

Original Article

Overseeing the Calibration of In-Office 3D Printers

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ABSTRACT

Desktop 3D printers often do not include mechanisms for manually fine-tuning printing parameters, which can lead to inconsistencies and errors across prints. To address this, the present study developed a method to track and evaluate printer calibration in office-based settings. A specialized calibration coupon was created with defined tolerances and dimensions to represent ideal geometry and to quantify deviations in the X–Y axes and surface curvature. Two stereolithography (SLA) printers were tested across ten print cycles using two different resin types. Additionally, coupons were positioned at five distinct locations on the build platform to investigate positional effects on accuracy. Analysis revealed no significant differences in X or Y axis measurements across varying positions or resin types ($p > 0.05$). As desktop 3D printers currently lack a standardized calibration workflow linking design and production, the proposed calibration coupon offers a practical tool for monitoring printer performance and maintaining consistent print quality.

Keywords: Calibration, Desktop 3D printers, Stereolithography (SLA), Print accuracy, Dental resins

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Introduction

Three-dimensional (3D) printing has gained widespread attention in recent years, driven by lower production costs and faster printing speeds [1, 2]. In 1983, Charles Hull produced the first 3D object using a stereolithography (SLA) printer [3], which initially drew interest in fields such as architecture and aerospace engineering [4] due to its ability to fabricate parts with millimeter-level precision. The technology began to find applications in medicine during the 1990s [5]. In dentistry, 3D printing is now widely used thanks to advances in digital scanning, where data from intraoral or desktop scanners and cone-beam computed tomography (CBCT) enable the design and fabrication of prosthetic components, significantly reducing reliance on external dental laboratories [6]. SLA was the first commercially available printer for rapid prototyping [7]. It operates by using a laser to

trace each layer of a photopolymerizable resin, with the build platform lowering incrementally as new resin layers are applied. The process continues layer by layer until the object is completed [8]. Support structures are required during printing to counteract gravitational forces and ensure stability during resin spreading. Postprocessing involves washing printed parts in alcohol to remove residual resin, followed by UV curing to solidify any uncured material. SLA technology is particularly common for manufacturing surgical guides for dental implants [1, 9]. Beyond SLA, several other 3D printing technologies are available, each utilizing distinct mechanisms and suited to specific materials, speeds, and precision requirements. These include selective laser sintering (SLS), fused deposition modeling (FDM), photopolymer jetting (PPJ), and digital light processing (DLP) [1, 10, 11] (Table 1).

Table 1. Summary of 3D printing technologies

3D Printing Technology	Mechanism	Advantages	Limitations
Stereolithography (SLA)	Uses a vat of liquid photopolymer selectively cured by light-activated polymerization	Low cost, high-resolution prints, smooth surface finish	Requires extensive postprocessing, slower printing speed
Selective Laser Sintering (SLS)	Applies thermal energy to selectively fuse regions within a powder bed	Produces high-quality surfaces, allows large build volumes, no need for support structures, minimal postprocessing	Expensive equipment, complex operation, challenging calibration and maintenance
Fused Deposition Modeling (FDM)	Extrudes melted material through a nozzle or orifice layer by layer	User-friendly, compatible with a wide range of thermoplastics, suitable for bioprinting	Longer print times, lower print resolution compared to other methods
Photopolymer Jetting (PPJ)	Deposits layers of photopolymer which are cured by light as the print head passes	High-resolution output, supports large build volumes, multicolor printing, complex structures achievable with multiple print heads	High equipment and maintenance costs, resulting prints tend to be brittle
Digital Light Processing (DLP)	Operates similarly to SLA using light to cure photopolymer layers	Smooth surface finish, accurate prints, faster than SLA	Postprocessing is required

3D printing has a wide range of applications in dentistry, including the production of dental models, implant drilling and cutting guides, crown copings, partial denture frameworks, temporary and definitive removable prostheses, provisional crowns, and orthodontic aligners [12, 13]. Its growing popularity is partly due to lower production costs and reduced material waste compared with traditional additive manufacturing techniques [14].

Certain applications, such as surgical guides and anatomical models, demand higher precision, requiring excellent reproducibility and contour accuracy [6, 15]. There has been a notable trend toward the use of in-office 3D-printed surgical guides rather than laboratory-fabricated ones [16], which lowers both cost and turnaround time while maintaining comparable accuracy for implant placement. While industrial-grade 3D printers can be calibrated and verified using quality control systems that create a closed-loop workflow, most dental office printers lack the capability to adjust individual parameters for consistent precision, potentially leading to unnoticed inaccuracies that could compromise patient care [17].

Printing accuracy is influenced by multiple factors, including material type, object geometry and topology, nominal dimensions, wall thickness, solid or hollow structures, and postprocessing methods. Several studies have proposed “test cubes” [6] or benchmark parts [18] to evaluate printer performance, helping to assess accuracy and adjust printing parameters [6, 19]. However, these designs are often complex and may be impractical for users without specialized training in rapid prototyping, including many dentists and dental technicians. This highlights the need for a

standardized, user-friendly quality control protocol tailored to dental professionals [20].

To address this, the present study developed a simple calibration coupon to evaluate the impact of resin type and coupon position on the build platform on printing accuracy. Variances were analyzed for coupons printed with two different resin materials, and because print accuracy can depend on the coupon’s location on the platform, measurements were taken from five different positions [5]. The null hypotheses were that variances along the X and Y axes are consistent across all five positions on the build platform and that they are equivalent between Dental SG and Grey V4 resins at the first position.

Materials and Methods

- Slicing software: Chitubox (Shenzhen, China)
- SLA 3D printers: Form 2 (Formlabs, Somerville, MA, USA)
- Resins: Formlabs Dental SG and Grey V4 (Formlabs, Somerville, MA, USA)
- Resin cleaning station: Veri Wash (Whip Mix, Louisville, KY, USA)
- 99% isopropyl alcohol (Florida Laboratories Inc., Fort Lauderdale, FL, USA)
- Digital calipers: IGaging Absolute Origin (IGaging, Los Angeles, CA, USA)

Calibration coupon design

The coupon was designed to be simple, compact, and robust enough to withstand repeated printing cycles while occupying minimal space on the build platform. After initial approval, the coupon was designed using Chitubox (Shenzhen, China) to allow measurement of

variances in the X–Y axes and curvature. In this study, curvature measurements were not analyzed (**Figure 1**). The Z-axis was considered controlled by the printer’s mechanical build platform components, and thus was not addressed as part of the calibration process [21].

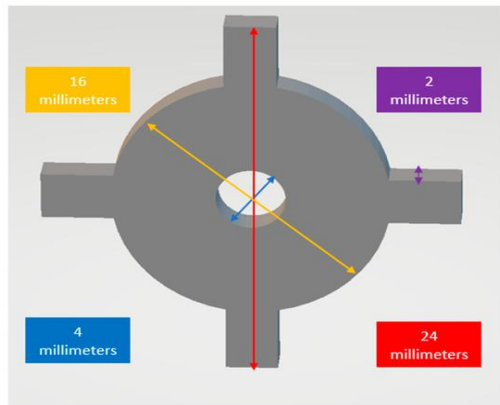


Figure 1. Final digital design of the calibration coupon illustrating its overall dimensions.

The calibration coupon’s size was finalized by balancing printer X–Y resolution with practical ease of measurement. Initial trial prints began at 12 mm × 12 mm × 1 mm, but this proved too delicate for accurate assessment. Iterative testing led to a larger, more robust design of 24 mm × 24 mm × 2 mm (**Figure 1**), which was then subjected to further evaluation.

To examine print reliability, coupons were first printed on an LCD-based SLA printer (Anycubic Photon, Anycubic Technology Co., Hong Kong) at the Additive Manufacturing Institute of Science and Technology (AMIST). Each print run placed coupons at the four corners and the center of the build platform across five cycles. Postprocessing followed manufacturer instructions. Direct printing onto the build platform caused difficulty in removal and frequent chipping, prompting the addition of small rafts to improve handling and minimize defects prior to measurement (**Figure 2**).

Subsequent tests were conducted on the Form 2 SLA printer (Formlabs, Somerville, MA, USA) at the University of Louisville School of Dentistry, the machine intended for the main study. These tests revealed that center-positioned coupons frequently failed, and corner-positioned prints were occasionally distorted (**Figure 3**). The Form 2’s “heatmap” function, which tracks laser exposure across the resin tank, indicated that the center area had been used disproportionately, reducing tank translucency and affecting print consistency (**Figure 4**). Other contributing factors may have included partial pre-curing of resin and an expired resin cartridge that exceeded its recommended three-month usage period.

After replacing the resin tank and installing a fresh cartridge, printing inconsistencies were eliminated. The final calibration coupon retained dimensions of 24 mm × 24 mm × 2 mm, with an inner circle of 4 mm and an outer circle of 16 mm (**Figure 1**).

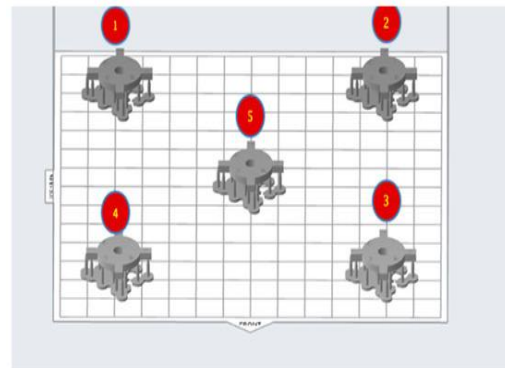


Figure 2. Arrangement of the designed calibration coupons on the 3D printer’s build platform using PreForm software (Formlabs, Somerville, MA, USA). Numbering was added with Microsoft PowerPoint (Microsoft Corporation, Redmond, WA, USA).



Figure 3. Examples of distorted calibration coupons observed during SLA 3D printing. The leftmost coupon exhibits incomplete formation of the top vertical strut, the middle coupon shows overall shape deformation with missing right-side and bottom struts, and the rightmost coupon has incomplete vertical struts on the top and left sides.

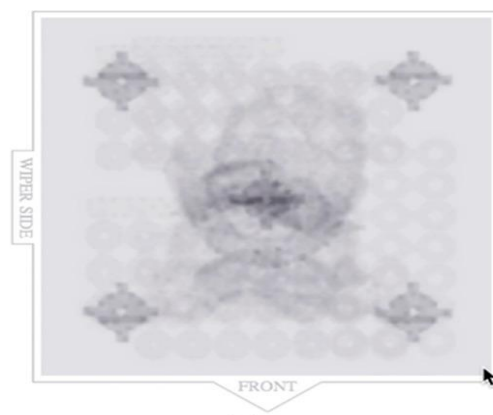


Figure 4. Dashboard heatmap from the 3D printer account (Formlabs, Somerville, MA, USA) indicating previous object placements on the build platform.

To ensure consistent measurement orientation, the coupon was marked using Meshmixer software (Autodesk, San Rafael, CA). The vertical struts were engraved with the letters “X” and “Y,” while the circular portion was labeled with numbers “1” through “4.” These identifiers allowed the coupons to be properly aligned after removal from the platform and enabled measurements to be conducted at specific, predesignated locations (**Figure 5**).

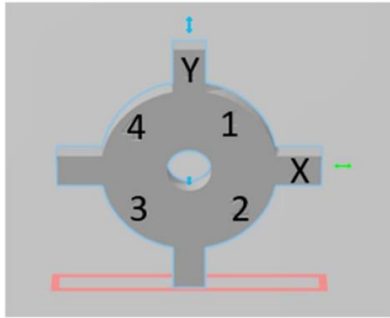


Figure 5. Final design of the calibration coupon showing engraved letters “X” and “Y” and numbers “1” through “4” (Meshmixer software, Autodesk, San Rafael, CA), used to ensure proper orientation and accurate measurement of the coupons.

Coupon placement and printing procedure

For the study, two Form 2 SLA 3D printers (Formlabs, Somerville, MA, USA) were loaded with dental resins commonly used in clinical applications: Dental SG for surgical guides and Grey V4 for dental models.

To investigate whether print accuracy varied with location on the build platform, coupons were positioned at the four corners and the center. Since the Form 2 printer utilizes a 405 nm laser mounted in one corner, the distance from the laser may affect print outcomes due to changes in intensity and potential beam refraction. Coupons were oriented horizontally and supported with small rafts to prevent defects during printing (**Figure 2**). Printing was performed at a layer resolution of 50 micrometers for both resins.

Each printer completed ten successive printing runs, producing five coupons per run, resulting in a total of 100 coupons (50 per resin type). After printing, coupons were cleaned in 99% isopropyl alcohol—10 minutes for Grey V4 and 20 minutes for Dental SG—and allowed to dry. Support structures were then removed prior to measurement (**Figures 6 and 7**).

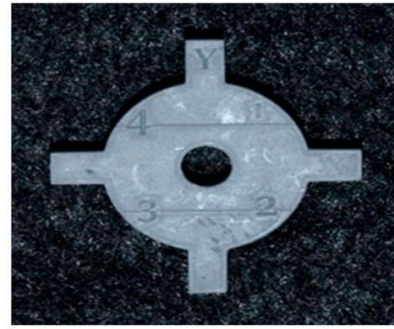


Figure 6. Completed calibration coupon printed using Grey V4 resin for dental models (Formlabs, Somerville, MA, USA).



Figure 7. Completed calibration coupon printed using Dental SG resin for surgical guides (Formlabs, Somerville, MA, USA).

Coupon measurement

Measurements were taken along the X and Y axes using digital calipers with precision to two decimal places (**Table 2**). For X-axis measurements, the caliper’s lower jaws were positioned between the vertical struts, with one jaw touching the strut marked “X” and the other aligned with the opposing strut. Y-axis measurements were taken similarly, with the jaws spanning from the strut labeled “Y” to its opposite strut (**Figure 8**).

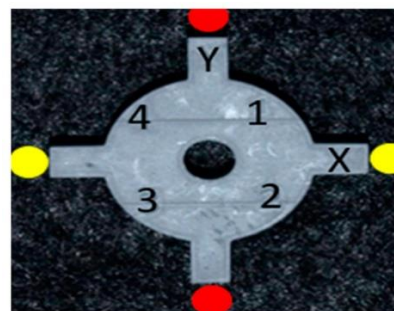


Figure 8. Illustration showing the positioning of the digital caliper jaws for measurement. Red dots indicate the placement for Y-axis measurements, while yellow dots indicate the placement for X-axis measurements.

Table 2. X–Y axes measurements of the coupons printed in two resins (Dental SG and Grey V4, Formlabs, Somerville, MA, USA) at five different positions on the platform.

Printing Cycle	Position on the Platform	Dental SG Resin		Grey V4 Resin	
		X-Axis (In Millimeters)	Y-Axis (In Millimeters)	X-Axis (In Millimeters)	Y-Axis (In Millimeters)
1	1	23.64	23.68	23.82	23.84
	2	23.66	23.61	23.8	23.81
	3	23.72	23.69	23.79	23.78
	4	23.69	23.7	23.81	23.77
	5	23.67	23.65	23.81	23.82
2	1	23.63	23.62	23.81	23.79
	2	23.63	23.63	23.81	23.76
	3	23.66	23.72	23.78	23.78
	4	23.64	23.76	23.77	23.72
	5	23.62	23.64	23.78	23.82
3	1	23.5	23.53	23.82	23.77
	2	23.54	23.57	23.81	23.84
	3	23.59	23.68	23.77	23.77
	4	23.6	23.62	23.79	23.79
	5	23.63	23.57	23.85	23.84
4	1	23.66	23.65	23.76	23.77
	2	23.65	23.65	23.77	23.75
	3	23.65	23.69	23.75	23.74
	4	23.66	23.7	23.74	23.77
	5	23.64	23.56	23.78	23.73
5	1	23.54	23.58	23.8	23.83
	2	23.5	23.61	23.85	23.8
	3	23.6	23.71	23.82	23.79
	4	23.61	23.59	23.79	23.84
	5	23.53	23.57	23.83	23.84
6	1	23.72	23.71	23.86	23.87
	2	23.77	23.7	23.87	23.88
	3	23.74	23.84	23.83	23.85
	4	23.7	23.78	23.81	23.84
	5	23.71	23.69	23.85	23.9
7	1	23.67	23.63	23.84	23.84
	2	23.68	23.68	23.81	23.88
	3	23.68	23.77	23.81	23.82
	4	23.67	23.73	23.86	23.81
	5	23.69	23.66	23.9	23.9
8	1	23.61	23.64	23.86	23.84
	2	23.64	23.64	23.85	23.86
	3	23.66	23.74	23.85	23.84
	4	23.63	23.73	23.83	23.84
	5	23.6	23.59	23.84	23.88
9	1	23.65	23.65	23.87	23.87
	2	23.67	23.68	23.84	23.9
	3	23.68	23.78	23.86	23.83
	4	23.68	23.74	23.86	23.86
	5	23.68	23.67	23.84	23.9
10	1	23.65	23.69	23.85	23.78
	2	23.68	23.67	23.84	23.81
	3	23.72	23.75	23.75	23.73

4	23.66	23.7	23.8	23.77
5	23.68	23.65	23.79	23.81

Statistical analyses

After collecting data from ten printing cycles, X- and Y-axis measurements for both resins were entered into SPSS version 28.0. Rather than directly comparing variances between Grey V4 and Dental SG resins, the analysis focused on differences across the five positions on the build platform for each axis. Specifically, the X-axis measurement of a coupon printed with Dental SG at position 1 was compared with the X-axis measurement of a Grey V4 coupon at the same position. This comparison was repeated for all positions along the X-axis, and corresponding analyses were performed for the Y-axis.

To evaluate differences in variance between the two resins (Dental SG and Grey V4) along both axes,

Levene's test for equality of variances was applied with a significance threshold of 5%.

Results and Discussion

Table 2 summarizes the X- and Y-axis measurements for coupons printed with both resins across the five platform positions. The data indicate that Grey V4 coupons were generally closer to the intended dimensions (24×24 mm) compared with Dental SG. For Grey V4 resin, the mean X-axis measurements across positions 1 through 5 ranged from 23.81 to 23.82 mm, while the mean Y-axis measurements ranged from 23.80 to 23.85 mm (**Table 3**).

Table 3. Descriptive statistics of positions for Dental SG and Grey V4 resins at.

Resin Material	Dimension	Position	N	Min	Max	Mean	Median	SD
Grey V4	X	1	10	23.76	23.87	23.83	23.83	0.034
		2	10	23.77	23.87	23.83	23.83	0.032
		3	10	23.75	23.86	23.81	23.81	0.039
		4	10	23.74	23.86	23.81	23.81	0.039
		5	10	23.78	23.90	23.83	23.84	0.036
	Y	1	10	23.77	23.87	23.83	23.84	0.032
		2	10	23.75	23.90	23.83	23.84	0.051
		3	10	23.74	23.85	23.80	23.80	0.035
		4	10	23.72	23.86	23.80	23.81	0.043
		5	10	23.73	23.90	23.85	23.81	0.043
Dental SG	X	1	10	23.50	23.72	23.63	23.64	0.064
		2	10	23.50	23.77	23.64	23.66	0.075
		3	10	23.74	23.59	23.67	23.67	0.049
		4	10	23.60	23.70	23.65	23.66	0.033
		5	10	23.53	23.71	23.64	23.66	0.055
	Y	1	10	23.53	23.71	23.64	23.64	0.053
		2	10	23.57	23.70	23.64	23.64	0.040
		3	10	23.68	23.84	23.74	23.73	0.050
		4	10	23.59	23.78	23.69	23.70	0.061
		5	10	23.56	23.69	23.62	23.62	0.048

For the Dental SG resin (Formlabs, Somerville, MA, USA), the average X-axis measurements at positions 1 through 5 ranged from 23.63 to 23.67 mm, while Y-axis values varied between 23.62 and 23.69 mm (**Table 3**).

Resin material comparison

Table 3 presents descriptive statistics for all five positions along both axes. Levene's test results exceeded the 0.05 significance threshold, indicating

that the variability of measurements did not differ significantly between Dental SG and Grey V4 resins for either the X or Y axes ($p > 0.05$).

Effect of build platform position

Analysis across the five platform positions showed no meaningful differences in variance for either resin type. The p-values from Levene's test were greater than 0.05, suggesting that coupon location on the build platform had no statistically significant impact on

measurement consistency along the X or Y axes for both Dental SG and Grey V4 resins (**Tables 4 and 5**).

Table 4. Significance of Levene’s test when comparing different positions on the build platform at the X-axis according to the p-value.

Position on the Build Platform	p-Value
1	0.197
2	0.167
3	0.592
4	0.097
5	0.167

Table 5. Significance of Levene’s test when comparing different positions on the build platform at the Y-axis according to the p-value.

Position on the Build Platform	p-Value
1	0.289
2	0.348
3	0.348
4	0.278
5	0.732

Discussion

The adoption of digital technologies in dentistry continues to grow, with a shift from traditional subtractive methods toward additive manufacturing [22]. This trend has increased the prevalence of desktop 3D printers, making monitoring their performance and output quality increasingly important. Many manufacturers emphasize printer resolution as a selling point; however, a higher resolution does not automatically equate to accurate prints. Understanding key concepts such as accuracy, precision, trueness, and tolerance is essential [23]. Precision refers to the consistency among repeated measurements [23, 24], whereas trueness describes how closely the average of multiple measurements aligns with a known reference value [23]. Tolerance defines the acceptable range of deviation, which varies depending on the application [25]. For instance, surgical guides demand stricter tolerances than dental models to achieve clinically acceptable outcomes. A printer may operate within a project’s tolerance but still lack precision, or conversely, it may be precise yet produce parts that do not accurately reflect the reference model. Factors affecting errors include the choice of printing technology, material properties, postprocessing, and the printer’s calibration [24].

Evaluating accuracy has become particularly important for the production of surgical guides. Comparisons of different additive technologies, including PolyJet, SLA, and DLP, have shown that PolyJet often achieves the lowest 3D deviations at the implant entry point and apex, with statistically significant differences between

PolyJet and DLP but not between PolyJet and SLA. DLP, however, offers faster printing times. Other studies have reported no significant differences across technologies [26-28].

In this study, a calibration coupon with defined dimensions was created to measure X and Y axis variances, with a tolerance set at ± 0.1 mm, considered clinically acceptable [29]. The coupon was placed at five positions on the build platform, and pre-cure measurements were obtained to evaluate whether distance from the printer’s laser affected accuracy.

Results indicated no significant differences due to coupon placement or between the two resin types. Nonetheless, when analyzing individual cycles, Dental SG resin (Formlabs, Somerville, MA, USA) exhibited slightly larger deviations from the intended dimensions—up to 0.5 mm—compared with Grey V4 resin, which showed deviations up to 0.26 mm (**Table 2**). Both materials showed limited precision, suggesting that material properties can influence print accuracy, though these differences were not statistically significant in this study. Resins with lower elastic modulus are more prone to dimensional changes before curing. Dental SG resin, recently discontinued and replaced by a higher-modulus Surgical Guide Resin (>2400 MPa versus ~1500 MPa for Dental SG) [30], is more susceptible to deformation than Grey V4 resin, which has a flexural modulus of 2.2 GPa [31]. The position of the coupon relative to the mounted laser did not significantly affect accuracy, implying that the coupon can be placed in any of the five tested positions, though confirmation with a larger sample size is recommended. Overall, the null hypotheses could not be rejected.

The calibration coupon proved useful in assessing the printer’s overall performance. During initial test prints on an SLA printer with an overused resin tank, coupons were visibly deformed, and some failed entirely after multiple attempts. This highlights the importance of following manufacturer guidelines for printer maintenance, including timely replacement of resin tanks and cartridges. Strategically positioning parts across the platform can extend the tank’s lifespan and enhance print quality. Proper postprocessing, in accordance with material-specific instructions, also plays a crucial role in ensuring the accuracy and mechanical integrity of printed objects. Adhering to these recommendations generally minimizes observable printing errors.

In dental research, there is a notable lack of studies focused on the calibration of 3D printers, despite the growing adoption of additive manufacturing in clinical practice. Currently, most dental professionals rely on the “autocalibration” feature of their printers; however,

implementing a standardized calibration protocol is crucial to detect and address any inconsistencies or inaccuracies in the printing process efficiently. The calibration coupon developed in this study provides a practical tool for evaluating printer performance. Optimal printer performance can first be ensured by adhering to the manufacturer's maintenance recommendations. If discrepancies in accuracy persist, technical support may be engaged, potentially involving manual recalibration. Regular monitoring of printer calibration ultimately contributes to delivering high-quality dental care.

This study has some limitations, including a relatively small sample size and potential human error in taking measurements with digital calipers. Additionally, the study focused only on X- and Y-axis variances; future research should include assessments of curvature deviations, which are particularly relevant for dental applications such as guide sleeve holes in implant surgical guides.

For future investigations, machined quick-check GO/NO-GO calibration gauges could be developed. These gauges, commonly used in engineering, allow rapid verification of whether printed parts fall within specified tolerances. The test involves two checks: a "GO" measurement, which the part must fit, and a "NO-GO" measurement, which the part must not fit. For example, for a coupon with a ± 0.1 mm tolerance on X–Y axes, the gauge would have a GO end at 24.1 mm and a NO-GO end at 23.89 mm. A coupon that fits the GO end but not the NO-GO end would meet the tolerance requirements (**Figure 9**). This approach could also be applied to assess curvature deviations. Such gauges would simplify quality checks for dental staff and offer a reliable alternative to digital calipers. Further studies could explore post-curing dimensional changes to identify potential shrinkage during the curing process. Examining longer intervals between printing cycles could also provide insights into how resin properties change over time once dispensed in the tank. Overall, there are multiple avenues for extending this work to enhance the accuracy and reliability of in-office 3D printing in dentistry.

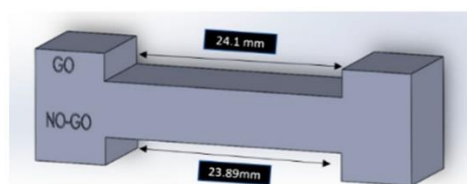


Figure 9. GO-NO calibration gauge created for X–Y measurement of the coupon, with the GO end featuring a 24.1 mm opening and the NO-GO end a 23.89 mm opening.

Conclusion

The success of 3D printing is influenced by multiple factors. Since most in-office 3D printers lack manual calibration options, user control is limited; nevertheless, adhering to manufacturer guidelines is essential for achieving high-quality prints. Key practices include timely replacement of the resin tank and cartridge, following material-specific postprocessing instructions, and, if available, consulting the heat map to optimally position parts to prevent excessive wear on certain areas, as overuse can negatively impact print quality, which was evident in this study.

Maintaining quality control is critical for accurate printing, yet it remains insufficient in medical- and dental-grade printers. The coupon developed in this study serves as a tool to evaluate print accuracy. Results indicated no significant difference in coupon placement across the platform, meaning it can be positioned in any of the five tested locations alongside the object or printed independently. If a coupon falls outside the tolerance range, it is important first to verify whether all manufacturer-recommended procedures for printing and postprocessing were followed; any deviations should be corrected and the print repeated. Persistent issues may require contacting the printer manufacturer to address technical problems or perform recalibration.

In this study, deviations in trueness and precision for one resin (Dental SG, Formlabs, Somerville, MA, USA) were likely due to intrinsic material properties, particularly the flexural modulus, highlighting the importance of selecting materials suited to the specific project. Establishing a standardized calibration protocol for in-office 3D printers would support clinicians in delivering high-quality treatment. Future research should explore the coupon's applicability across different 3D printer models and a wider range of resin materials.

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Ethics Statement: None

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