role in the quality of daily life. The condition of tooth loss, known as edentulousness, is a significant and quite common health problem in society, with the highest incidence rate recorded in the 40-to-65-year age group. The prevalence of edentulousness in Indonesia reaches 0.9% in urban areas and 1.7% in rural areas. High rates of tooth loss, especially among the elderly, can interfere with the ability to chew or masticate, and if left untreated for a long period of time, this condition has the potential to cause problems with the temporomandibular joint (TMJ) [1].

To prevent the various complications that arise from tooth loss, it is important for us to replace missing teeth with dental prostheses. According to data from the 2018 Basic Health Research, the rate of denture use in Indonesia was recorded at 1.4%. The main purpose of dentures is to replace all missing teeth and tissue, thereby restoring chewing function, speech, aesthetic appearance, and psychological well-being. Furthermore, these prostheses also play a role in correcting various abnormalities, disorders, and diseases that arise from the condition of complete toothlessness [2].

Denture base materials are generally classified into two main categories: metallic and non-metallic. Among the various options available, heat-polymerized acrylic resin is the most popular choice for denture fabrication. This is due to several advantages, such as its non-toxicity, non-irritating nature, resistance to dissolution by oral fluids, aesthetic appearance, ease of manipulation and repair, and minimal dimensional changes. However, acrylic resin also has several disadvantages, such as being susceptible to fracture if dropped, tending to change color after prolonged use in the mouth, and its ability to absorb water, which can lead to crazing [3]. Crazing is a surface damage characterized by the presence of microcracks, which can ultimately worsen the roughness of the denture base surface. The curing process for acrylic resin can be carried out by heating it in water at 70°C for eight hours, or by heating it in water for one and a half hours, then increasing the temperature to 100°C and maintaining it for one hour. However, in practice, dental technicians often use a stove for heating, which produces an imprecise and inaccurate temperature, so that the denture base is prone to various deficiencies such as excessive pores and brittleness that is easily broken [4], [5].

To address the frequent fracture problems of dentures, 3D printing (CAD-CAM) technology has been developed as a viable alternative to conventional dentures. Traditional denture manufacturing methods have several drawbacks, such as poor accuracy during manual printing, time-consuming production processes, and suboptimal denture comfort [6]. In contrast, 3D printing technology allows for the design and printing of highly detailed structures for both fixed and removable dentures. Fixed and removable dentures produced through 3D printing have been shown to be acceptable in clinical practice, with physical properties comparable to those of conventionally manufactured dentures [7], [8].

A study conducted by Gad and colleagues explored the differences between 3D-printed and thermally heated denture base resins, specifically in terms of flexural strength, impact strength, hardness, and surface roughness. This research provides important insights into how different production methods can affect the mechanical and aesthetic properties of these materials, which are relevant for clinical applications in dentistry. One hundred and twenty specimens were fabricated and distributed into two groups: heat-polymerized (Major.Base.20) as a control and 3D-printed (NextDent) as an experimental group. Flexural strength (MPa), impact strength (kJ/m^2), hardness (VHN), and surface roughness (μm) were measured using a universal testing machine, a Charpy impact tester, a Vickers hardness tester, and a profilometer, respectively. The results showed significant differences in all tested properties between the heat-polymerized and 3D-printed denture base materials ($p < 0.001$). 3D printed resins have lower flexural strength, impact strength, and hardness values than heat-polymerized resins, but exhibit superior surface roughness [9]. The average impact strength of heat-cured acrylic denture base resin is 1.67 kJ/m^2, while the average impact strength of 3D-printed denture base material is 1.15 kJ/m^2 [10]. According to research [10], the calculated t-statistic value between the two types of resins reached 2.269, with a p-value of 0.031. This clearly shows that the difference in impact strength between the two resins is indeed statistically significant.

To avoid the risk of breakage or fracture in dentures, acrylic resin needs to be equipped with adequate impact strength. Such damage often occurs during the daily process of cleaning dentures, such as when dentures made of acrylic resin are accidentally dropped and hit a hard floor surface [11]. In addition, denture bases made of heat-cured acrylic resin are susceptible to fracture or cracking due to lack of impact strength, both when the denture is outside the oral cavity, for example due to an accidental fall, or during use in the mouth, where flexural fatigue can occur due to repetitive stress from chewing activities [12].

The physical and mechanical properties of resins used in 3D printing technology are influenced by various process factors, particularly print orientation and post-printing curing duration. [13] emphasized that suboptimal process parameters, particularly inadequate curing time, can lead to incomplete polymerization, thus reducing the mechanical performance of the material. In line with these findings, [14] conducted an experimental study on the effect of curing time on the impact strength of 3D-printed resins with curing time variations of 30 minutes, 45 minutes, and 90 minutes. The results showed a significant difference in impact strength values between treatment groups. Specimens with longer curing durations showed a higher increase in impact strength compared to specimens with shorter curing times. Extended curing time contributed to an increase in the degree of polymerization and the stability of the material structure. Thus, curing duration is a crucial factor in determining the mechanical quality of 3D prints and supports the results of this study which show that appropriate curing time settings can significantly improve material performance.

To date, studies on the strength of denture materials produced using 3D printing technology are limited. Consequently, it is important to conduct mechanical tests on these materials to better understand their performance.

RESEARCH METHODS

This research is a laboratory experimental study with a post-test only control group design. The sample used for the impact strength test was a RAPP beam measuring 55 × 10 × 10 mm with a v-notch depth of 2 mm forming a 45° angle (ISO 179-1:2000) [15].

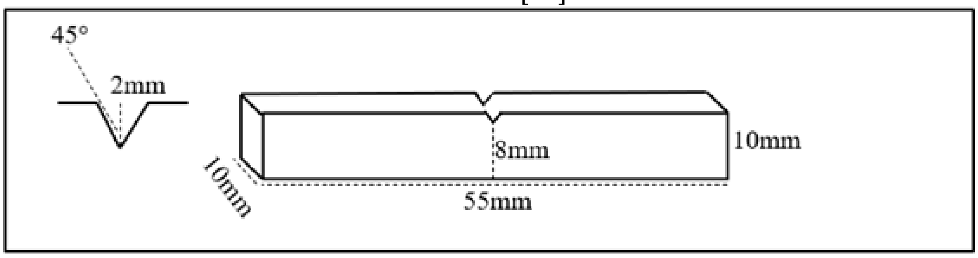

Figure 1. Test Sample Size

This study was a laboratory experimental study with a post-test only control group design. The minimum sample size was determined using the Federer formula [16], namely $(t-1)(r-1) \geq 15$, where t indicates the number of treatment groups and r the number of replications for each group. In this study, there were four treatment groups, consisting of three groups of 3D-printed resin denture bases with curing time variations of 4.5 seconds, 5.0 seconds, and 5.5 seconds, and one control group using heat-polymerized acrylic resin. Based on the number of groups, the t value was set at four, so the calculation showed that the minimum number of samples required for each group was six. To anticipate possible damage or failure of specimens during the research process, the number of samples in each group was increased to nine, so that the total sample used in this study was 36 specimens.

The independent variable in this study was the curing time of the 3D printing resin, which consisted of 4.5 seconds, 5.0 seconds, and 5.5 seconds, while the dependent variable was the impact strength. The controlled variables included the shape and size of the specimen, the ratio of powder and liquid of hot polymerized acrylic resin of 2:1, the ratio of plaster mix to water, the time of mixing the plaster, the type of 3D printing machine, and the type of curing machine. The uncontrollable variables in this study included the stirring speed of the hot polymerized acrylic resin and the pressing pressure.

The fabrication of hot-polymerized acrylic resin and 3D-printed acrylic resin samples was conducted at the Dental Services and Industry Unit (UJI) of the Faculty of Dentistry, University of North Sumatra. Furthermore, impact strength testing was conducted at the Faculty of Mechanical Engineering, Harapan University, Medan. This research was conducted from November to December 2025.

Data analysis was performed using SPSS version 26 software. Data normality was tested using the Shapiro–Wilk test at a significance level of $p > 0.05$. If the data were normally distributed, the analysis was continued with a one-way ANOVA test at a significance level of $p < 0.05$ to determine differences in impact strength between groups. The post-hoc Least Significant Difference (LSD) test was used to identify specific differences between pairs of groups. Conversely, if the data were not normally distributed, the analysis was performed using the Kruskal–Wallis test with $p < 0.05$, which was then followed by the Mann–Whitney test for pairwise comparison analysis.

RESULT AND DISCUSSION

Research data on the effect of curing time on the impact strength of resin denture bases made by 3D printing technique were obtained through measuring specimen dimensions including height, width, and length, as well as testing the impact strength of specimens with curing time variations of 4.5 seconds; 5.0 seconds; 5.5 seconds; and RAPP as a control group. All data obtained were then analyzed to describe the characteristics of the specimens and determine the differences in impact strength between treatment groups.

Table 1. Average Impact Strength Results for Each Group

No	Code	3D 4.5 Seconds	3D 5.0 Seconds	3D 5.5 Seconds	RAPP
1	Specimen (1)	1.55	1.41	1.23	3.09
2	Specimen (2)	1.60	1.39	1.04	3.32
3	Specimen (3)	1.40	1.75	1.54	4.92
4	Specimen (4)	1.38	1.58	1.58	3.31
5	Specimen (5)	1.54	1.39	1.43	3.66
6	Specimen (6)	1.55	1.78	1.24	1.88
7	Specimen (7)	1.42	1.59	1.23	2.24
8	Specimen (8)	1.39	1.60	1.37	2.61
9	Specimen (9)	1.39	1.57	0.87	1.93
Average		1.47 ± 0.09	1.56 ± 0.14	1.28 ± 0.23	2.99 ± 0.97

ased on the mean values obtained, the RAPP group demonstrated the highest impact strength (2.99 ± 0.97 kJ/m^2) compared with all 3D-printed resin groups, although the relatively large standard deviation indicates substantial variability within the specimens. This finding is consistent with previous in-vitro studies reporting that conventionally heat-cured PMMA denture base resins possess superior mechanical properties compared with additively manufactured resins. Heat-cured acrylic undergoes more complete polymerization, producing a denser polymer network with fewer voids and lower residual monomer content, which contributes to higher resistance to sudden impact loading. [10] reported that the mean impact strength of heat-cured acrylic resin (1.67 ± 0.79 kJ/m^2) was significantly higher than that of 3D-printed denture base resin (1.15 ± 0.40 kJ/m^2), confirming the mechanical advantage of conventional processing. The stronger intermolecular bonding and more homogeneous microstructure formed during thermal polymerization are therefore considered key factors explaining the higher impact performance observed in the RAPP control group.

Within the 3D-printing groups, a curing time of 5.0 seconds produced the highest mean impact strength (1.56 ± 0.14 kJ/m^2), followed by 4.5 seconds (1.47 ± 0.09 kJ/m^2), while 5.5 seconds showed the lowest value (1.28 ± 0.23 kJ/m^2). This trend indicates the presence of an optimal post-curing duration, where sufficient light exposure enhances the degree of conversion and cross-link density, thereby improving mechanical strength. Studies on photopolymer dental resins have demonstrated that post-curing significantly affects mechanical behavior, with strength and hardness increasing as polymerization progresses [17]. However, excessive curing may not always yield further improvement and can even reduce performance due to internal stresses, cure heterogeneity, or increased material brittleness. In addition, the layer-by-layer fabrication inherent in 3D printing introduces interlayer interfaces that may act as crack-propagation pathways, contributing to lower impact resistance compared with conventionally polymerized materials [18]. Statistical comparison using the Kruskal–Wallis test was therefore appropriate, given the non-normal data distribution, to robustly evaluate differences between curing-time variations and the traditional RAPP control.

Table 2. Kruskall Wallis Test of Differences in Impact Strength Values for Each Group

No	Group	*x*	Sig.
1	3D Printing 4.5 seconds	138.38	0.000*
2	3D Printing 5.0 seconds	138.94	
3	3D Printing 5.5 seconds	141.38	
4	RAPP	134.25	

*There is a significant difference

The Kruskal–Wallis test results listed in Table 2 show a significance value of 0.000, which is well below the threshold of 0.05. This finding indicates that there is a statistically significant difference in impact strength among the tested groups. The use of the Kruskal–Wallis test is appropriate for comparing more than two independent groups when the data distribution is not normal, which is common in mechanical testing of dental polymers due to variability in fabrication and specimen structure [19]. The significant difference observed in this study confirms that fabrication method and post-processing parameters play a crucial role in determining the mechanical performance of denture base resins. Previous investigations have demonstrated that additively manufactured denture base materials exhibit different impact strength values compared with conventionally polymerized PMMA, largely due to differences in polymer network formation and structural homogeneity [20].

More specifically, variations in curing time of the 3D-printed resin, when compared with the RAPP control group, were found to significantly influence denture base impact strength. Post-curing duration affects the degree of conversion and cross-link density within photopolymer resins, which in turn governs their resistance to crack propagation under sudden loading [21]. Insufficient curing may leave residual monomers that weaken the polymer matrix, whereas excessive curing can increase brittleness and internal stresses, both of which negatively affect impact resistance [22]. To determine precisely where these intergroup differences occurred, the analysis was continued using the Mann–Whitney post hoc test.

Table 3. Mann-Whitney Test of Differences in Impact Strength Values for Each Test Group

Group	3D 4.5 Seconds	3D 5.0 Seconds	3D 5.5 Seconds	RAPP
3D 4.5 Seconds	-	0.144	0.058	0.000*
3D 5.0 Seconds	0.144	-	0.007*	0.000*
3D 5.5 Seconds	0.058	0.007*	-	0.000*
RAPP	0.000*	0.000*	0.000*	-

*There is a significant difference ($p= <0.05$)

The Mann-Whitney test results showed that there was no statistically significant difference between the 4.5-second and 5.0-second 3D curing time groups ($p = 0.144$), as well as between the 4.5-second and 5.5-second groups ($p = 0.058$). In contrast, a significant difference was observed between the 5.0-second and 5.5-second groups ($p = 0.007$). In addition, all 3D-printed resin groups showed a clear difference compared to the RAPP group ($p = 0.000$), indicating that the impact strength of the 3D-printed resin was indeed significantly different from that of conventional resins.

To avoid the risk of breakage or fracture in dentures, acrylic resin needs to have adequate impact strength. Such fractures often occur during routine denture cleaning, such as when dentures made of acrylic resin are dropped and hit a hard floor [11]. Impact-related denture base fractures remain one of the most frequently reported clinical failures of polymethyl methacrylate (PMMA) prostheses, particularly when the material exhibits limited toughness and crack resistance [23]. From the results of impact strength tests on resin denture bases produced using 3D printing techniques with varying curing times, significant differences in impact strength values were observed between the groups. This difference can be explained by the resin polymerization process and the nature of the material structure formed during the curing stage. Additively manufactured denture base resins undergo photopolymerization that forms polymer chains through light-activated cross-linking, and the effectiveness of this process determines the final mechanical properties of the material [24], [25].

Based on Table 1, the results of the study indicate that the impact strength of 3D printing resin is influenced by variations in curing time, but increasing the curing duration is not always followed by an increase in impact strength values. In the 3D printing resin group, a curing time of 5.0 seconds produced the highest average impact strength compared to curing times of 4.5 and 5.5 seconds. This indicates that at this duration there is an optimal balance between the degree of polymerization and the internal structure of the material. Post-curing exposure has been shown to significantly influence the degree of monomer conversion and cross-link density, which are directly associated with improvements in mechanical strength and resistance to fracture [25]. A curing time of 4.5 seconds shows a relatively high impact strength value with small data variations, but this duration is thought not to produce completely homogeneous polymerization. Incomplete polymerization may result in residual monomer and internal structural defects that reduce the material's ability to absorb impact energy.

Conversely, at a curing time of 5.5 seconds, the average impact strength decreased, accompanied by increased data variation. This condition can be attributed to the possibility of over-curing, which causes the polymer structure to become stiffer and brittle, thus reducing its ability to absorb impact energy. The RAPP group showed the highest average impact strength compared to all 3D printing resin groups. This indicates that conventional resins still have better impact resistance, which is likely related to the more mature and controlled fabrication method and polymerization process.

The initial increase in impact strength at a duration of 5.0 seconds is thought to be related to the optimal degree of monomer conversion, resulting in a homogeneous polymer network that is able to absorb impact energy well. The increase in impact strength values in line with the increase in curing duration is explained through the concept of the degree of polymerization and the cross-linking network structure formed during the curing process. The duration and intensity of curing affect the conversion of monomers into a more complete polymer, thus affecting the density of the polymer network and the resin's ability to absorb impact energy [26].

In the world of 3D printing techniques, the curing process plays a crucial role in increasing the rate of conversion of monomers into polymers, known as the degree of conversion. The higher this conversion rate, the less monomer remains in the resin structure, resulting in a more compact material both chemically and mechanically. As a result, the material's ability to withstand impacts also increases. This process is highly dependent on the length and strength of the curing process, which ultimately affects the overall impact strength [27]. This finding aligns with a study conducted by Murat and colleagues, where they found that extending the curing duration can significantly strengthen 3D resins [26].

However, further increasing the curing duration to 5.5 seconds did not increase the impact strength, and even tended to decrease its average value. This is likely due to the formation of a polymer network that is too dense and stiff (over-curing), resulting in reduced impact strength even though the surface hardness or flexural strength may remain the same or increase. Excessive post-curing can increase cross-link density and reduce chain mobility, which ultimately lowers the material’s ability to dissipate impact energy. This phenomenon is in line with studies reporting that extended post-curing time improves certain mechanical properties only up to an optimal threshold, after which mechanical performance particularly toughness may decline [17], [28].

In Table 2, statistical analysis of the impact strength of resin denture bases using the Kruskal-Wallis test revealed significant differences between the observed groups. To further identify which groups exhibited these differences, a follow-up Mann-Whitney test was then applied. The results of this Mann-Whitney test highlight variations in impact strength values, particularly between the resin groups produced via 3D printing with varying curing times, compared to the RAPP control group. Similar non-parametric analytical approaches have been widely used to detect mechanical property differences in denture base materials processed using different polymerization techniques [29].

The higher impact strength of RAPP compared to 3D printing resins can be explained by differences in the polymer structure formation mechanism and the homogeneity of the material network. Heat-cured acrylic resins undergo a polymerization reaction under relatively stable and uniform thermal conditions, resulting in longer polymer chains, more consistent cross-linking throughout the specimen volume, and lower internal porosity. This homogeneous polymer structure enables the material to absorb and distribute impact energy more effectively, thereby increasing overall toughness [30], [31]. In contrast, 3D printing resins undergo layer-by-layer photopolymerization, which may produce variations in the degree of monomer conversion between layers, interfacial regions with different polymerization levels, and internal defects such as voids or delamination [32].

As a result, the material's ability to absorb impact energy is reduced, which makes the impact strength of 3D-printed resins typically lower compared to RAPP. Comparative investigations on additively manufactured denture bases have demonstrated lower toughness and impact resistance relative to conventional heat-polymerized PMMA, primarily due to anisotropic layering and incomplete interlayer bonding [18], [33].

The results of the analysis using the Mann-Whitney test revealed that all resin groups produced using the 3D printing technique including curing time variations of 4.5 seconds, 5.0 seconds, and 5.5 seconds showed significant differences in impact strength when compared to the control group based on hot acrylic resin (RAPP). This finding indicates that the impact strength properties of 3D-printed resin denture bases are significantly different from those produced by conventional heat-cured acrylic resin. The consistency of this difference across groups reinforces the concept that fabrication technique and polymerization processing play decisive roles in determining denture base mechanical performance [34].

The results of this study are also consistent with previous investigations comparing conventional and additively manufactured denture base materials. Heat-cured acrylic resin demonstrates higher resistance to sudden loading due to its dense polymer matrix, high cross-link uniformity, and minimal porosity. Conversely, additively manufactured resins exhibit heterogeneous microstructures and localized stress concentration points caused by incremental photopolymerization, which predispose the material to lower impact resistance [35], [36].

Based on the research results, it can be concluded that variations in curing duration in 3D-printed denture base resins affect impact strength, with the highest value obtained at the optimal curing duration.

Increasing curing duration beyond this optimal point may reduce impact strength due to the formation of an excessively rigid and heterogeneous polymer network, thereby lowering material toughness. Meanwhile, acrylic resin processed through heat polymerization (RAPP) demonstrates superior impact strength because the process produces a more homogeneous polymer network, consistent cross-linking, and a microstructure capable of absorbing impact energy more effectively [32].

CONCLUSION

This study shows that curing time significantly affects the impact strength of denture bases fabricated using 3D printing resin. Increasing the curing time from 4.5 seconds to 5.0 seconds tends to increase the impact strength, but extending the curing time to 5.5 seconds actually causes a decrease in the impact strength, indicating an optimal curing duration. Furthermore, there is a significant difference in impact strength between the 3D printing resin and heat-polymerized acrylic resin, with the heat-polymerized acrylic resin showing a higher average impact strength. These findings indicate that although optimizing the curing time can improve the mechanical performance of 3D printing resins, heat-polymerized acrylic resins still have superior impact resistance as denture base materials. Future research is recommended to explore a wider range of curing times, both shorter and longer, to more precisely determine the optimal curing duration in increasing the impact strength of 3D printing resins. Furthermore, the use of various types and brands of 3D printing resins needs to be considered to make the research results more representative and generalizable. Testing of other mechanical properties, such as tensile strength, elastic modulus, and wear resistance, is also needed to obtain a more comprehensive characterization of the material. Furthermore, further research could examine the effects of simulated oral environmental conditions, such as temperature variations, humidity, and thermal cycling, to evaluate the durability and long-term performance of 3D printing resins in clinical applications.

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