JIPS 7 (1) (2026)
Jurnal Inovasi Pendidikan dan Sains
E-ISSN 2721-9119
https://ejournal.unwmataram.id/JIPS

The Effect of Exposure Time Per Layer on Dimensional Accuracy and Flexural Strength of 3D Printed Denture Bases

Sumitro[1*], Kriswandy Putra[2], Nabila Rifani Nasution[3], Nur Aini Putri Nauli Br Tambunan[4]

[1,2,3,4] Undergraduate Program in Dentistry Education, Faculty of Medicine, Dentistry, and Health Sciences, Universitas Prima Indonesia, Indonesia

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Corresponding Author:
Author Name*: Sumitro
Email*: sumitro.dds@gmail.com

Accepted: December 29th 2025. Approved: January 25th 2026. Published: February 04th 2026

ABSTRACT

Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM)-based 3D printing technology is widely used in the manufacture of denture bases due to its precision and efficiency. However, the quality of the printed results is greatly influenced by printing parameters, especially the exposure time per layer that plays a role in the polymerization process of photopolymer resin. This study aims to analyze the effect of exposure time per layer on the dimensional accuracy and flexural strength of denture bases fabricated using Open System 3D Printing technology. This laboratory experimental study used a post-test only control group design. Denture bases were printed using an open system with exposure time variations of 4.5, 5, and 5.5 seconds, and compared with Close System 3D Printing and heat-polymerized acrylic resin (RAPP). Dimensional accuracy was measured in length, width, and height parameters, while flexural strength was tested using the three-point bending test method. Statistical analysis was performed using Welch's ANOVA test and Tukey's extended test ($\alpha = 0.05$). The results showed that exposure time per layer had a significant effect on dimensional accuracy and flexural strength ($p = 0.000$). In the open system, the highest length accuracy value was obtained at an exposure time of 5.5 seconds (64.99 ± 0.07 mm), followed by 4.5 seconds (64.98 ± 0.09 mm) and 5 seconds (64.94 ± 0.05 mm). The highest flexural strength value in the open system was obtained at an exposure time of 4.5 seconds (68.90 ± 1.27 MPa), followed by 5.5 seconds (67.29 ± 1.49 MPa) and 5 seconds (66.08 ± 2.32 MPa). The closed system group showed the highest flexural strength value (90.61 ± 2.72 MPa), while RAPP was 73.76 ± 3.60 MPa. It was concluded that the exposure time setting per layer plays an important role in optimizing the dimensional accuracy and mechanical properties of 3D printed denture bases.

Keywords: 3D printing, exposure time per layer, dimensional accuracy, flexural strength, denture base

INTRODUCTION

The development of digital technology in dentistry has brought significant changes to the planning and manufacturing of prosthodontic devices, including denture bases. One of the main applications of this digital transformation is the use of Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) systems, which enable the design and fabrication process to be carried out more efficiently, precisely, and standardized. In line with this, one of the emerging technologies is 3D printing, also known as additive manufacturing. Additive manufacturing is the process of creating 3D solid objects from a digital file [1]. CAD/CAM technology plays a crucial role in improving the quality of the final result, product consistency, and patient comfort, while reducing reliance on the manual skills of dental laboratory technicians. The use of CAD/CAM technology in the manufacture of complete dentures is increasing because it can accelerate the production process and produce dentures with better retention and mechanical and physical properties than conventional methods based on cold-curing resin pressing [2].

Conventionally, denture bases are generally manufactured using heat-polymerized acrylic resin (RAPP). However, this conventional process has several limitations, such as relatively long processing times, the potential for dimensional distortion due to the polymerization process, and variations in results influenced by operator technique and experience. These limitations encourage the development and adoption of CAD/CAM technology as a modern alternative in denture base fabrication. CAD/CAM technology in dentistry is generally divided into two main approaches, namely subtractive manufacturing (milling) and additive manufacturing (3D printing). Both approaches offer advantages in the form of increased production efficiency, higher precision, and reduced errors due to human factors during the fabrication process [3]. 3D printing is developing rapidly with increasing accuracy and reliability, making it an attractive technology that is widely applied in the health sector, including medicine, dentistry, orthopedics, tissue engineering, and medical devices [4], [5]. However, compared to the milling method, 3D printing technology has additional advantages in the form of material efficiency, the ability to print complex geometries, and flexibility in digital design. The working principle of 3D printing is to make an object using the layer-by-layer method, namely by making a layer that is then overlaid with the next layer, and this is done continuously so that it forms an object that is in accordance with what we designed [6], [7], [8].

Along with the rapid development of 3D printing technology and photopolymer resin materials specifically designed for dental applications, the use of 3D printing in the manufacture of denture bases is increasingly widespread both in research and clinical practice. Three-dimensional (3D) printing as an additive manufacturing technology has the potential to revolutionize the manufacturing field by turning 3D models into reality based on successive layering mechanisms [9], [10]. Various studies have reported that 3D printing-based denture bases show the potential for good dimensional accuracy and competitive mechanical properties when compared to conventional methods [3], [11]. Dimensional accuracy of the printed results is very important in determining the success of denture treatment, and the printing technique is a factor that greatly influences this dimensional accuracy, as well as the determination of the right printing material [12]. The presence of 3D printing technology has a significant impact, especially in the industrial sector. However, this technology still has weaknesses in terms of dimensional accuracy, which can result in differences in the size of the printed product compared to the original design [13]. The low-dimensional accuracy and mechanical properties of FDM printing results are one of the shortcomings of this process [14]. However, dimensional accuracy plays a major role in the clinical success of impression materials [15]. Therefore, evaluation of dimensional accuracy and mechanical strength is a crucial aspect in assessing the clinical feasibility of 3D-printed denture bases.

However, the final quality of denture bases made using 3D printing technology is not only determined by the type of resin material but is also greatly influenced by various printing process parameters. These parameters include layer thickness, printing orientation, and the curing process, both during printing and post-printing. The thickness and orientation of the printed layers affect the compressive strength and dimensional accuracy of the 3D-printed specimen [16]. Inaccurate setting of these parameters can lead to dimensional errors, structural deformation, and reduced mechanical properties, ultimately affecting the clinical performance of the denture base [17].

One of the important parameters in the photopolymer-based 3D printing process is exposure time, which is the duration of light exposure on each layer during the printing process. Exposure time plays a direct role in determining the degree of resin polymerization. Suboptimal polymerization can result in imperfect polymer cross-linking, thus impacting the dimensional stability and mechanical strength of the material. Previous research has shown that variations in the duration and intensity of light exposure during the exposure time process significantly affect the mechanical properties and dimensional accuracy of the printed results [18], [19].

In addition, other factors such as printing orientation have also been reported to affect dimensional accuracy and mechanical properties. Certain printing orientations can produce smaller dimensional errors than other orientations [3]. Correspondingly, printing orientation is a key parameter that affects the mechanical and surface properties of 3D-printed dentures [20]. These findings indicate that printing process parameters interact with each other and need to be systematically studied to obtain optimal results.

However, to date, scientific studies specifically evaluating the effect of exposure time per layer on the dimensional accuracy and flexural strength of 3D-printed denture bases are relatively limited. Most studies tend to focus on comparing conventional and digital methods, or assess the influence of other parameters such as layer orientation and thickness separately. However, exposure time is a fundamental parameter that directly influences the polymerization process in each layer, potentially significantly impacting the structural and mechanical quality of the denture base.

Based on these problems, there is a need for research that specifically and systematically examines the effect of variations in exposure time per layer on the dimensional accuracy and flexural strength of denture bases produced with 3D printing technology. The novelty of this research lies in the focus of the analysis on exposure time as the main variable in the printing process, as well as its simultaneous assessment of two important parameters, namely dimensional accuracy and flexural strength, both of which are the main indicators of the clinical feasibility of denture bases.

Therefore, this study aims to analyze the effect of exposure time per layer on the dimensional accuracy and flexural strength of 3D-printed denture bases. The results of this study are expected to provide scientific contributions in the development of more optimal digital fabrication protocols, as well as serve as a basis for selecting appropriate printing parameters to improve the quality, predictability, and clinical success of future prosthodontic treatments.

RESEARCH METHODS

This study is an in vitro laboratory experiment with a true experimental design that aims to analyze the effect of variations in exposure time per layer on the dimensional accuracy and flexural strength of denture base resin made using 3D printing technology. Specimen manufacturing was carried out at the Dental Industrial Services Unit (UJI) and the Department of Prosthodontics, Faculty of Dentistry, University of North Sumatra (USU), while mechanical testing was conducted at the Impact and Fracture Research Center (IFRC), Master of Mechanical Engineering Study Program, USU, using a Universal Testing Machine (UTM). The study was conducted in the period September–November 2025.

The number of samples was determined using the Federer formula [21], namely (t − 1) (r − 1) ≥ 15. This study consisted of five treatment groups, including three groups of 3D-printed acrylic resin open systems with exposure time variations of 4.5 seconds, 5 seconds, and 5.5 seconds; one group of 3D-printed acrylic resin close systems with parameters according to manufacturer recommendations; and one group of heat-polymerized acrylic resin (RAPP) as a control. The number of replications was set at seven specimens per group to anticipate specimen failure, so that the total sample used was 35 specimens.

All specimens were made in the form of blocks measuring 65 mm × 10 mm × 3.5 mm according to the ISO 20795-1:2013 standard. 3D printing open system resin specimens were printed using digital designs in STL format with a Piocreat HALOT-X1 printer based on MSLA technology, 60° orientation, 50 µm layer thickness, and Rayshape DT resin material. The slicing process was carried out using Chitubox Pro with exposure time settings per layer according to the treatment group, followed by a washing process using 99.9% isopropyl alcohol and post-curing for ±14 minutes.

Closed-system 3D printing resin specimens were fabricated using a SprintRay Pro S printer with DENTCA Denture Base resin. The design files were processed using RayWare software with a 10–20° orientation, printed according to the manufacturer's protocol, then washed using ≥91% isopropyl alcohol and post-cured for 2 minutes using SprintRay ProCure. The RAPP control group was fabricated using a conventional method through a two-stage flasking, pressing, and water bath curing process at 70°C for 90 minutes and 100°C for 30 minutes.

All specimens underwent an initial finishing process using graded abrasive paper, then soaked in distilled water for 48 ± 2 hours at 37°C before testing. Dimensional accuracy was measured using a digital caliper on the length, width, and thickness dimensions, with three measurements on each specimen to obtain the average value. The percentage of dimensional error was calculated by comparing the measurement results to the digital design dimensions.

Flexural strength testing was conducted using the three-point bending test on a UTM with a support spacing of 30 mm and a compression speed of 5 mm/min. Flexural strength values were calculated based on the maximum load to fracture according to the ISO 20795-1 standard formula.

Data analysis began with the Shapiro–Wilk normality test and Levene's homogeneity test. Normally distributed data were analyzed using one-way ANOVA, while data that did not meet the assumptions were analyzed using the Kruskal–Wallis test. A Tukey HSD post-hoc test was performed if there was a significant difference with a significance level of $p < 0.05$.

RESULT AND DISCUSSION

The development of 3D printing technology in dentistry has brought significant changes to the denture base manufacturing process, particularly in terms of dimensional precision and production efficiency. This technology enables the creation of complex structures with a high degree of accuracy through controlled printing parameters, such as exposure time per layer, layer thickness, and print orientation. Among these parameters, exposure time per layer plays a crucial role because it is directly related to the resin polymerization process during printing. The polymerization process that occurs in each layer significantly determines the dimensional stability of the printed object, so variations in exposure time have the potential to affect the level of dimensional conformity between the digital design and the printed result. Therefore, dimensional accuracy is a key parameter that needs to be analyzed to assess the quality of 3D-printed denture bases, particularly in ensuring the accuracy of shape and size according to clinical needs. The results of measurements of the length, width, and height of the denture base dimensions are shown in the following figure.

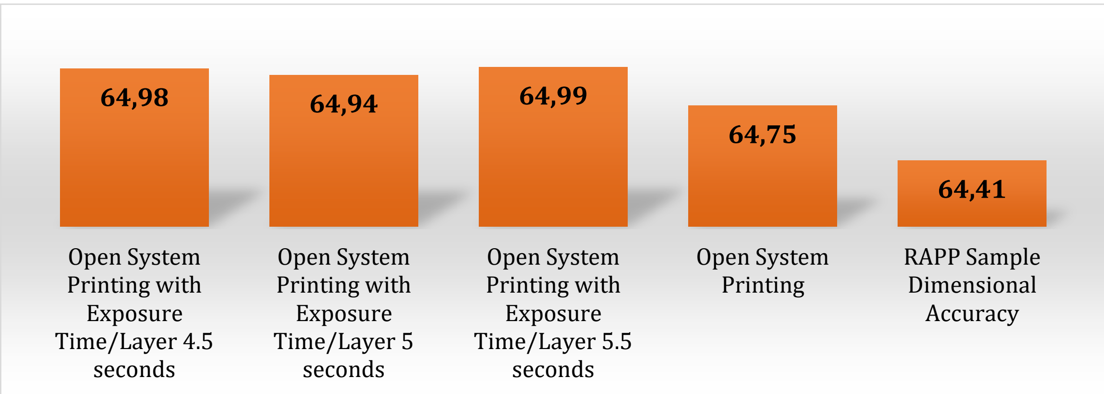

Figure 1. Average Length Accuracy of Denture Base Dimensions

Based on Figure 1, it can be seen that the average length of the 3D printed denture base shows variations in values for each exposure time setting per layer and printing system. In open system printing, the highest average length was obtained at an exposure time of 5.5 seconds at 64.99 mm, followed by an exposure time of

4.5 seconds at 64.98 mm, and an exposure time of 5 seconds at 64.94 mm. The difference in the average length values for the three exposure time variations is relatively small, indicating that changes in exposure time within this range produce almost uniform length dimensions.

Meanwhile, in the closed system printing, the average length produced was lower, namely 64.75 mm, and showed a greater deviation compared to the results in the open system. This value indicates a more significant dimensional shrinkage in the closed system printing. For comparison, the dimensional accuracy of the RAPP sample showed the lowest average length, namely 64.41 mm, which indicates a fairly clear dimensional difference compared to the entire group of 3D printing results.

In general, these results indicate that open system printing with varying exposure times per layer tends to produce length dimensional accuracy closer to the design value compared to closed system printing and RAPP samples. This finding indicates that the exposure time setting per layer and the type of printing system play a significant role in determining the stability and length dimensional accuracy of 3D-printed denture bases.

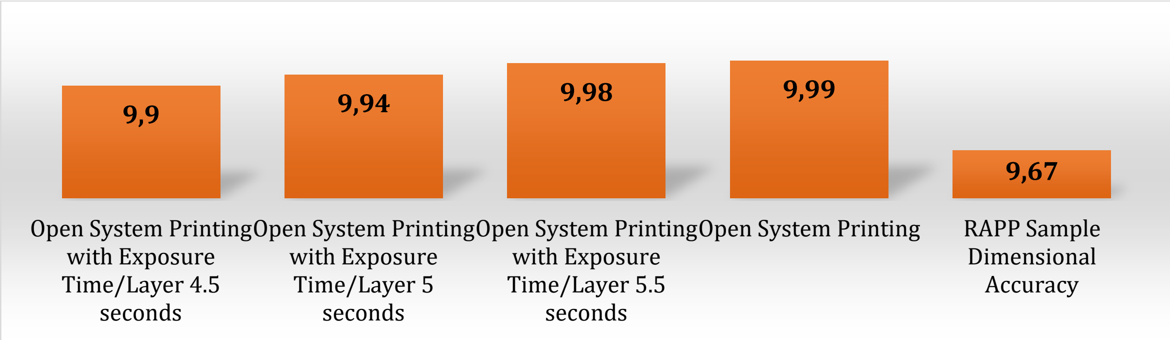

Figure 2. Average Width Accuracy of Denture Base Dimensions

Based on Figure 2, the average width of the 3D-printed denture base shows variations in values for each exposure time setting per layer and the printing system used. In open system printing, the lowest average width was obtained at an exposure time of 4.5 seconds at 9.90 mm, then increased at an exposure time of 5 seconds at 9.94 mm, and reached the highest value at an exposure time of 5.5 seconds at 9.98 mm. This increase in the average width value indicates a tendency that increasing exposure time per layer in the open system contributes to the width dimension getting closer to the design size.

In the closed system printing, the average width produced was 9.99 mm, which was the highest value compared to all treatment groups. This indicates that the closed system printing can produce width dimensions very close to the reference value, although different from the results obtained in the open system. As a comparison, the dimensional accuracy of the RAPP sample showed the lowest average width, namely 9.67 mm, which indicates a greater deviation in width dimensions compared to all 3D printing groups. Overall, these results indicate that variations in exposure time per layer and the type of printing system affect the dimensional accuracy of the denture base width, with a tendency for accuracy to increase with increasing exposure time in the open system printing, and the results closest to the design dimensions were obtained in the closed system printing.

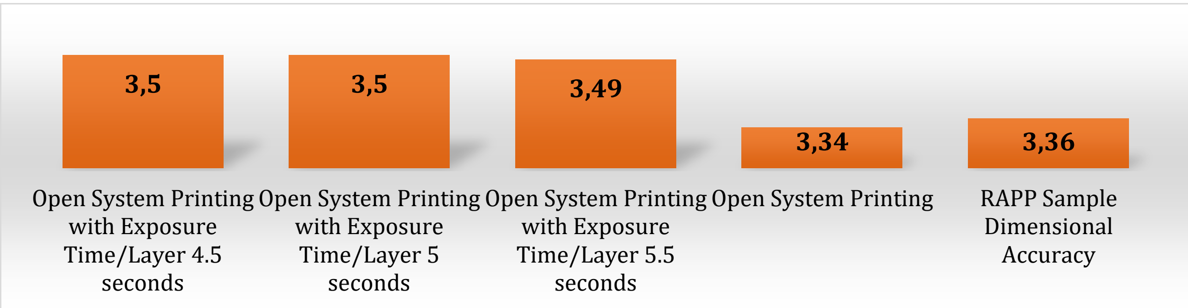

Figure 3. Average Height of Denture Base Dimensional Accuracy

Based on Figure 3, the average height of the 3D printed denture base shows different values for each variation of exposure time per layer and printing system. In open system printing, the average height produced at exposure times of 4.5 seconds and 5 seconds shows the same value, namely 3.50 mm, while at exposure time of 5.5 seconds it decreases slightly to 3.49 mm. The difference in the average height value for the three exposure time variations is relatively small, which indicates that changes in exposure time within this range do not have a significant effect on the height dimension in the open system.

In contrast, in the closed system printing, the average height produced was 3.34 mm, which was the lowest value compared to all treatment groups. This indicates a greater dimensional shrinkage in height in the closed system printing. Meanwhile, the dimensional accuracy of the RAPP samples showed an average height of 3.36 mm, which was higher than the results of the closed system but still lower than all results in the open system. Next, normality and homogeneity tests were conducted for the samples. The results are shown in the following table.

Table 1. Results of the Shapiro-Wilk Normality Test and Levene's Homogeneity Test for Dimensional Accuracy

Length					
	3D Printing Open System with Exposure Time/Layer 4.5 seconds	3D Printing Open System with Exposure Time/Layer 5 seconds	3D Printing Open System with Exposure Time/Layer 5.5 seconds	3D Printing Close System	RAPP
Shapiro-Wilk Normality	0.04	0.05	0.15*	0.96*	0.06*
Levene's Test of Homogeneity	0.093*				
Wide					
	3D Printing Open System with Exposure Time/Layer 4.5 seconds	3D Printing Open System with Exposure Time/Layer 5 seconds	3D Printing Open System with Exposure Time/Layer 5.5 seconds	3D Printing Close System	RAPP
Shapiro-Wilk Normality	0.00	0.00	0.07*	0.48*	0.55*
Levene's Test of Homogeneity	0.000				
Height					
	3D Printing Open System with Exposure Time/Layer 4.5 seconds	3D Printing Open System with Exposure Time/Layer 5 seconds	3D Printing Open System with Exposure Time/Layer 5.5 seconds	3D Printing Close System	RAPP
Shapiro-Wilk Normality	0.00	0.00	0.00	0.26*	0.29*
Levene's Test of Homogeneity	0.006				

*Significant, RAPP (Hot Polymerized Acrylic Resin)

Based on Table 1, the results of the Shapiro–Wilk normality test on the length dimension show that most groups have a significance value of $p \geq 0.05$, namely in the 3D Printing Open System sample with an exposure time of 5.5 seconds (Sig. = 0.15), 3D Printing Close System (Sig. = 0.96), and RAPP (Sig. = 0.06). Thus, the data in these groups are normally distributed. However, in the 3D Printing Open System sample with an exposure time of 4.5 seconds (Sig. = 0.04) and 5 seconds (Sig. = 0.05), the significance value is at the limit ($p \leq 0.05$), so the data is declared not normally distributed. Meanwhile, the results of the Levene's homogeneity test on the length dimension show a significance value of 0.093 ($p \geq 0.05$), so the variance between groups is declared homogeneous.

In the width dimension, the Shapiro–Wilk test results show that the data on the 3D Printing Open System samples with exposure times of 4.5 seconds and 5 seconds have a significance value of 0.00 ($p \leq 0.05$), so they are not normally distributed. Meanwhile, samples with an exposure time of 5.5 seconds (Sig. = 0.07), 3D Printing Close System (Sig. = 0.48), and RAPP (Sig. = 0.55) have $p \geq 0.05$ so they are normally distributed. The results of the Levene's homogeneity test in the width dimension show a significance value of 0.000 ($p \leq 0.05$), which indicates that the variance between groups is not homogeneous.

In high dimensions, the results of the Shapiro–Wilk normality test show that all 3D Printing Open System samples with exposure times of 4.5 seconds, 5 seconds, and 5.5 seconds have a significance value of 0.00 ($p \leq 0.05$), so the data is not normally distributed. In contrast, the 3D Printing Close System samples (Sig. = 0.26) and RAPP (Sig. = 0.29) have a normal distribution ($p \geq 0.05$). Meanwhile, the Levene's homogeneity test in high dimensions obtained a significance value of 0.006 ($p \leq 0.05$), so the variance between groups is not homogeneous.

Overall, the results of the assumption test indicate that the data do not meet the assumption of homogeneity of variance (Levene's Test $p \leq 0.05$) and/or there are violations of the assumption of normality in some groups. This condition makes the conventional one-way ANOVA inappropriate to use, considering that classical ANOVA requires normal data distribution and homogenous variance between groups. Therefore, Welch's ANOVA was used, which is a development of one-way ANOVA that does not require homogeneity of variance and is more robust against violations of the assumption of normality, especially in relatively balanced sample sizes. Welch's ANOVA adjusts the degrees of freedom so that it is able to provide more accurate test results when there are differences in variance between groups. Next, an ANOVA test was conducted to determine the effect of exposure time per layer on the dimensional accuracy of denture bases fabricated using 3D printing technology.

Table 2. Results of Welch's ANOVA Test

Panjang					
	3D Printing Open System with Exposure Time/Layer 4.5 seconds	3D Printing Open System with Exposure Time/Layer 5 seconds	3D Printing Open System with Exposure Time/Layer 5.5 seconds	3D Printing Close System	RAPP
Dimensional Accuracy	64.98±0.09	64.94±0.05	64.99±0.07	64.75±0.02	64.41±0.03
P-*value*	0.000*				
Lebar					
	3D Printing Open System with Exposure Time/Layer 4.5 seconds	3D Printing Open System with Exposure Time/Layer 5 seconds	3D Printing Open System with Exposure Time/Layer 5.5 seconds	3D Printing Close System	RAPP
Dimensional Accuracy	9.9±0	9.94±0.05	9.98±0.06	9.99±0.01	9.67±0.02
P-*value*	0.000*				
Tinggi					
	3D Printing Open System with Exposure Time/Layer 4.5 seconds	3D Printing Open System with Exposure Time/Layer 5 seconds	3D Printing Open System with Exposure Time/Layer 5.5 seconds	3D Printing Close System	RAPP
Dimensional Accuracy	3.5±0.01	3.5±0.01	3.49±0	3.34±0.01	3.36±0.03
P-*value*	0.000*				

*Significant, RAPP (Hot Polymerized Acrylic Resin)

Based on Table 2, the results of the Welch Anova statistical test, a p-value of 0.000 ($p \leq 0.05$) was obtained for the length dimension, which indicates that there is a significant influence of group differences on the accuracy of the length dimension. Thus, it can be concluded that group variations, which include 3D Printing Open System samples with various exposure times (4.5 seconds; 5 seconds; and 5.5 seconds), 3D Printing Close System, and RAPP samples, provide a significant difference in the accuracy of the resulting length dimension.

For the width dimension, the test results also showed a p-value of 0.000 ($p \leq 0.05$). This indicates that there is a significant effect of the group on the accuracy of the width dimension. Differences in printing methods and variations in exposure time in each group caused differences in the level of accuracy of the width dimension, so it can be stated that the treatment group plays an important role in determining the results of the accuracy of the dimensions.

Furthermore, in the height dimension, the p-value of 0.000 ($p \leq 0.05$) again indicates a significant influence of the group on the height dimension accuracy. This result confirms that group differences, both based on the 3D printing system and exposure time variations, have a significant impact on the height dimension accuracy of the resulting samples. Overall, the analysis results show that the treatment group has a significant effect on the accuracy of the length, width, and height dimensions, so that differences in the 3D printing system and exposure time per layer are important factors that affect the dimensional quality of the printed results. However, the results of this significance test do not specifically describe which group pairs show significant differences, so further analysis is needed through post hoc tests to identify differences between groups in more detail.

Tabel 3. Hasil Post-hoc Uji Tukey Variabel Panjang

***p-value* (Length)**					
	3D Printing Open System with Exposure Time/Layer 4.5 seconds	3D Printing Open System with Exposure Time/Layer 5 seconds	3D Printing Open System with Exposure Time/Layer 5.5 seconds	3D Printing Close System	RAPP
3D Printing Open System with Exposure Time/Layer 4.5 seconds		0.796	0.993	0.000*	0.000*
3D Printing Open System with Exposure Time/Layer 5 seconds	0.796		0.548	0.000*	0.000*
3D Printing Open System with Exposure Time/Layer 5.5 seconds	0.993	0.548		0.000*	0.000*
3D Printing Close System	0.000*	0.000*	0.000*		0.000*
RAPP	0.000*	0.000*	0.000*	0.000*	

*Significant, RAPP (Hot Polymerized Acrylic Resin)

Based on the results of the post hoc test on the accuracy of the length dimension, it was found that there was no significant difference between the 3D printing open system groups with variations in exposure time per layer of 4.5 seconds, 5 seconds, and 5.5 seconds, as indicated by p-values > 0.05 (p = 0.796; p = 0.993; and p = 0.548). This finding indicates that the difference in exposure time within this range in the open system does not have a significant effect on the length dimension of the denture base.

In contrast, a comparison between the entire open system 3D printing group and the closed system 3D printing group showed a significant difference (p = 0.000). Similar results were also found in the comparison between the entire open system 3D printing group and the RAPP sample, which also showed a significant difference (p = 0.000). Furthermore, a comparison between the closed system 3D printing and the RAPP sample showed a statistically significant difference (p = 0.000).

Overall, the results of this post hoc test indicate that differences in length dimensional accuracy are primarily influenced by the type of 3D printing system used, while variations in exposure time per layer in open system printing do not show significant differences. This finding reinforces the results of previous analyses that the printing system plays a more dominant role in determining the length dimensional accuracy of 3D-printed denture bases.

Table 4. Post-hoc Results of Tukey's Test for Variable Width

P-value (Wide)					
	3D Printing Open System with Exposure Time/Layer 4.5 seconds	*3D Printing Open System with Exposure Time/Layer 5 seconds*	*3D Printing Open System with Exposure Time/Layer 5.5 seconds*	*3D Printing Close System*	RAPP
3D Printing Open System with Exposure Time/Layer 4.5 seconds		0.236	0.003*	0.001*	0.000*
3D Printing Open System with Exposure Time/Layer 5 seconds	0.236		0.332	0.208	0.000*
3D Printing Open System with Exposure Time/Layer 5.5 seconds	0.003*	0.332		0.999	0.000*
3D Printing Close System	0.001*	0.208	0.999		0.000*
RAPP	0.000*	0.000*	0.000*	0.000*	

*Significant, RAPP (Hot Polymerized Acrylic Resin)

Based on the results of the post hoc test on the accuracy of the width dimension, it was found that there were significant differences in several pairs of treatment groups. The comparison between the open system 3D printing with an exposure time of 4.5 seconds and the open system 5.5 seconds showed a significant difference (p = 0.003). Significant results were also found in the comparison between the 4.5-second open system and the printing of the closed system (p = 0.001), and between the 4.5-second open system and the RAPP sample (p = 0.000). These findings indicate that the 4.5-second exposure time resulted in a significant difference in the accuracy of the width dimension compared to certain groups.

In contrast, there was no significant difference between the open system with an exposure time of 4.5 seconds and 5 seconds (p = 0.236), and between the open system with an exposure time of 5 seconds and 5.5 seconds (p = 0.332). Furthermore, the comparison between the open system with a 5-second printing system and the printing with a closed system also showed no significant difference (p = 0.208), nor did the comparison between the open system with a 5.5-second printing system and the printing with a closed system (p = 0.999). This indicates that at certain exposure time variations, different printing systems can produce relatively comparable width dimension accuracy.

Furthermore, all 3D printing groups, both open and closed systems, showed significant differences compared to the RAPP sample (p = 0.000). Overall, the results of this post hoc test indicate that the effect of exposure time variations per layer on width dimension accuracy is selective, with a more prominent difference at an exposure time of 4.5 seconds, while at exposure times of 5 and 5.5 seconds the width dimension accuracy tends to be more stable and closer between groups.

.TTable 5. Post-hoc Results of Tukey's Test of High Variables

***P-value* (Height)**					
	3D Printing Open System with Exposure Time/Layer 4.5 seconds	*3D Printing Open System with Exposure Time/Layer 5 seconds*	*3D Printing Open System with Exposure Time/Layer 5.5 seconds*	*3D Printing Close System*	RAPP
3D Printing Open System with Exposure Time/Layer 4.5 seconds		1.000	0.998	0.000*	0.000*
3D Printing Open System with Exposure Time/Layer 5 seconds	1.000		0.998	0.000*	0.000*
3D Printing Open System with Exposure Time/Layer 5.5 seconds	0.998	0.998		0.000*	0.000*
3D Printing Close System	0.000*	0.000*	0.000*		0.023
RAPP	0.000*	0.000*	0.000*	0.023	

*Significant, RAPP (Hot Polymerized Acrylic Resin)

Based on the results of the post hoc test on high dimensional accuracy, it was found that there was no significant difference between the 3D printing open system groups with variations in exposure time per layer of 4.5 seconds, 5 seconds, and 5.5 seconds, as indicated by a p-value close to 1 (p = 1.000; p = 0.998). This finding indicates that variations in exposure time within this range in the open system do not have a significant effect on the height dimension of the denture base.

In contrast, all open system 3D printing groups showed significant differences compared to the closed system printing (p = 0.000) and the RAPP sample (p = 0.000). These results indicate that the type of printing system plays a dominant role in influencing high dimensional accuracy. Furthermore, the comparison between the closed system printing and the RAPP sample also showed a statistically significant difference (p = 0.023), although the significance level was lower than the comparison with the open system. Overall, the results of this post hoc test indicate that differences in high dimensional accuracy are more influenced by differences in the 3D printing system than variations in exposure time per layer, with the open system printing producing more stable and consistent high dimensions than the closed system printing and the RAPP sample.

In addition to dimensional accuracy, flexural strength evaluation was conducted to assess the mechanical ability of the 3D-printed denture base to withstand bending loads during clinical use. Flexural strength is an important parameter that reflects the quality of the bond between layers and the degree of polymerization of the material, which is greatly influenced by variations in exposure time per layer and the 3D printing system used. Therefore, flexural strength testing was conducted to analyze the effect of different printing systems and variations in exposure time per layer on the mechanical strength of the resulting denture base.

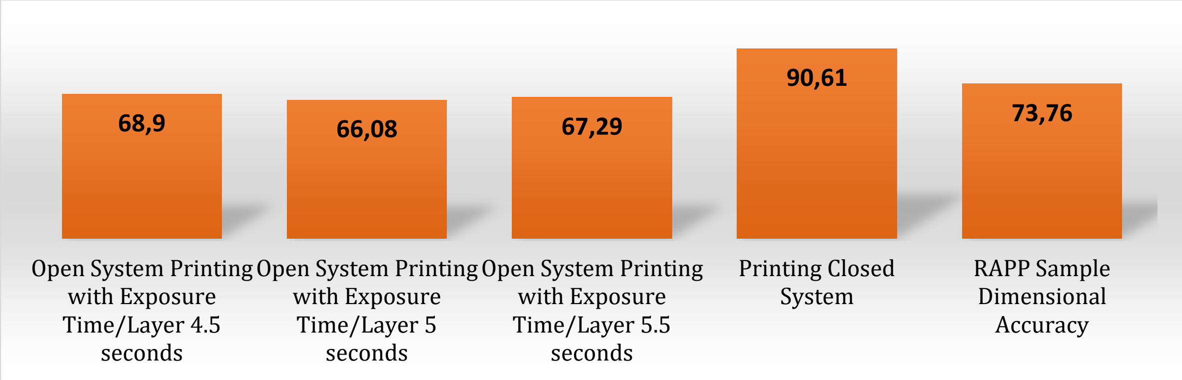

Figure 4. Average Flexural Strength of 3D Printed Denture Base

Based on Figure 4, the average flexural strength of the 3D-printed denture bases showed differences in each treatment group. In open system printing, the highest average flexural strength value was obtained at an exposure time of 4.5 seconds at 68.9 MPa, followed by an exposure time of 5.5 seconds at 67.29 MPa, and the lowest value at an exposure time of 5 seconds at 66.08 MPa. The differences in flexural strength values between exposure time variations in the open system were relatively small, indicating that changes in exposure time within this range did not have a significant effect on the material's flexural strength.

In contrast, in the closed system printing, the average flexural strength produced reached 90.61 MPa, which is the highest value compared to all treatment groups. This value indicates that the closed printing system is able to produce denture bases with higher flexural strength. Meanwhile, the RAPP sample showed an average flexural strength of 73.76 MPa, which is higher than all open system groups, but still lower than the closed system printing. Overall, these results indicate that the type of 3D printing system has a more dominant influence on flexural strength than variations in exposure time per layer in the open system, with the closed system printing producing the highest flexural strength in the 3D printed denture bases. Next, normality and homogeneity tests were conducted regarding the flexural strength of various samples. The results are shown in the following table.

Next, the normality and homogeneity tests of the samples were conducted. Based on the results of the normality test, all groups showed a significance value ($p \geq 0.05$), namely in the 3D Printing Open System group with an exposure time of 4.5 seconds (Sig. = 0.29), an exposure time of 5 seconds (Sig. = 0.25), an exposure time of 5.5 seconds (Sig. = 0.24), 3D Printing Close System (Sig. = 0.99), and RAPP (Sig. = 0.10). This indicates that the data in all groups are normally distributed. However, the results of the homogeneity of variance test using the Levene Test produced a significance value of 0.012 ($p \leq 0.05$), which indicates that the variance between groups is not homogeneous. Thus, although the normality assumption is met, the homogeneity of variance assumption is not met, so the selection of further statistical tests needs to consider this condition, namely by using a test that does not require homogeneity of variance, namely the Welch ANOVA.

Table 6. Results of Welch's ANOVA Test

Group	*Flexural strength*	P-value
Open System 3D Printing with 4.5 seconds Exposure Time/Layer	68.9±1.27	0.000*
Open System 3D Printing with 5 seconds Exposure Time/Layer	66.08±2.32	
Open System 3D Printing with 5.5 seconds Exposure Time/Layer	67.29±1.49	
Closed System 3D Printing	90.61±2.72	
RAPP	73.76±3.6	

*Significant, RAPP (Hot Polymerized Acrylic Resin)

Based on the results of the one-way ANOVA test on the flexural strength value, a p-value of 0.000 ($p \leq 0.05$) was obtained, indicating a significant difference between the treatment groups. These results indicate that variations in the 3D printing system and exposure time per layer have a significant effect on the flexural strength of the resulting denture base.

Descriptively, the close system printing showed the highest average flexural strength value, namely 90.61 ± 2.72 MPa, followed by the RAPP sample at 73.76 ± 3.6 MPa. Meanwhile, the open system printing group with exposure time variations of 4.5 seconds, 5 seconds, and 5.5 seconds produced relatively lower and closer average flexural strength values, respectively at 68.9 ± 1.27 MPa, 66.08 ± 2.32 MPa, and 67.29 ± 1.49 MPa. The results of this ANOVA test confirm that not all groups have the same flexural strength capabilities, so further analysis using a post hoc test is needed to identify pairs of groups that show significant differences specifically.

Table 7. Post-hoc Results of Tukey's Test

	p-value				
	3D Printing Open System with Exposure Time/Layer 4.5 seconds	*3D Printing Open System with Exposure Time/Layer 5 seconds*	*3D Printing Open System with Exposure Time/Layer 5.5 seconds*	*3D Printing Close System*	RAPP
3D Printing Open System with Exposure Time/Layer 4.5 seconds		0.219	0.727	0.000*	0.007*
3D Printing Open System with Exposure Time/Layer 5 seconds	0.219		0.885	0.000*	0.000*
3D Printing Open System with Exposure Time/Layer 5.5 seconds	0.727	0.885		0.000*	0.000*
3D Printing Close System	0.000*	0.000*	0.000*		0.000*
RAPP	0.000*	0.000*	0.000*	0.000*	

*Significant, RAPP (Hot Polymerized Acrylic Resin)

Based on the results of the ANOVA test and further tests (post hoc), the comparison between the two groups is declared statistically significantly different if the value ($p \le 0.05$), while the value ($p \ge 0.05$) indicates that there is no statistically significant difference. The results of the analysis show that the comparison of accuracy between 3D Printing Open System and RAPP in all exposure time variations shows a p value of 0.000 ($p \le 0.05$). This indicates that the difference in fabrication methods has a significant effect on the accuracy of the printed results, so that the accuracy of the model produced by 3D Printing Open System is significantly different compared to RAPP.

Furthermore, the comparison between the 3D Printing Open System and 3D Printing Closed System also showed a p-value of 0.000 ($p \le 0.05$) in all treatment groups. This finding indicates that the difference between the open and closed system printing systems has a significant effect on the accuracy of the print results, which is likely related to differences in device configuration, printing parameters, and polymerization process control in each system.

Furthermore, the comparison between the 3D Printing Close System and RAPP showed a p-value of 0.000 ($p \le 0.05$) across all treatment groups. This indicates that the differences in technology and working principles between the two methods result in significantly different levels of accuracy, thus the printing method makes a significant contribution to the variation in accuracy of the resulting model.

Overall, the results of this study indicate that the type of printing method and system significantly impacts the accuracy of the print, regardless of the exposure time used. Therefore, the choice of 3D printing system and fabrication method is an important factor to consider to achieve optimal print accuracy. The final measurement relates to the elastic modulus of the denture base. The results are shown in the following table.

Table 8. Average Elastic Modulus

Group	Elastic modulus $\bar{x} \pm SD$
Open System 3D Printing with 4.5 seconds Exposure Time/Layer	13.54 ±0.33
Open System 3D Printing with 5 seconds Exposure Time/Layer	13.22 ±0.35
Open System 3D Printing with 5.5 seconds Exposure Time/Layer	13.71 ±0.2
Closed System 3D Printing	16.42 ±0.31
RAPP	18.98 ±0.87

*RAPP (Hot Polymerized Acrylic Resin), SD (Standard Deviation)

Based on the results of elastic modulus measurements, there are differences in material stiffness values between treatment groups. In the 3D Printing Open System group, variations in exposure time show relatively close elastic modulus values, namely 13.54 ± 0.33 at an exposure time of 4.5 seconds, 13.22 ± 0.35 at an exposure time of 5 seconds, and 13.71 ± 0.20 at an exposure time of 5.5 seconds. These results indicate that changes in exposure time in the open system have an effect on the elastic modulus, with a tendency to increase the stiffness value at an exposure time of 5.5 seconds compared to lower exposure times.

Meanwhile, the 3D Printing Closed System group had a higher elastic modulus value, namely 16.42 ± 0.31, compared to all open system groups. The highest value was obtained in the RAPP group, namely 18.98 ± 0.87, which indicates that the characteristics of the printing system and materials used in this group resulted in the greatest level of stiffness. Overall, these results indicate that both exposure time and the type of printing system play a role in determining the elastic modulus of the printed material.

The results of the normality test showed a significant value ($p \geq 0.05$) for all groups, namely the 3D Printing Open System group with an exposure time of 4.5 seconds (Sig. = 0.367), an exposure time of 5 seconds (Sig. = 0.339), an exposure time of 5.5 seconds (Sig. = 0.454), 3D Printing Close System (Sig. = 0.534), and RAPP (Sig. = 0.333). This indicates that the data in all groups are normally distributed. However, the results of the homogeneity of variance test using the Levene Test produced a significance value of 0.025 ($p \leq 0.05$), which indicates that the variance between groups is not homogeneous. Thus, although the assumption of normality is met, the assumption of homogeneity of variance is not met, so further statistical analysis needs to use methods that do not require homogeneity of variance, such as Welch ANOVA.

Table 9. Results of Welch's ANOVA Test

Group	*Elastic modulus*	*p value*
3D Printing Open System with 4.5 seconds Exposure Time/Layer	13.54 ±0.33	0.000*
3D Printing Open System with 5 seconds Exposure Time/Layer	13.22 ±0.35	
3D Printing Open System with 5.5 seconds Exposure Time/Layer	13.71 ±0.2	
3D Printing Closed System	16.42 ±0.31	
RAPP	18.98 ±0.87	

*Significant, RAPP (Hot Polymerized Acrylic Resin)

Based on the results of the elastic modulus test, a p-value of 0.000 ($p \leq 0.05$) was obtained, indicating a significant effect of differences in exposure time and printing system on the elastic modulus value. However, the results of the significance test did not specifically indicate which sample groups had significant differences from each other. Therefore, to determine in more detail the pairs of sample groups that had a significant effect on the elastic modulus value, further analysis was carried out using the Tukey post-hoc test, as presented in Table 10.

Table 10. Post-hoc Results of Tukey's Test

	p-value				
	3D Printing Open System with Exposure Time/Layer 4.5 seconds	*3D Printing Open System with Exposure Time/Layer 5 seconds*	*3D Printing Open System with Exposure Time/Layer 5.5 seconds*	*3D Printing Close System*	RAPP
Open System 3D Printing with 4.5 seconds Exposure Time/Layer		0.717	0.963	0.000*	0.000*
Open System 3D Printing with 5 seconds Exposure Time/Layer	0.717		0.328	0.000*	0.000*
Open System 3D Printing with 5.5 seconds Exposure Time/Layer	0.963	0.328		0.000*	0.000*
Closed System 3D Printing	0.000*	0.000*	0.000*		0.000*
RAPP	0.000*	0.000*	0.000*	0.000*	

*Significant, RAPP (Hot Polymerized Acrylic Resin)

Based on the comparative test results presented in the Table of Differences in Exposure Time Per Layer on Elastic Modulus between Two Groups, it was obtained that the comparison between the elastic modulus of 3D Printing Open System and RAPP showed a p-value of 0.000 in all variations of exposure time/layer (4.5 seconds; 5 seconds; and 5.5 seconds). The value ($p \leq 0.05$), so statistically it can be concluded that there is a significant difference between the elastic modulus of 3D Printing Open System and RAPP. Furthermore, the comparison results between 3D Printing Open System and 3D Printing Close System also showed a p-value of 0.000 in all variations of exposure time/layer. This value ($p \leq 0.05$) indicates that there is a statistically significant difference between the elastic modulus of 3D Printing Open System and 3D Printing Close System. In addition, the comparison results between 3D Printing Close System and RAPP showed a p-value of 0.000. This value indicates that there is a significant difference between the elastic modulus of 3D Printing Close System and RAPP. Thus, it can be concluded that the elastic modulus of the materials produced by the 3D Printing Open System, 3D Printing Close System, and RAPP show significant differences from each other, which are statistically influenced by the differences in the printing system and curing method used.

The results of this study indicate that differences in exposure time per layer and 3D printing system significantly influence the mechanical properties and dimensional accuracy of denture bases, particularly on the elastic modulus and flexural strength values. This finding is in line with various previous studies which state that printing process parameters, such as exposure time and system type (open and closed system), play an important role in determining the degree of resin polymerization, which in turn affects the mechanical strength and dimensional stability of the printed product. 3D printed resin with optimal process settings is able to produce higher and more consistent flexural strength values compared to conventional methods, due to the formation of a more homogeneous polymer structure [22]. Furthermore, a systematic review study by [23] confirmed that the dimensional accuracy of 3D printed results is significantly influenced by printing and post-curing parameters, although clinically still within acceptable tolerance limits. Recent research in the field of dentistry also states that variations in exposure time can cause significant differences in mechanical properties between samples, so selecting the right printing parameters is a crucial factor in producing denture bases with optimal strength and accuracy [24]. Thus, the results of this study strengthen the evidence that control of exposure time and printing system is an important aspect in optimizing the quality of denture bases based on 3D printing technology.

CONCLUSION

Based on the results of the study on the effect of exposure time per layer on the dimensional accuracy and flexural strength of denture bases fabricated using 3D printing technology, it can be concluded that exposure time per layer has a significant effect on the dimensional accuracy and flexural strength of denture bases printed using the 3D Printing Open System, where variations in the exposure duration affect the dimensional stability and flexural strength due to differences in the degree of resin polymerization. In addition, there are significant differences in both dimensional accuracy and flexural strength between denture bases fabricated using the 3D Printing Open System, 3D Printing Close System, and Hot Polymerized Acrylic Resin (RAPP), which reflects the influence of material characteristics, polymerization mechanisms, and the level of control and standardization of the fabrication process. Comparatively, the 3D Printing Open System shows superiority in the consistency of dimensional accuracy, especially in the length and height parameters, while the 3D Printing Close System produces the highest flexural strength value compared to the other groups. However, all groups in this study have not met the minimum flexural strength value according to the ISO 20795-1 standard. In the 3D Printing Open System group, an exposure time per layer of 5 seconds showed a relatively more optimal flexural strength value compared to other exposure time variations, although it was still below the required standard, so that setting the right printing parameters remains a crucial factor in improving the quality of denture bases based on 3D printing technology.

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