



BASIC RESEARCH:

Influence of Printing Orientation on the Mechanical, Surface, and Polymerization Properties of Two 3D-Printed Dental Resins

Influencia de la orientación de impresión en las propiedades mecánicas, superficiales y de polimerización de dos resinas dentales impresas en 3D

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ABSTRACT: This study aimed to evaluate the effect of printing orientation on the accuracy, flexural strength, surface roughness, and degree of conversion of two methacrylate-based resins commonly used in dental 3D printing. Rectangular specimens (64×10×3.3 mm) were designed according to ISO 20795-1:2013 standards and printed using an Asiga Max UV printer at three orientations (0°, 45°, and 90°) with two commercial resins: VeriGuide OS and VeriModel OS (Whip Mix). Dimensional accuracy was measured using a digital caliper, surface roughness by profilometry, and flexural strength through a three-point bending test. The degree of conversion (DC) was assessed using Attenuated Total Reflection Fourier Transform Infrared Spectroscopy (ATR-FTIR). Data were analyzed with one-way ANOVA and Tukey's post hoc test ($\alpha=0.05$). Printing orientation significantly influenced several properties of the tested resins ($p\leq 0.05$). Specimens printed at a 45° angle showed the highest dimensional accuracy in length, width, and thickness. Flexural strength increased as the printing orientation became more vertical, with significant differences between 0° and 90° for both resins. Surface roughness was highest at 45°, while smoother surfaces were observed at 0°. The mean DC values were approximately 40% for all groups, with statistically significant differences observed only for the VeriGuide resin, where specimens printed at 0° achieved higher conversion compared to 45° and 90° orientations. Specimens printed at 45° demonstrated superior dimensional accuracy and higher surface roughness, while vertical orientations enhanced flexural strength. None of the resins achieved complete polymerization.

KEYWORDS: 3D printing; Printing orientation; Dental resins; Flexural strength; Surface roughness; Degree of conversion.



RESUMEN: Este estudio tuvo como objetivo evaluar el efecto de la orientación de impresión sobre la exactitud dimensional, la resistencia a la flexión, la rugosidad superficial y el grado de conversión de resinas metacrílicas comúnmente utilizadas en la impresión 3D dental. Se diseñaron especímenes rectangulares ($64 \times 10 \times 3,3$ mm) según la norma ISO 20795-1:2013 y se imprimieron en una impresora Asiga Max UV en tres orientaciones (0° , 45° y 90°) utilizando dos resinas comerciales: VeriGuide OS y VeriModel OS (Whip Mix). La exactitud dimensional se evaluó con calibrador digital, la rugosidad superficial mediante perfilómetro y la resistencia a la flexión mediante prueba de flexión en tres puntos. El grado de conversión (DC) se determinó mediante espectroscopía infrarroja por transformación de Fourier con reflectancia total atenuada (ATR-FTIR). Los datos se analizaron con ANOVA de una vía y prueba post hoc de Tukey ($\alpha=0,05$). La orientación de impresión influyó significativamente en varias propiedades ($p \leq 0,05$). Los especímenes impresos a 45° mostraron la mayor exactitud dimensional en longitud, ancho y espesor. La resistencia a la flexión aumentó conforme la orientación fue más vertical, observándose diferencias significativas entre 0° y 90° para ambas resinas. La rugosidad superficial fue mayor a 45° , mientras que las superficies más lisas se obtuvieron a 0° . Los valores medios de DC fueron cercanos al 40% en todos los grupos, con diferencias significativas únicamente en VeriGuide, donde los especímenes impresos a 0° alcanzaron mayor conversión que los impresos a 45° y 90° . La orientación de impresión desempeña un papel determinante en las propiedades mecánicas, superficiales y de polimerización de las resinas dentales impresas en 3D. Los especímenes impresos a 45° mostraron mejor exactitud dimensional, mientras que las orientaciones verticales favorecieron la resistencia a la flexión. Ninguna resina alcanzó conversión completa, lo que evidencia la necesidad de optimizar protocolos de fotopolimerización posterior.

PALABRAS CLAVE: Impresión 3D; Orientación de impresión; Resinas dentales; Resistencia a la flexión; Rugosidad superficial; Grado de conversión.

INTRODUCTION

Computer aided design (CAD) and computer aided manufacturing (CAM) have positively impacted restorative dentistry by enhancing procedures. Manufacturing procedures can be classified into subtractive manufacturing and additive manufacturing. Subtractive manufacturing involves extracting the desired shape by cutting or removing material from a block or workpiece. The fabrication of a structure by means of 3D printing is considered an additive method (AM), that offers several advantages. These include simplified equipment, the ability to produce intricate and complex shapes and lower production costs as well as less wasted materials (1-3).

The ISO/ASTM 52900 standard, (4) provides a standardized terminology for AM processes and categorizes them into seven categories: vat-photopolymerization, material jetting, material extrusion, binder jetting, powder bed fusion (PBF), sheet lamination and directed energy deposition.

Stereolithography (SLA) and digital light processing (DLP) are the most commonly used additive manufacturing processes in dentistry. SLA uses laser beams, while DLP employs short-wave light to solidify liquids (photopolymers). Both technologies have become a valuable tool in the dental industry due to its ability to produce precise and highly customizable dental models, surgical guides, crowns, bridges, and other dental prosthe-

tics (1). This kind of fabrication method requires accuracy and resistance, but there are many possible variables that can affect these characteristics (5-8).

One significant factor that can influence the characteristics of printed objects is the angulation of the object on the printing platform. The placement and orientation of the object can affect its overall quality, surface finish, and dimensional accuracy as well as flexural strength. Proper positioning and angulation are essential to minimize errors and achieve the desired outcomes (5,9,10).

There are several research papers published about the previous problem; (11-13) however, the market constantly offers us new products for dental printing, and it is of interest for research groups to conduct tests on the products most commonly used in dentistry. Printed dental models, as well as surgical guides are among the most common uses of additive manufacturing, and these need to be accurate and resistant to serve the functions for which they are intended. Dental models need to have accurate dimensions, as these are frequently used for restorative dentistry and the fabrication and passivity checking of definitive restorations. On the other hand, the dimensional accuracy of surgical guides is vital to achieve a passive fit in the patient's mouth and ensure precise placement of dental implants. Therefore, structures printed for these two purposes, remain with an unmodified surface after printing and thus, it is important to evaluate how the printing orientation

affects the characteristics of the resins employed for those purposes.

The aim of the present study was to evaluate the effect of printing orientation on the accuracy, flexural strength, surface characteristics of two different printing resins. Also, a thorough analysis was performed to study the degree of conversion of these resins. The null hypothesis was that specimens with different printing orientations would depict the same printing accuracy, flexural strength, surface roughness.

MATERIALS AND METHODS

Rectangular specimens with the dimensions of 64×10×3.3 mm were designed in an open-source CAD software program (Autodesk® Meshmixer™ v 3.5.474) according to ISO 20795-1: 2013 standards. Specimens were exported as standard tessellation language (STL) files to Asiga Composer Software v 1.3.7 and placed in three different angulations on the building platform, 0°, 45° and 90°.

Specimens were printed from two methacrylate-based acrylic resins in an Asiga Max UV Printer TM (Lachlan Thompson, Omni Dental). The printing parameters were downloaded and installed from the official Asiga webpage, as indicated by the manufacturer. Ten specimens (n=10) were printed for each printing resin and each orientation with a layer thickness of 50 µm. The list of materials and its characteristics is summarized in Table 1.

Table 1. Description of the employed materials and experimental groups.

Experimental group	Printing orientation	Resin	Lot	Characteristics
1	0°	VeriGuide Os (Whip Mix)	41022005	3D Printing Resin for Dental Surgical Guides. Biocompatible resin formulated for DLP, SLA, and LCD 3D printers that operate at 385nm and 405nm.
2	45°			
3	90°			
4	0°	VeriModel Os (Whip Mix)	003112004	3D Printing Resin for producing dental models on printers with DLP, LCD, or SLA technologies using light sources at 385nm and 405nm. Color: White Flexural Strength: ≥ 80 MPa Flexural Modulus: ≥ 1850 MPa Residual Monomers: < 0.10% Density: Approximately 1.1 g/ml.
5	45°			
6	90°			

The temperature and relative humidity are 20 degrees Celsius and 54%, respectively.

After printing, the support structures were eliminated with low-speed rotary instruments (Kavo low speed dental hand piece), and any remaining surface monomers on the 3D-printed specimens were cleaned using isopropyl alcohol in an ultrasonic bath for 5 minutes and afterwards post-polymerized according to the manufacturer's instructions by using a UV light-polymerization unit (Asiga Flash TM) for 30 minutes.

Specimens' dimensions in length, thickness and width were measured with a digital caliper with 0.01-mm accuracy (Mitutoyo, Japan). Then, the percentage error (printing accuracy) was obtained, along with its mean and standard deviation. The

percentage error was calculated using the following formula:

$$\left(\frac{\text{Printedspecimenmeasurement} - \text{designedspecimenmeasurement}}{\text{designedspecimenmeasurement}} \right) * 100$$

Equation 1.

Afterwards surface roughness was measured by means of a profilometer. For this test, a profilometer (DektatXT Bruker) with the following characteristics was used: a 2-micron stylus tip, a line movement of 200 microns, a Stylus Force of 5 mg, Standard Scan, a stylus diameter range of 65.5 micrometers, a resolution of 0.017 µm/pt, and a duration of 40 seconds.

The flexural strength test was performed with a testing machine (ElectroPuls E3000, Instron)

applying force with a rod at a crosshead speed of 5 mm per minute until specimen fracture; specimens were placed on a jig with a span of 50 mm. Resulting data in MPa was calculated by the same equipment.

The degree of conversion (DC) was assessed using an Attenuated Total Reflection (ATR) Fourier Transform Infrared (FTIR) spectrometer (Frontier, Perkin Elmer) in absorbance mode.

The control for measuring the degree of conversion (DC) from methyl methacrylate (MMA) to polymethyl methacrylate (PMMA) involved the use of unpolymerized material. To polymerize both resins, a UV-395nm light was applied (Superfire, Guangdong, China), and the FTIR spectrum was recorded at intervals of 0s, 5s, 15s, 30s, 60s, 90s, 120s, 180s, and 240s. We focused on the peaks at 1608 cm⁻¹ and 1637 cm⁻¹, as the former corresponds to aromatic double bonds, and the latter corresponds to double bonds in alkenes. These peaks are associated with the conversion of carbon double bonds to single bonds, a process known as "double bond conversion" (DBC). A base line was considered by using as reference the values at 1860 cm⁻¹ and 3994.82 cm⁻¹ for VeriGuide samples, and 1827.10 cm⁻¹ and 3944.12 cm⁻¹ for VeriModel samples.

The degree of double bond conversion was determined in all specimens of the sample. To achieve this, we followed the approach proposed by Herrera-González *et al.*, (14) who proposed the calculation of the ratio between the absorption intensities at wavelengths 1608 cm⁻¹ and 1638 cm⁻¹ by means of the following formula (Equation 2):

$$DC\% = \left(1 - \frac{h_{1638}/h_{1608pol}}{h_{1638}/h_{1608mon}}\right)$$

Equation 2.

In this context, 'h1638' represents the peak height at 1638 cm⁻¹, which corresponds to the absorption band of the alkene bond, while 'h1608' signifies the peak height at 1608 cm⁻¹ for the aromatic ring. The term 'mon' denotes the spectrum of the unpolymerized monomer mixture, and 'pol' designates the spectrum of the polymerized material.

Using the aforementioned definition in equation 2 we estimated DC as a function of time.

Statistical analysis was conducted using SPSS version 19 (IBM, USA). The Shapiro-Wilk test and Levene test indicated that parametric tests could be applied to the data. Therefore, One-Way ANOVA and post-hoc Tukey tests were performed for pairwise comparisons, with a significance level set at less than 0.05.

RESULTS

ERROR RATES

Error rates for length (Figure 1) were lower in the specimens printed with VeriGuide at the 90° orientation. However, at the same orientation the error rates were higher among the specimens printed with VeriModel. There were statistically significant differences among all experimental groups within each printing resin ($p \leq 0,05$), with the only exception for VeriModel where specimens printed at 0° and 90° orientation did not show a statistically significant difference. Bars showing positive error rates imply specimens bigger in length, whereas bars showing negative error rates imply specimens shorter in length.

Error rates for width (Figure 1) were lower in the specimens printed at the 45° orientation. A statistically significant difference was observed between the two resins in the specimens printed at the 90° orientation ($p \leq 0.05$). Within each resin group,

no statistically significant differences were found for width among the three different printing angles.

Regarding the error rates in thickness, within each resin group there were statistically significant differences for all printing orientations ($p \leq 0.05$). For both resins, the error rates were higher for the 0° printing angle. Specimens printed at 45° had the lower error rates in thickness.

ROUGHNESS

In Table 2, the results obtained in the profilometry test are visualized, evaluating the roughness according to the inclination and type of resin. It is observed that there is a statistically significant difference between the two resins used for the 0° and 45° angles. The Verimodel resin produced specimens with less roughness for both angles. Only for the 90° angle, no significant difference was observed between the two resins.

FLEXURAL STRENGTH

Figure 2 describes median values for the flexural strength at break (MPa). It can be observed that, in general, flexural strength increases as the printing orientation becomes more vertical.

One Way Analysis of Variance (ANOVA) shows that for 0° and 90° of orientation there are statistically significant differences between both resins (Table 3). 45° printing orientation does not depict any significant difference between VeriGuide and Verimodel.

Table 4 presents the results of the post hoc test for the differences in flexural strength among each resin for different printing orientations. It can be observed that, for VeriGuide, there were no significant differences only between the

specimens printed at 0° and 45° orientation; all the other printing orientations showed differences between each other. On the other hand, for VeriModel, there were no significant differences between 45° and 90°.

POLYMERIZATION PROGRESS OF RAW RESIN USING EXPOSURE TIMES

Figure 3 shows the spectra obtained with FTIR of the unpolymerized resins to which light was applied at intervals of 0s, 5s, 15s, 30s, 60s, 90s, 120s, 180s, and 240s.

According to Herrera-González *et al.* (14), the intensity of the peak located at approximately 1608 cm^{-1} (I_1) undergoes minimal changes during the process. On the contrary, the intensity of the peak located at approximately 1638 cm^{-1} (I_2) decreases as the polymerization process progresses. These peaks are associated with the conversion of carbon double bonds to single bonds, a process known as "double bond conversion" (DBC).

For each resin, DC as defined by equation (2), was plotted against time, see Figure 4. In both cases, three regions can be distinguished. In the first one, DC is small, indicating the existence of an energy cost associated with the initiation of polymerization. After 15s of irradiation the DC increases quickly, suggesting an active polymerization process until it reaches a saturation region for which the DC is almost constant even though the DC is not 100%. In the case of the VeriGuide resin (triangles in Figure 4), the slope of the last region is close to zero, suggesting a cease of the conversion process. For the VeriModel resin, the plateau region seems to be reached at a slower rate, suggesting more time is needed to observe a steadier slowdown of the polymerization process (diamonds in Figure 4).

DEGREE OF DOUBLE BOND CONVERSION

As described earlier, we applied the Equation 2 employed by Herrera-González (14) for calculating the degree of conversion. Table 5 presents the results of this calculation, we can observe that values around 40% are obtained for the printed specimens.

Levene's test yielded a non-significant result, indicating homogeneity of variances, which

allows for a one-way analysis of variance (ANOVA) to be conducted. An ANOVA test was conducted, yielding a significant result ($p \leq 0.05$). Subsequently, a Tukey test was performed ($p \leq 0.05$), and the results are presented in Table 6. The post hoc test shows that statistically significant differences are only observed within the VeriGuide resin group. Specifically, this applies to the specimens printed at 0° , which were found to be different from those printed at the other two angles.

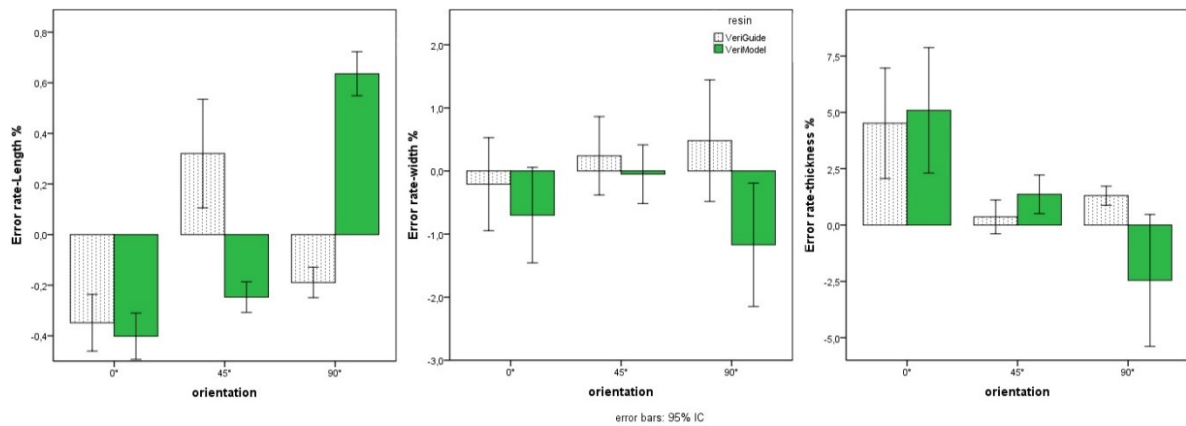


Figure 1. Error rates for length, width and thickness according to resin type and printing orientation.

Table 2. Roughness (μm) according to printing orientation and resin type.

Orientation	Resin	Media (μm)	Sig
0°	VeriGuide	0,29	$p \leq 0,001$
	VeriModel	0,64	
45°	VeriGuide	5,04	$p \leq 0,001$
	VeriModel	1,87	
90°	VeriGuide	1,58	$p = 0,32$
	VeriModel	1,29	

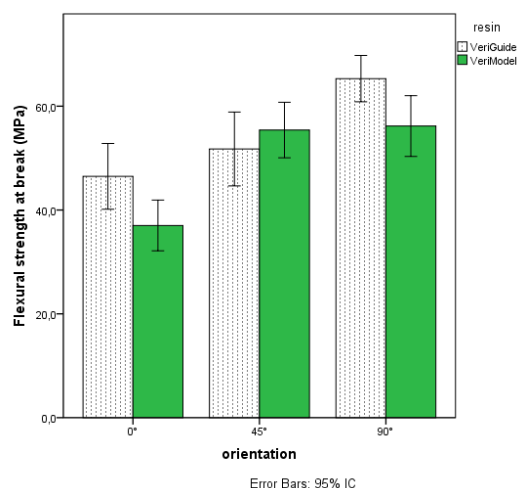


Figure 2. Flexural strength at break according to resin type and printing orientation.

Table 3. ANOVA for flexural strength according to resin type and according to orientation.

Orientation	Variable	Sig
0°	Resin	0,02
45°	Resin	0,37
90°	Resin	0,01

Table 4. Flexural strength Post Hoc Tukey Test for printing orientations according to resin type.

Resin	Orientation	Orientation	Sig.	Confidence Interval 95%	
				Inferior limit	Superior limit
VeriGuide	0°	45°	0,36	-14,68	4,14
		90°	0,00	-28,23	-9,41
	45°	90°	0,00	-22,96	-4,14
VeriModel	0°	45°	0,00	-26,85	-9,91
		90°	0,00	-27,62	-10,68
	45°	90°	0,97	-9,02	7,47

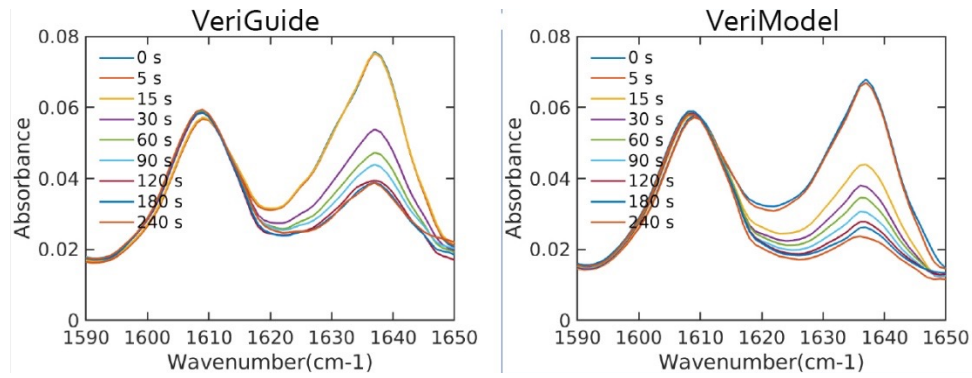


Figure 3. FTIR spectra according to different curing time intervals.

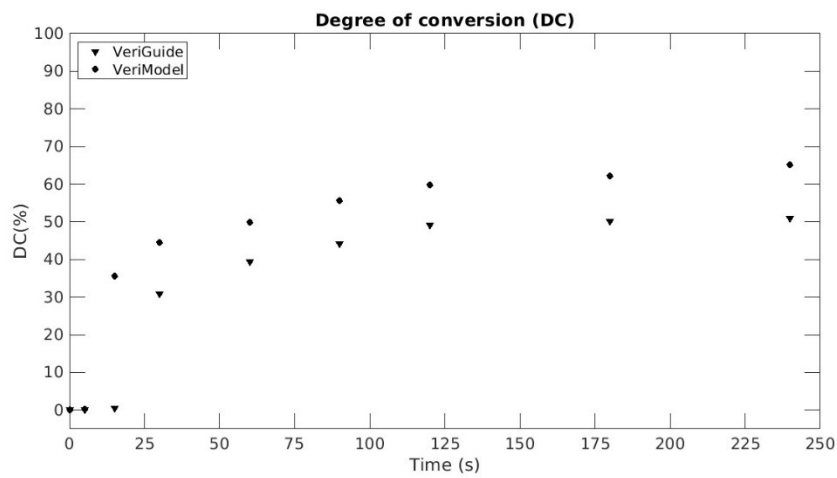


Figure 4. DC as a function of time for VeriGuideClear (triangles) and for VeriModelWhite (diamonds).

Table 5. Degree of conversion for VeriModel and VeriGuide resins according to printing angle.

angle	VeriModel	VeriGuide
	DC (sd)	DC (sd)
0	44,6 (1,9)	43,7 (1,3)
45	43,1 (2,1)	38,9 (1,4)
90	45,1 (2)	39,2 (1,7)

Table 6. Post hoc test for printing orientation according to resin type.

Resin	Orientation	Orientation	Sig.	Confidence Interval 95%	
				Upper limit	Lower limit
VeriModel	0°	45°	0,2	-0,7	3,8
		90°	0,8	-2,8	1,8
	45°	0,1	-4,3	0,2	
VeriGuide	0°	45°	0,0	3,1	6,4
		90°	0,0	2,8	6,2
	45°	0,9	-1,9	1,4	

DISCUSSION

The present study aimed to evaluate the influence of printing orientation on the accuracy, flexural strength, surface roughness, and degree of conversion of printing resins commonly used in dental applications. The results demonstrated that printing orientation significantly affects some properties, highlighting the need for careful consideration when selecting the optimal printing angle for specific clinical applications.

PRINTING ACCURACY

Our findings align with previous studies, such as those by Shim *et al.* (10) and Al-Dulaijan *et al.* (9), which reported that printing orientation plays a crucial role in dimensional accuracy. In our study, error rates for length were lower in VeriGuide specimens printed at 90°, while VeriModel specimens at the same orientation exhibited higher error rates. These results suggest that the interaction between printing orientation and resin composition affects dimensional stability, possibly due to differential polymerization shrinkage and post-curing effects.

For width, specimens printed at 45° exhibited the lowest error rates, and no significant differences were observed within each resin group. In terms of thickness, significant differences were observed across all orientations, with 0° exhibi-

ting the highest error rates. This trend is consistent with prior research indicating that horizontal orientations are more susceptible to inaccuracies due to potential resin pooling and inconsistent layer formation.

SURFACE ROUGHNESS

Surface roughness measurements revealed statistically significant differences between the two resins at 0° and 45°, but not at 90°. The roughest surfaces were observed at 45° and the smoothest surfaces were seen at 0°, a finding that corroborates previous reports (10) indicating that mid-angled prints may introduce greater surface irregularities due to incomplete polymerization or layering inconsistencies.

FLEXURAL STRENGTH

Flexural strength increased as the printing orientation became more vertical, with statistically significant differences observed between the two resins at 0° and 90°, but not at 45°. This trend suggests that vertically printed specimens exhibit higher structural integrity, likely due to improved polymerization along the direction of applied force, reducing weak interlayer bonding. These findings are consistent with studies by Derban *et al.* (11) and KEBLER *et al.* (2021), who found that flexural properties are enhanced when the print layers are oriented parallel to the applied stress direction.

Post hoc analysis revealed that, for VeriGuide, significant differences were observed between 0° and 90°, as well as 45° and 90°. For VeriModel, significant differences were noted between 0° and both 45° and 90°, but not between 45° and 90°. Although these findings contradict the results of Al-Dulaijan *et al.* (9) and Shim *et al.* (10), these variations suggest that the effect of printing orientation on mechanical properties may be resin-dependent, possibly due to differences in polymerization kinetics and cross-linking density.

DEGREE OF CONVERSION (DC)

The degree of conversion analysis on raw resin demonstrated that polymerization follows a three-phase process: an initial activation phase, a rapid conversion phase, and a plateau phase. This trend is consistent with previous FTIR-based studies (Herrera-González *et al.*, 2019). VeriGuide exhibited a rapid transition to the plateau phase, suggesting that its polymerization process stabilizes more quickly compared to VeriModel. Additionally, DC values for printed specimens remained around 40%, reinforcing findings from prior research that indicate incomplete polymerization is a common characteristic of 3D-printed resins. The differences in DC among printing angles were particularly notable for VeriGuide, where 0° specimens showed significantly higher DC compared to other orientations, emphasizing the impact of layer orientation on polymerization efficiency.

In contrast to our study, Perea-Lowery *et al.* (15) exclusively utilized the absorption intensity associated with the double bonds in the aromatic ring, which is considered to remain relatively constant during polymerization (Error: Reference source not found). For this reason, another method was sought; in this case, the one discussed by Herrera-González *et al.* was selected. This method uses the ratio between the absorption intensities at 1608 cm⁻¹ (double bonds in aromatic rings,

considered constant during polymerization) and 1638 cm⁻¹ (double bonds in alkenes, decreases during polymerization) (Equation).

CLINICAL IMPLICATIONS AND LIMITATIONS

The findings of this study highlight the importance of selecting the appropriate printing orientation for dental applications. For dental models requiring high dimensional accuracy, printing at 45° appears to be the most suitable. However, for applications demanding superior mechanical properties, vertical orientations may be preferable. Surface roughness variations suggest that additional post-processing steps, such as polishing or coating, may be necessary to optimize surface quality.

One limitation of this study is that only two resins were evaluated, and results may not be generalizable to all 3D printing materials. Additionally, long-term aging effects, such as water absorption and mechanical fatigue, were not assessed. Future research should explore these aspects to provide a more comprehensive understanding of 3D-printed dental resins. These findings emphasize the need for optimized printing strategies tailored to specific dental applications, ensuring both dimensional precision and mechanical reliability.

CONCLUSION

Within the limitations of this *in vitro* study, the authors reject the null hypothesis and conclude that:

- Specimens printed at a 45° angle generally exhibited the highest accuracy in length, width, and thickness.
- Specimens printed at more vertical orientations demonstrated greater flexural strength.
- The 45° printing angle produced higher surface roughness compared to the other orientations.
- None of the experimental groups achieved complete degree of conversion.

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