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Post-curing protocols and dimensional accuracy of 3D-printed resin materials

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ABSTRACT

Purpose: The study aims to evaluate the influence of various post-curing times and temperatures on the dimensional accuracy of 3D-printed resin space maintainers.

Materials and Methods: Using biocompatible printing resins, the study designed band samples of space maintainers, which were 3D printed with the SLA printer. Samples were grouped based on thickness (0.5 mm and 1.0 mm) and post-cured under different conditions of temperature and time (60°C-30 minutes, 60°C-90 minutes, 60°C-120 minutes, 60°C-60 minutes, 40°C-60 minutes, 80°C-60 minutes). The accuracy of the band part of the printed maintainers was analysed using the total and 4 comparison points' arithmetic mean of the surface deviation on the band's surface.

Results: The study revealed that the post-curing conditions notably influenced the dimensional accuracy of the printed samples. Post-curing temperature and duration variations produced significant differences in dimensional stability between the groups. Particularly, a post-curing period of 60°C for 60 minutes was identified as optimal for achieving better dimensional accuracy, especially for samples with 1.0 mm thickness.

Conclusions: Different post-curing parameters significantly affect the dimensional accuracy of 3D-printed resin space maintainers. The 1.0 mm band thickness and a 60°C and 60 minutes post-curing protocol optimize the accuracy of the maintainers.

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3D printing; accuracy; post-curing polymerization

Introduction

The preventive approaches to maintain children's oral health and the attempts to create caries-free generations have been widely popular. However, despite worldwide efforts, early loss of deciduous teeth still presents a problem. Accordingly, the early loss of a primary tooth may lead to various dental, skeletal, and functional problems and the extraction space should be preserved to prevent crowding and maintain the space for the permanent successor. In this regard, fixed and removable space maintainers have been performed in dental practices [1]. Nowadays, digital dentistry has taken the place of the time-lasting conventional procedures in which dental laboratories are also involved. Recently, 3-dimensional (3D) printing as a part of the digital dentistry workflow has been used widely in various areas of dentistry, including prosthodontics, surgical treatments, and orthodontics [2–4]. 3D printing could be used in paediatric dentistry for various treatment modalities and designing -producing a space maintainer is among them [5]. Since that date, metal powder has been used to manufacture 3D-printed space maintainers, and the endurance of metal alloys under occlusal forces has been proven by various studies and clinical applications [6]. However, considering the needs of patients with metal allergies and those with high aesthetic expectations, the need for an alternative to metal-based space maintainers in 3D applications has come to the fore [7–9].

Among the other mechanical and physical features, dimensional accuracy plays a great part in the clinical success of printed materials. In case the accuracy of the system was not settled, differences may be detected between the design and printed form of the product. Post-curing, being a post-printing procedure, also has a distinct effect on the conversion of the unreacted resin monomers through polymer chains. The duration of UV light exposure and the polymerization temperature can affect the physical features of the products, and the accuracy of the printed sample can also be affected by the possible changes in the temperature and duration of the UV light exposure [10,11]. Accordingly, the dimensions and the final thickness of the printed object may also affect the dimensional accuracy.

Dealing with a paediatric patient requires managing the treatment steps in one attempt and It is a vulnerable attempt to print a resin-based space maintainer in

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clinical conditions and adapt it into the patients mouth in only one session. As mentioned above, there are various factors affecting the success of this treatment procedure and adaptation of the printed sample into the scanned dental arch also takes great importance in that concept. A possible inconsistency may extend the chair time or lead to the reproducing of the space maintainers which also cause an extension in the session or perhaps an extra session [12]. Post printing procedures take a great part in the accuracy of the printed samples. The variations in the duration and the temperature as well as the dimensions of the printed samples are considered to affect the adaptation procedures of the printed fixed space maintainer. To the best of our knowledge, in the literature review, no study was detected assessing the effect of the variations in the post-curing procedures including duration and temperature and the dimensions of the band part of the fixed space maintainers. In light of the aforementioned data, the current study aimed to fill that gap in the literature by (1) comparing the accuracy of the band part of fixed space maintainers in case different post-curing durations and temperatures were recruited and (2) evaluating the effect of the band thickness on the accuracy of the printed samples. The null hypothesizes that the variation in the post-curing duration, temperature, and band thickness may not have a certain effect on the accuracy of the printed products.

Materials and methods

Humans or the data obtained from human participants were not recruited in the current study and accordingly, no ethical approval was provided.

Sample size determination

The study sample was determined with the aid of G*Power software (version 3.1). The values for each group were set at 15 to achieve > 95% power with an effect size of 0.20 and an alpha significance level of 5% (0.05). Thus, a total of 180 samples were planned to be used. The flow chart of the study can be seen in Figure 1.

Study groups and 3D printing process

Autodesk Fusion 360 (CA, USA) software was used to design the band samples representing the band part of space maintainers (Mesiodistal diameter: 10.7 mm, buccolingual diameter: 11.1 mm, and 4.00 mm height), and the data were converted to STL format for printing. The SLA printer (Form 3B, Formlabs, Somerville, MA, USA) was utilized to produce the samples ($n = 90$, for each group) with biocompatible printing resins (BioMed Clear Resin, Formlabs, Somerville, MA, USA). The printer was set in the horizontal/XY direction, and the resolution size can range from 30–140 microns. Also, the 100 µm layer thickness was arranged for printing. Following the printing process, the supports were removed by the application of manual force. The samples were immersed in the Form Wash tank (Formlabs, Somerville, MA, USA) for 20 minutes and the samples were divided into groups randomly regarding different post-curing temperatures and times. All post-curing procedures were performed in the Form Cure tank (Formlabs, Somerville, MA, USA). The recommended post-curing condition by the manufacturers was 60°C for 60 min and the arrangements on the post-curing conditions were performed regarding these values which means that the post-curing conditions in the groups were formed by enhancing and decreasing the related values. The groups are shown below:

Group A

The band samples with a 0.5 mm thickness ($n = 15$, total = 90) with post-curing at 60°C for 30 minutes (min), 60°C for 90 min, 60°C for 120 min, 60°C for 60 min, 40°C for 60 min, and 80°C for 60 min.

Group B

The band samples with a 1.0 mm thickness ($n = 15$, total = 90) with post-curing at 60°C for 30 minutes (min), 60°C for 90 min, 60°C for 120 min, 60°C for 60 min, 40°C for 60 min, and 80°C for 60 min.

The samples were printed and post-cured, and then, to get rid of polymerization residues, they were submerged in isopropyl alcohol in an ultrasonic cleaner (Sonorex Super, Bandelin Electronic, Berlin, Germany) for ten minutes.

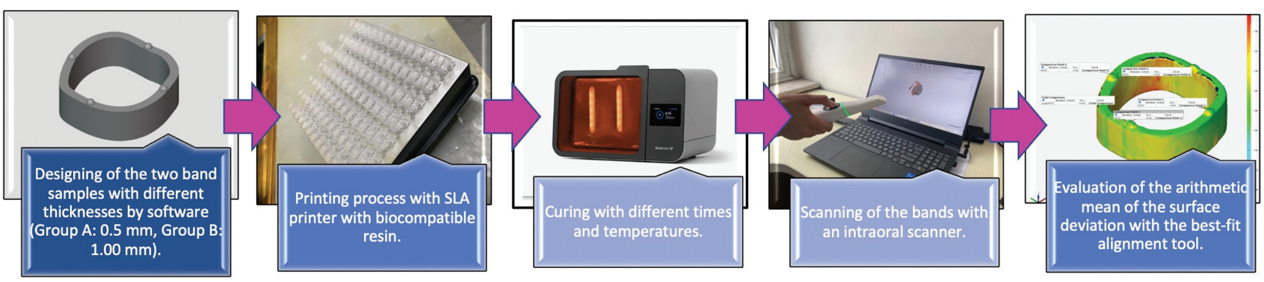

Figure 1. The flowchart of the study.

Comparison points

To evaluate the accuracy of the printed band with different thicknesses, researchers recorded the total and four comparison points' arithmetic mean of the surface deviation (Total Comparison, Comparison Point 1, Comparison Point 2, Comparison Point 3, and Comparison Point 4, Figure 2) of the band in the GOM Inspect Professional software (GOM 2018, Braunschweig, Germany). The process involved importing the scanned mesh model of the printed band and the original CAD design, then aligning them through a two-step process: initial pre-alignment followed by a comprehensive local best-fit alignment to achieve optimal positioning. Surface comparison analysis was performed using the 'Surface comparison on CAD' function to determine the total difference between surfaces and at four strategically placed points on the designed model. These four points correspond to critical areas where orthodontic space maintainer bands typically contact tooth surfaces, directly affecting clinical fit and retention. Colour difference maps defined the comparison points. For the comparison, the deviation value, also referred to as the tolerance range, between +0.25 mm and −0.25 mm, was visualized on the colour scale. To ensure reliability, a single inspector repeated all measurements three times under standardized conditions on identical surfaces.

Statistical analyses

The data were recorded using Microsoft Office Excel, and the statistical analyses were performed using the open-source statistical analysis program Jamovi (The Jamovi Project 2022, ver. 2.3.21.0, www.jamovi.org). The data did not exhibit a normal distribution, based on the Shapiro-Wilk normality test results. The Kruskal-Wallis test was performed to compare the variations between the values. Furthermore, a post hoc comparison between groups was conducted using the Mann-Whitney U test. A threshold of $p < 0.05$. was established for statistical significance.

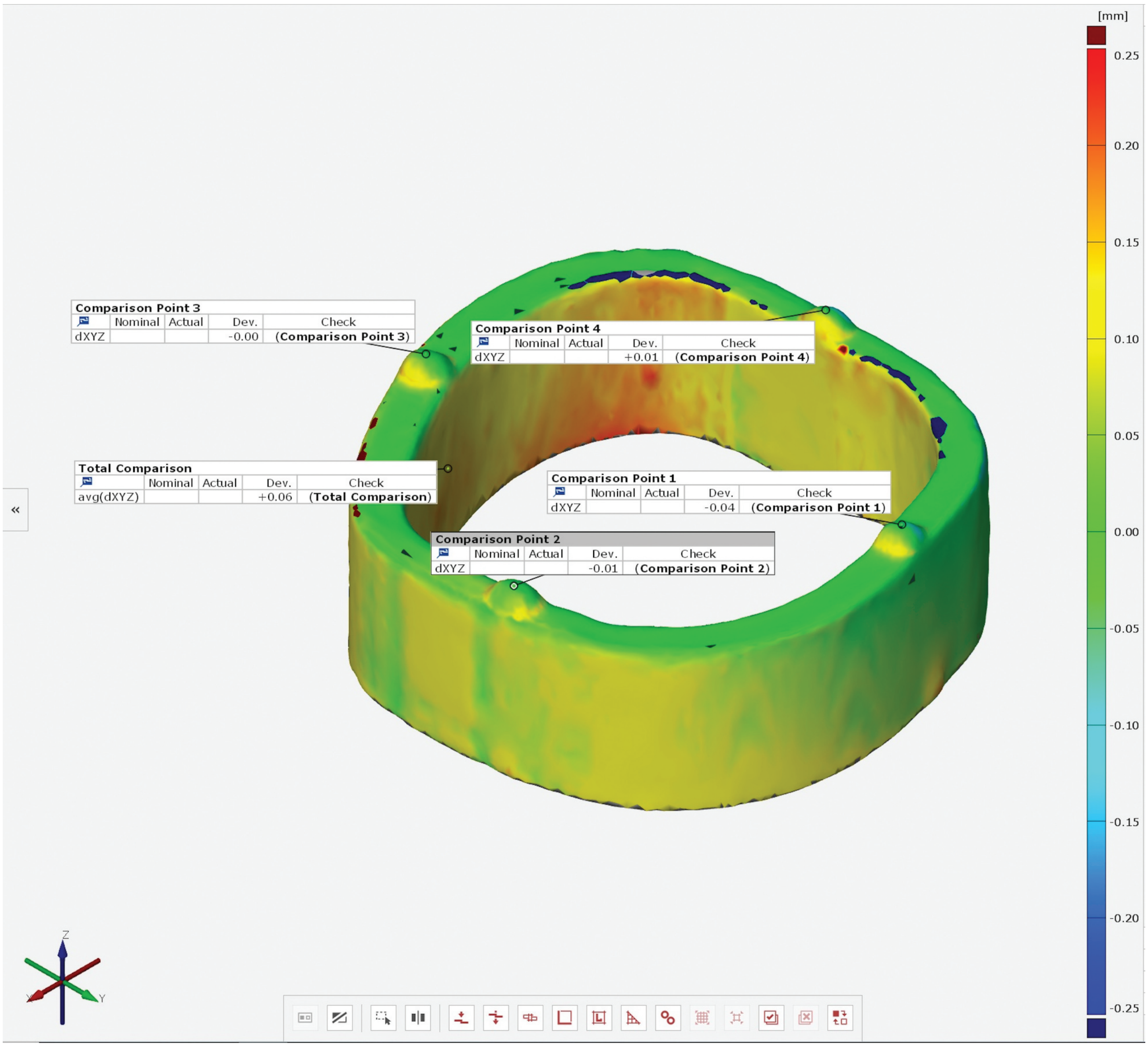

Figure 2. Representation of the comparison point on band samples of space maintainers.

Results

In present study, to evaluate the measurements' reliability, the measurements were repeated three times by the same operatör (Y.S) and the data obtained were analysed by intraclass correlation coefficient (ICC). The ICC value obtained was 0.980–0.997, indicating that the tests were reliable and the measurements had a high level of repeatability.

The descriptive statistics and post hoc comparisons of the total comparison points of Group A and Group B can be seen in Table 1. Accordingly, in the same thicknesses (intragroup comparisons) no statistical difference was detected between different post-curing conditions. Statistically significant differences were detected between the groups of 60°C – 90 min, 60°C – 60 min, and 40°C – 60 min (Intergroup comparisons) ($p = 0.027$, $p = 0.031$, $p = 0.044$) However, no statistical difference was detected between different post curing periods in intragroup comparisons. In the 60°C – 60 min post-curing period, which is the recommended condition by manufacturers, dimensional accuracy was detected to be better in Group B.

In Table 2, the values of point 1 can be seen. Accordingly, statistically significant differences were detected between the values of post-curing periods 60°C –90 min, 60°C –120 min, and 40°C – 60 min for Group A and Group B ($p = 0.014$, $p = 0.001$, $p = 0.004$; respectively). In groups of 60°C –60 min, although no statistical difference was detected between the values of Group A and Group B ($p = 0.438$), the dimensional accuracy was worse in Group B. In the intra-group comparisons, no difference was detected in all post-curing periods ($p > 0.05$).

In Table 3, statistical difference was detected at 60°C –60 min ($p = 0.016$). The dimensional accuracy of Group B was better than Group A. In Group B, intra-group comparisons statistical difference was detected between different post-curing periods ($p = 0.011$). The most dimensional deviation was detected in the post-curing period of 60°C – 90 min in Group B. The less dimensional deviation was detected at 80°C –60 min.

Table 1. Descriptive statistics and post-hoc comparisons of the total comparison values of groups A and B.

	Group A		Group B		
Post-curing Periods	Median	25%-75%	Median	25%-75%	P
60°C- 30 min	0.07	0.07–0.08	0.08	0.065–0.085	0.781
60°C- 90 min	0.08	0.075–0.095	0.07	0.06–0.08	0.027*
60°C- 120 min	0.09	0.075–0.1	0.08	0.065–0.085	0.114
60°C- 60 min	0.09	0.075–0.1	0.07	0.07–0.08	0.031*
40°C- 60 min	0.09	0.08–0.1	0.08	0.075–0.09	0.044*
80°C- 60 min	0.09	0.08–0.09	0.09	0.08–0.09	0.116
P	0.137		0.053		

Group A: 0.5 mm thickness, Group B: 1.00 mm thickness, min: Minute, SD: Standard deviation, Min: Minimum, Max: Maximum, 25%: 25 percentile, 75%: 75 percentile. *There is a statistically significant difference at $p < .05$. Different letters show statistical differences.

Table 2. Descriptive statistics and post-hoc comparisons of the point 1 values of groups A and B.

	Group A		Group B		
Post-curing Periods	Median	25%-75%	Median	25%-75%	P
60°C- 30 min	0.04	0.025–0.045	0.05	0.015–0.065	0.573
60°C- 90 min	0.02	0.01–0.035	0.06	0.025–0.075	0.014*
60°C- 120 min	0.02	0.01–0.035	0.05	0.03–0.095	0.001*
60°C- 60 min	0.03	0.01–0.045	0.03	0.015–0.05	0.438
40°C- 60 min	0.03	0.015–0.04	0.06	0.04–0.08	0.004*
80°C- 60 min	0.03	0.02–0.045	0.02	0.01–0.06	0.834
P	0.488		0.087		

Group A: 0.5 mm thickness, Group B: 1.00 mm thickness, min: Minute, SD: Standard deviation, Min: Minimum, Max: Maximum, 25%: 25 percentile, 75%: 75 percentile. *There is a statistically significant difference at $p < .05$. Different letters show statistical differences.

Table 3. Descriptive statistics and post-hoc comparisons of the point 2 values of groups A and B.

	Group A		Group B		
Post-curing Periods	Median	25%-75%	Median	25%-75%	P
60°C- 30 min	0.04	0.02–0.05	0.02^{ab}	0.01–0.045	0.357
60°C- 90 min	0.03	0.01–0.05	0.06^{a}	0.03–0.075	0.057
60°C- 120 min	0.02	0.015–0.04	0.03^{ab}	0.01–0.04	0.801
60°C- 60 min	0.04	0.03–0.05	0.02^{ab}	0.01–0.03	0.016*
40°C- 60 min	0.02	0.015–0.035	0.03^{ab}	0.015–0.035	0.816
80°C- 60 min	0.02	0.01–0.04	0.01^{b}	0.01–0.02	0.140
P	0.159		0.011*		

Group A: 0.5 mm thickness, Group B: 1.00 mm thickness, min: Minute, SD: Standard deviation, Min: Minimum, Max: Maximum, 25%: 25 percentile, 75%: 75 percentile. *There is a statistically significant difference at $p < .05$. Different letters show statistical differences.

Table 4. Descriptive statistics and post-hoc comparisons of the point 3 values of groups A and B.

	Group A		Group B		
Post-curing Periods	Median	25%-75%	Median	25%-75%	P
60°C- 30 min	0.05[a]	0.025–0.06	0.04[cd]	0.02–0.065	0.645
60°C- 90 min	0.02[ab]	0.005–0.03	0.06[c]	0.04–0.085	<0.001*
60°C- 120 min	0.02[b]	0.01–0.03	0.06[c]	0.035–0.09	0.005*
60°C- 60 min	0.03[ab]	0.03–0.05	0.03[cd]	0.015–0.065	0.660
40°C- 60 min	0.02[ab]	0.02–0.035	0.04[cd]	0.015–0.055	0.396
80°C- 60 min	0.03[ab]	0.005–0.045	0.02[d]	0.01–0.02	0.310
P	0.005*		0.005*		

Group A: 0.5 mm thickness, Group B: 1.00 mm thickness, min: Minute, SD: Standard deviation, Min: Minimum, Max: Maximum, 25%: 25 percentile, 75%: 75 percentile. *There is a statistically significant difference at $p < .05$. Different letters show statistical differences.

Table 5. Descriptive statistics and post-hoc comparisons of the point 4 values of groups A and B.

	Group A		Group B		
Post-curing Periods	Median	25%-75%	Median	25%-75%	P
60°C- 30 min	0.03	0.01–0.035	0.03	0.01–0.04	0.769
60°C- 90 min	0.02	0.01–0.04	0.03	0.01–0.04	0.526
60°C- 120 min	0.03	0.02–0.045	0.03	0.015–0.04	0.801
60°C- 60 min	0.03	0.015–0.04	0.02	0.02–0.06	0.555
40°C- 60 min	0.01	0.01–0.04	0.03	0.015–0.04	0.217
80°C- 60 min	0.02	0.015–0.05	0.02	0.01–0.02	0.100
P	0.487		0.596		

Group A: 0.5 mm thickness, Group B: 1.00 mm thickness, min: Minute, SD: Standard deviation, Min: Minimum, Max: Maximum, 25%: 25 percentile, 75%: 75 percentile. *There is a statistically significant difference at $p < .05$. Different letters show statistical differences.

In Table 4, the values of point 3 can be seen. In the post-curing periods of 60°C −90 min and 60°C −120 min statistical difference was detected ($p <$ 0.001, $p = 0.005$). For 60°C −60 min, although there was no statistical difference, the values of Group were worse than Group A ($p > 0.05$). Statistical differences were detected in intra-group comparisons both in Group A and Group B ($p = 0.005$). Regarding the results pointed out in Table 5, no statistical difference was detected in intra and inter-group comparisons ($p > 0.05$).

Discussion

Dimensional accuracy is one of the most important features of a printed product, where the extensions in the sessions to adjust the printed sample to the supported teeth or an additional session for reproducing the space maintainer may be a major problem. Although there has been a recommended post-curing condition for the studied SLA resin, these values can reveal variations considering the shape of the printed object, and the post-curing conditions for a printed sample in a ring form with space inside were not studied previously. The results of the current study revealed that the analysed parameters, post-curing times, and temperatures affected the accuracy of the printed samples. Producing a resin space maintainer with a 3D printer was previously discussed, and the printed samples were analysed regarding the fracture strength, colour stability, and microhardness values [8,9].

The results of the current study revealed that in the same thicknesses (intragroup comparisons) no statistical difference was detected between different post-curing conditions regarding the total superimposition values. This indicates the importance of the thickness of the design studied, rather than the post curing duration and temperature, which means choosing an accurate thickness for the personalized design is essential in clinical protocols. Group A revealed better results regarding dimensional accuracy for Point 1 and Point 3, however, in the assessment of Point 2, Group B was superior to Group A. These results indicated that although the total superimposition values were constant in the same thicknesses, the assessments of different points revealed various results. Additionally, being geometrically symmetrical, Point 2 and Point 4 revealed different results which can be attributed to the printing orientation. In the literature review, a 0.20 to 0.50 mm has been considered acceptable for clinical applications [13,14]. The highest total dimensional change (0.0893 ± 0.0105) was detected in the group of 0.5 mm thickness and the post-curing conditions with 80°C- 60 min. This value was less than the clinically acceptable values, which indicates that all the tested times and temperatures were clinically suitable for the post-curing procedures of 3D-printed samples. The results also revealed that no contraction was detected in the printed band samples and the total superimposition values revealed no statistical differences. This outcome means that the design of the band part of the space maintainer can be done suitable with the scanned surfaces of the tooth and there is no need to design the product in an extended form considering a possible contraction situation which was not detected in the current study. In accordance with the outcomes of the current study, leaving a place considering the cement interface can be an appropriate approach in the design of the band part of a fixed space maintainer.

Previously, Shahidi et al. [15] conducted a systematic review to assess the accuracy of 3D-printed full-arch dental models and they revealed that manufacturing parameters such as layer thickness, base design, post-processing, and storage significantly influenced the model's accuracy [15]. Abualsaud et al. [16] have assessed the precision and trueness of 3D-printed zirconia crowns. Accordingly, the trueness of the occlusal and axial surfaces revealed better results. These studies emphasized the importance of the variations in the post-curing conditions on the dimensional accuracy of the 3D printed samples and the fact that different surfaces of a printed sample may reveal different dimensional changes parallel with the outcomes of the current study wherein different assessment points revealed various dimensional changes [16].

In a similar study, Mc Carty et al. [17] evaluated the effect of print orientation and UV light curing duration on the dimensional accuracy of a clear aligner. The products post-cured for 20 minutes −80°C and 40 minutes- 80°C. Following post-curing, the samples were digitally scanned and superimposed with the input for 3D deviation analysis. Accordingly, a significantly lower standard deviation was observed in the post-curing group of 40 minutes [17]. In the current study, in the assessments of Point 2, less deviation was detected in the post-curing conditions of 80°C −60 min and the accuracy were decreased when the post-curing time increased to 90 min while the temperature was decreased. When the results of the current study and the previously mentioned study of Mc Carty's were considered together, it can be concluded that at a constant degree of 80°C, the increases in the post-curing time to certain points (40–60 min) may have a positive effect on the dimensional accuracy of the printed samples. However, the duration above these points (90 min) may affect adversely the accuracy of the printed samples.

Silva et al. [18] assessed the effect of post-curing time and type on the flexural and dimensional stability of 3D-printed interim SLA resins. 15, 20, 30 min UV post-curing was conducted in a group while the other group underwent a process of 5, 8, 10 min of microwave post-curing with or without water. Before and after post-curing values (length, width, and thickness) were measured to assess the dimensional stability, and microwaves with water and UV revealed similar results. UV-15 min group showed the greatest variations in its dimensions, and 30 min revealed the most acceptable results (among the other UV groups).18 In the current study, post-curing for 30 min revealed similar results with post-curing for 60 min, which was the recommended time by the manufacturers, and these outcomes are in line with the previous study's results. Dohyun Kim et al. [19] have conducted a similar study, and they revealed that at least 60 minutes post-curing is essential for providing the mechanical and physical features of 3D printed samples, which conflicts with the outcomes of the current study.

Hyun Kim et al. [10] studied the alterations of the post-curing conditions on the dimensional accuracy of 3D-printed dental restorative materials. DLP samples underwent a post-polymerization process with five different post-polymerization devices. Form cure device revealed the highest shrinkage rate (60 min 80 °C max). The group presented at a constant temperature of 60 °C revealed the highest dimensional change (Form Cure). These results are not consistent with the outcomes of the current study. However, these variations might be attributed to the fact that different post-curing devices were utilized in the previous study and the current study we held, and also, the post-curing time and temperature patterns were different in the current and previous studies.

In the literature review, although various studies were detected assessing the effect of the variations on the layer thickness, to the best of our knowledge, no study was detected analysing the effect of the final thickness of the printed object on the dimensional accuracy of the printed samples [20]. The current study pointed out that the band samples with a 1 mm thickness revealed better dimensional accuracy compared to the samples with a thickness of 0.5 mm. The values of 1 mm and 0.5 mm were detected regarding the band thickness of conventional metal fixed space maintainers, and 1 mm was detected considering the possible difficulties in adjusting the printed band in the interdental space between support teeth and the teeth in the mesial or distal contact. 0.5 mm was decided as the lower thickness to ensure the adequate mechanical strength of the printed resin sample. However, these results were obtained by recruiting one commercial resin (BioMed Clear Resin) and changing the features of 3D- printable resin might have a certain effect on the clinical outcomes of the study. Accordingly, in that regard, a further study assessing the effect of the variations of the printable resins on the analysed features of the 3D printed space maintainers seems to have great importance. Moreover, an increase in the clinical studies that assess the accuracy of resin-printed space maintainers is also essential before recommending the use of 3D printers in producing resin space maintainers in paediatric dentistry practices. It should also be taken into consideration that the design of a 3D printed resin space maintainer has a strong effect on both the durability and biofilm-food retention features of the preferred space maintainers. Which points out another aspect of 3D printed resin space maintainers that needed to be discussed prior to fabrication of this kind of maintainers for paediatric patients.

Within the limitations of the current in-vitro study, it can be concluded that:

(1) Although, in the same thicknesses (intra-group comparisons) different superimposition points revealed statistical differences utilizing dimensional accuracy, the changes in the post-curing conditions did not reveal a statistical difference considering the total superimposition values.
(2) Intergroup comparisons showed that the variations in the thickness revealed statistically significant differences at some post-curing conditions. Employing total superimposition values, at 60°C and 60 min, the group with 1 mm thickness revealed better accuracy compared to the group with 0.5 mm in thickness.
(3) In the conditions and the limitations of the current study, the total superimposition values revealed no statistically significant contraction which pointed out that the design of the band part of the space maintainer can be performed in parallel with the scanned tooth surface data and there is no need to make an extension in the design considering a possible dimensional contraction.

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CRediT: **Merve Aksoy:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing; **Kübra Gülnur Topsakal:** Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing; **Yağızalp Süküt:** Data curation, Formal analysis, Software; **Gökhan Serhat Duran:** Project administration, Supervision, Writing – review & editing.

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The authors did not provide data availability details for this article(s).

Ethical approval

No need for ethical approval.

Informed consent

Not applicable.

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