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열가소성 장치 제작이 3D 프린팅 치아모형의 체적안정성에 미치는 영향

강병민[1], 최성권[2,*]

[1]원광대학교 치과병원 치과교정과
[2]원광대학교 일반대학원 치의학과

Effects of thermoplastic appliance fabrication on the dimensional stability of 3D printed dental models

Byung-Min Kang[1], *Sung-Kwon Choi*[2,*]

[1]*Department of Orthodontics, School of Dentistry, Wonkwang University, Iksan, Repbulic of Korea*
[2]*College of Dentistry, Graduate school of Wonkwang University, Iksan, Republic of Korea*

본 연구의 목적은 열가소성 장치제작이 3D 프린팅된 치아모형의 체적안정성에 미치는 영향을 평가하는 것이다. 두가지 재료를 다양한 밀도[acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA); 20, 40 and 60%]로 프린팅하여 디지털 기준 모형을 만들었다. 프린팅된 모형 상에서 열가소성 장치를 3번 제작 하였으며, 모형은 프린팅된 직 후, 장치제작 1회, 3회 후에 스캔하였다. 프린팅된 모형의 정확도와 체적안정성을 평가하기 위해 치아와 치열궁 측정을 시행하였다. 프린팅된 모형은 재료와 밀도에 관계없이 디지털 기준 모형과 유의한 차이를 보이지 않았다. 한번의 장치 제작 후 PLA모형 계측치의 대부분이 0.05 mm에서 0.24 mm 범위에서 감소된 반면($p<0.05$), ABS 모형의 계측치는 몇몇 수치에서만 감소되었다($p<0.05$). 세번의 장치 제작 후 계측치는 PLA 모형에서 0.04에서 0.42 mm의 범위로 감소하였으며($p<0.05$), ABS 모형에서는 0.08에서 0.27 mm 범위로 감소하였다($p<0.05$). ABS 모형은 상대적으로 더 나은 체적안정성을 보여준 반면, PLA 모델은 한번의 장치제작으로도 유의미한 체적 변화를 보였다. 반복된 장치제작은 프린팅된 모형의 체적 변화를 일으키며, 이는 특히 PLA에서 두드러졌다.

색인단어 : 3D 프린팅, 체적안정성, Fused deposition modeling (FDM), Acrylonitrile butadiene styrene (ABS), Polylactic acid (PLA).

Introduction

3D printers are rapidly spreading in clinical orthodontics (1). Although digital models have advantages of no storage requirement, instant accessibility, no risk of breakage, wear or loss and ability to do digital diagnostic or treatment simulations, physical models are still required to fabricate orthodontic appliances and also preferred by practitioners

Byung-Min Kang (ORCID: 0000-0002-3520-923X)

*Correspondence: Sung-Kwon Choi (ORCID: 0000-0001-9546-9837)
Muwanglo 895, Iksan, Jeonlabookdo 54538, Republic of Korea Affiliation: Department of Orthodontics, Wonkwang University Dental Hospital, Iksan, Jeonlabookdo, Repbulic of Korea
Tel: +82-63-859-2962, Fax: +82-303-3440-2962
E-mail: chsk8814@hanmail.net

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because they are tangible (2, 3). Therefore, the use of 3D printers for printing physical dental models are gradually increasing, replacing conventional plaster models produced from an alginate impression (4).

One of the most popular 3D printing techniques in the marketplace today are fused deposition modeling (FDM) printing due to the low price of printers and printing materials (5). The patent of thermo-fusion technology for 3D printers expired in 2009 and after then, low-cost thermo-fusion 3D printers appeared on the market and were widely distributed (6). With the widespread of FDM 3D printers, orthodontic treatment using thermoplastic appliance has been performed in many local clinics.

Various materials are avaliable for FDM printers, the most important selection criteria for FDM materials are heat transfer characteristics and rheology (7). Materials should have the right flow properties for extrusion from nozzle and fusion of the layer when heated to certain temperature which is as low as used in 3D printers. In this regard, acrylonitrile butadiene styrene (ABS) has been successfully used due to its high strength and thermal stability as well as its good flow properties when heated to about 250℃. As dental models made from ABS are also considered relatively heat-resistant and durable, models used for fabrication of thermoplastic orthodontic appliance are often used to remake the appliance. Currently, there are attempts to replace ABS with polylactic acid (PLA) (8). PLA shows lower strength and thermal resistance than ABS but, it is made from renewable raw materials like corn-starch that it is more biocompatible than ABS. Using PLA materials, there is no odor or smoke that appears when pringting with ABS materials. In addition, dimensional accuracy of PLA is higher than that of ABS due to less polymerization shinkage during building and postcuring (9).

As demands for orthodontic treatment in adult patients have increased, improved esthetic orthodontic appliances are highly desirable. Orthodontic treatment without the brackets and wires was introduced for the first time as early as 1945 by Kesling, who reported the use of a flexible tooth positioning appliance (10). Recently, transparent thermoplastic removable appliances have been introduced using computer aided design (CAD)/computer aided manufacturing (CAM) technology or 3D printing technology combined with laboratory techniques that fabricate a series of customized orthodontic appliances (11). With increasing interest of thermoplastic orthodontic appliance, related studies have also been reported. Kohda et al (12) and Iljima et al (13) examined orthodontic force imparted by thermoplastic orthodontic appliance. The orthodontic force magnitudes produced by the thermoplastic appliances were similar with those of nickel-titanium orthodontic wires that can be enough to move teeth.

There are a few studies about the factors which can be affected on clinical indication of thermoplastic orthodontic appliance. Some studies about the accuracy of intraoral scanners have reported high precision and trueness with possibility of replacement for conventional impression (14-17). Accuracy and reproducibility of 3D printed dental models has also been reported. Hazeveld et al (3) assessed the accuracy and reproducibility of 3D printed models compared with plaster models and concluded that dental models printed by several 3D printing technique were considered clinically acceptable in terms of accuracy and reproducibility. Lee et al (18) evaluated the accuracy of replica teeth printed with FDM and Polyjet printers compared with extracted teeth. They suggested that FDM and Polyjet technologies were accurate enough to be clinically usable. Kim et al (19) investigated precision and trueness of dental models printed with different 3D printing techniques compared with digital reference models. The differences were all within 0.5 mm which were considered clinically acceptable.

However, no study has examined the dimensional changes of 3D printed dental models after fabrication of thermoplastic orthodontic appliances. Therefore, this study was designed to assess the dimensional stability of dental models printed with ABS and PLA after fabrication of thermoplastic orthodontic appliances and dimensional changes according to the repeated fabrication of the appliances. The null hypothesis was that there would be significant dimensional changes in models printed with ABS and PLA after fabrication of thermoplastic appliances and dimensional changes would be significantly increasing with repeated fabrication of the appliances.

Materials and Methods

1. Printing of dental models and fabrication of thermoplastic orthodontic appliance

A reference stereolithography (STL) file of a maxillary arch form was created based on a dental typodont model (D85DP-500B.1, Nissin Dental Prod. Inc., Kyoto, Japan). The dental model was scanned using an intraoral scanner (CS 3600®. Carestream, Rochester, NY, USA). Scanned file was converted to STL file format using a 3D modeling software (Rapidform 2006, INUS Technology, Seoul, Korea). The STL file were cleaned and prepared for 3D printing using Maestro 3D ortho studio (AGE Solutions, Pisa, Italy). Prepared STL file was printed using a FDM 3D printer (CUBICON Style-210D, CUBICON, Seongnam-si, Korea). Printing materials were PLA and ABS. Densities of printed models were 20, 40 and 60%; 20% is minimal and 60% is maximum density setting provided by the printer. The digital reference model was printed 5 times per each material and density. After printing out models, they were all scanned by a model scanner (Freedom HD, DOF Inc, Seoul, Korea).

Thermoplastic orthodontic appliances were fabricated in vacuum former under heat (Ministar S®, Scheu-Dental, Iserlohn, Germany) with 0.75 mm polymer sheets

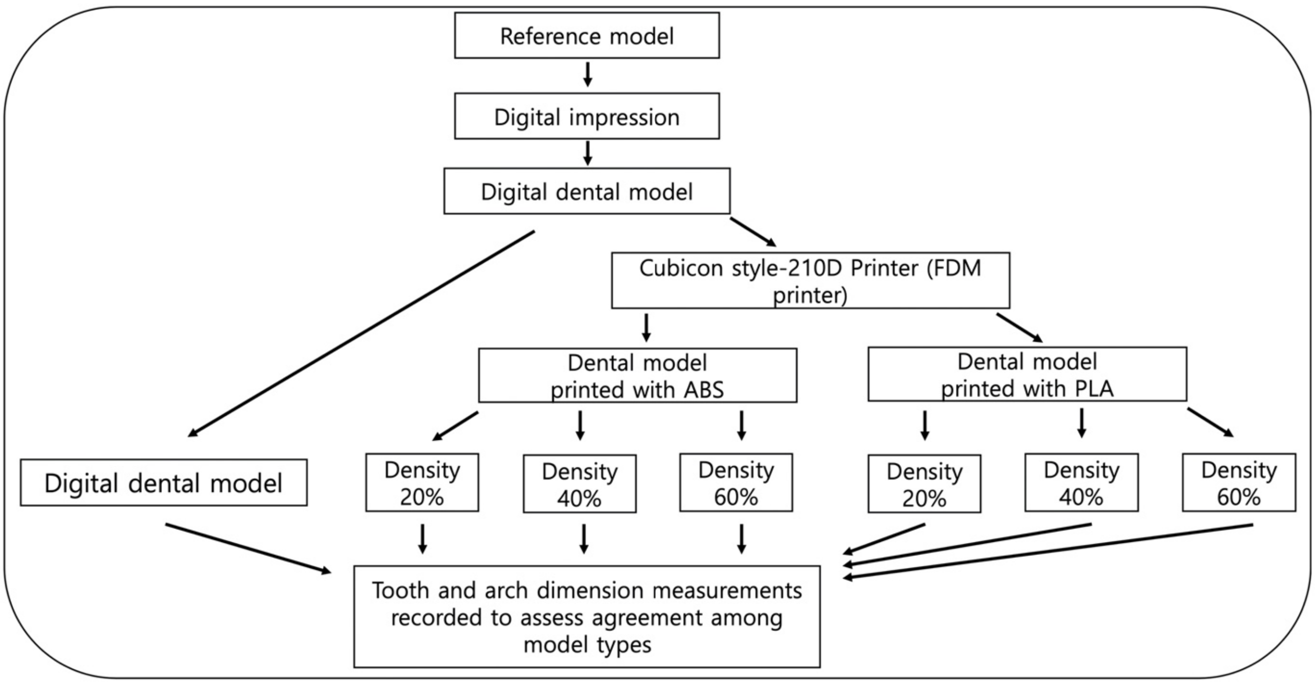

Figure 1. Printing procedures of dental models.

(Duran®, Scheu-Dental, Iserlohn, Germany) following manufacturer's instructions. Models were scanned by same model scanner after print out, one-time and three times of the fabrication. The entire printing procedures of dental models are summarized in Figure 1.

2. Measurements of the dimensional changes

Measurements of 3D printed models were all obtained using Rapidform 2006 software. Prior to the measurements, all scanned dental models were arranged and superimposed with the digital reference model in the program. For tooth measurements of the maxillary right central incisor (#11), canine and first molar (#13, #16); (1) the mesiodistal width was measured by the distance between the mesial and distal contact points (Figure 2A). (2) The buccolingual thickness was obtained by measuring the parallel buccolingual distance in the cross-section view of the horizontal plane which was 4.0 mm gingivally positioned from the incisal edge of #11 (Figure 2B) (19).

For measuring arch dimension, four points were selected in accordance with Kim et al (20); the cusp tips

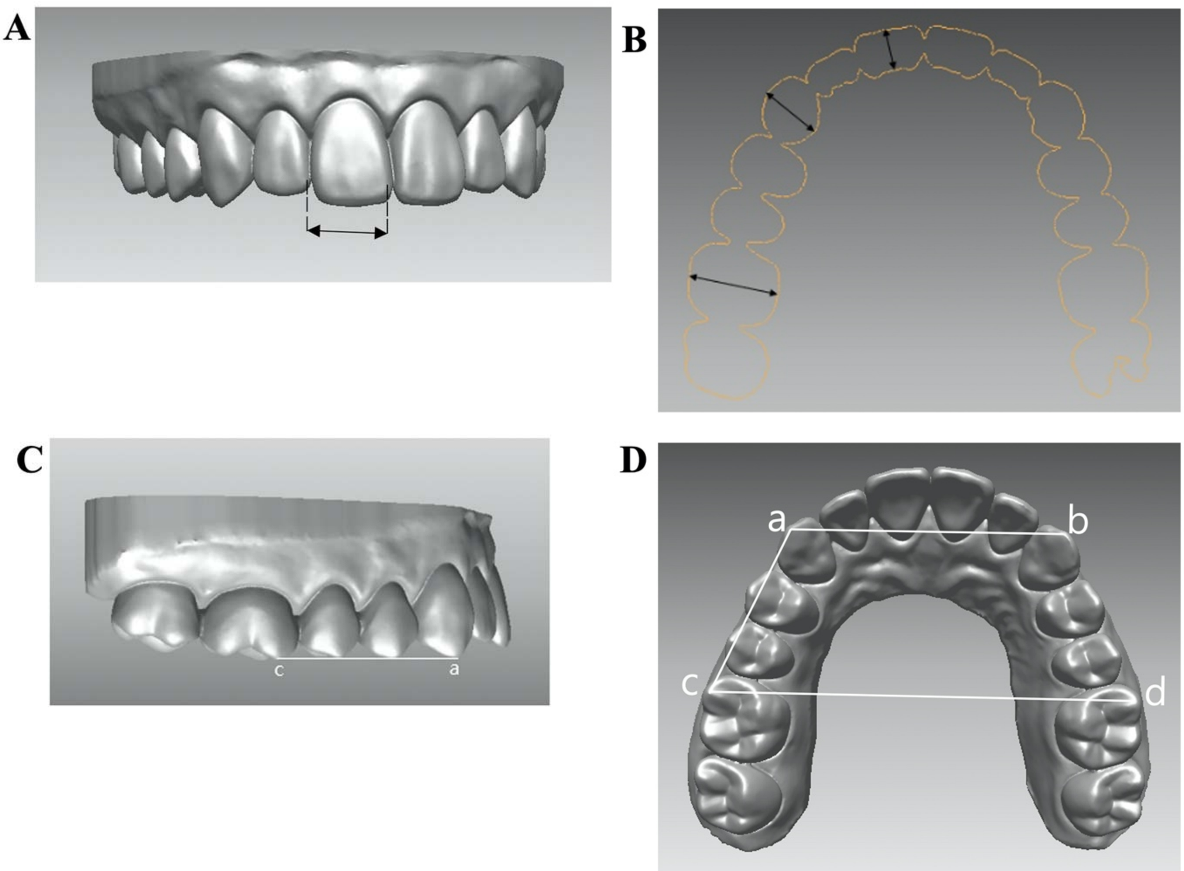

Figure 2. Measurements: (A) mesiodistal width of the maxillary right central incisor is the distance between the mesial and distal contact point; (B) buccolingual thicknesses were measured between the middle points of buccal and lingual margin in the maxillary right incisor, between point close to cusp tip and the middle point of lingual margin in the canine and between points close to buccal and lingual groove in the maxillary right first molar; (C) reference points for measurements were set using geometric function of Rapidform 2006 program; (D) occlusal view of arch measurements.

of the right and left canines, the mesiobuccal cusp tips of the right and left first molars (Figure 2C).

The following linear measurements on the maxillary dental arch were investigated: (1) From the cusp tip of the right canine to that of the left canine (a to b), (2) From the mesiobuccal cusp tip of the right first molar to that of the left first molar (c to d) (3) From the cusp tip of the canine to the mesiobuccal cusp tip of the first molar on the right side (a to c) (Figure 2D and Table 1) (20).

Measurements were performed on printed models comparing with the digital reference model by one examiner.

3. Statistical analysis

The Shapiro-Wilk test was applied to verify the data distribution and normality of measurements was found. One-way ANOVA was conducted to evaluate the accuracy of printed models compared with the digital reference model. Paired t-test was used to evaluate dimensional changes of printed models after fabrication of thermoplastic appliances. All measurements of the digital reference model and ABS models printed with 20% density were recorded twice at 1-week interval by the same examiner to examine the reproducibility of the measurements. The intraclass correlation coefficients were from 0.997 to 0.999, indicating that all measurements were highly reproducible.

All statistical analyses were performed using the SPSS version 12.0 software (SPSS Inc., Chicago, IL, USA). The 95% confidence level ($p<0.05$) was considered statistically significant.

Results

1. Accuracy of printed models compared with the digital reference model

There was no significant difference in all measurements between the digital reference model and ABS models with different densities. Although there was no significance in measurements, all measurements were decreased as the density increased in ABS models. Measurements in arch dimension, most of values were also smaller compared with the digital reference model (Table 2).

PLA models were not significantly different from the digital reference model in all measurements, regardless of the different printed densities. However, buccolingual thickness tended to be more different than mesiodistal width (Table 3).

2. Dimensional changes of printed models after one-time fabricationof thermoplastic orthodontic appliance

Tables 4 and 5 show dimensional changes in printed models after one-time fabrication of thermoplastic orthodontic appliance. In ABS models with 20% density,

Table 1. Definitions of measurements on the upper dental arch

Reference point	Measurement	Definition
a-b	Intercanine distance	Linear distance between the cusp tips of the canines
c-d	Intermolar distance	Linear distance between the mesiobuccal cusp tip of the first molars
a-c	Arch length	Linear distance between the cusp tip of canine and the mesiobuccal cusp tip of 1st molar

Table 2. Accuracy of models printed with acrylonitrile butadiene styrene (ABS) compared with the digital reference model

Variable		Digital reference model	Models printed with ABS			
			20%	40%	60%	
		Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	p-value
Mesiodistal width	#11	8.93 ± 0.051	8.89 ± 0.051	8.88 ± 0.056	8.88 ± 0.073	0.712
	#13	8.28 ± 0.046	8.29 ± 0.039	8.30 ± 0.030	8.28 ± 0.045	0.639
	#16	11.03 ± 0.036	10.94 ± 0.074	10.93 ± 0.062	10.89 ± 0.078	0.092
Buccolingual thickness	#11	5.34 ± 0.006	5.32 ± 0.054	5.32 ± 0.050	5.29 ± 0.061	0.712
	#13	7.60 ± 0.036	7.62 ± 0.073	7.60 ± 0.077	7.58 ± 0.130	0.919
	#16	11.58 ± 0.006	11.57 ± 0.111	11.56 ± 0.048	11.55 ± 0.084	0.951
Intercanine distance		36.61 ± 0.305	36.63 ± 0.179	36.60 ± 0.279	36.46 ± 0.219	0.710
Intermolar distance		56.20 ± 0.100	56.00 ± 0.135	55.92 ± 0.270	55.94 ± 0.142	0.210
Arch length		23.78 ± 0.049	23.65 ± 0.075	23.55 ± 0.196	23.48 ± 0.228	0.115

One-way ANOVA was performed for comparison between the digital reference model and models printed with acrylonitrile butadiene styrene (ABS) according to their densities. ABS, acrylonitrile butadiene styrene; SD, standard deviation; #11, maxillary right central incisor; #13, maxillary right canine; #16, maxillary right first molar.

Table 3. Accuracy of models printed with polylactic acid (PLA) compared with the digital reference model

Variable		Digital reference model	Models printed with PLA			
			20%	40%	60%	
		Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	p-value
Mesiodistal width	#11	8.93 ± 0.051	8.94 ± 0.066	8.91 ± 0.023	8.91 ± 0.059	0.761
	#13	8.28 ± 0.046	8.25 ± 0.060	8.26 ± 0.040	8.24 ± 0.058	0.730
	#16	11.03 ± 0.036	10.96 ± 0.048	10.97 ± 0.065	10.94 ± 0.084	0.337
Buccolingual thickness	#11	5.34 ± 0.006	5.28 ± 0.045	5.24 ± 0.048	5.27 ± 0.060	0.093
	#13	7.60 ± 0.036	7.62 ± 0.040	7.63 ± 0.031	7.66 ± 0.026	0.092
	#16	11.58 ± 0.006	11.67 ± 0.063	11.62 ± 0.053	11.69 ± 0.077	0.073
Intercanine distance		36.61 ± 0.305	36.83 ± 0.305	36.81 ± 0.186	36.71 ± 0.240	0.710
Intermolar distance		56.20 ± 0.100	56.25 ± 0.183	56.03 ± 0.130	56.02 ± 0.269	0.208
Arch length		23.78 ± 0.049	23.60 ± 0.134	23.58 ± 0.125	23.52 ± 0.247	0.223

One-way ANOVA was performed for comparison between the digital reference model and models printed with polylactic acid (PLA) according to their densities. PLA, polylactic acid; SD, standard deviation; #11, maxillary right central incisor; #13, maxillary right canine; #16, maxillary right first molar.

Table 4. Dimensional changes of models printed with acrylonitrile butadiene styrene (ABS) after one-time fabrication of thermoplastic orthodontic appliance

Variable		Models printed with ABS					
		20%		40%		60%	
		Mean (SD)	p-value	Mean (SD)	p-value	Mean (SD)	p-value
Mesiodistal width	#11	-0.14 (0.100)	0.035*	-0.05 (0.052)	0.098	-0.01 (0.034)	0.710
	#13	-0.04 (0.018)	0.009**	-0.01 (0.019)	0.235	-0.01 (0.043)	0.772
	#16	-0.05 (0.069)	0.169	-0.04 (0.022)	0.016*	-0.06 (0.059)	0.103
Buccolingual thickness	#11	-0.01 (0.056)	0.709	-0.03 (0.037)	0.125	0.00 (0.021)	1.000
	#13	-0.04 (0.088)	0.924	-0.03 (0.048)	0.263	-0.01 (0.069)	0.855
	#16	-0.19 (0.204)	0.101	-0.03 (0.064)	0.382	0.06 (0.032)	0.697
Intercanine distance		-0.01 (0.141)	0.859	-0.06 (0.149)	0.392	-0.03 (0.268)	0.827
Intermolar distance		-0.15 (0.177)	0.131	-0.02 (0.151)	0.802	-0.02 (0.257)	0.857
Arch length		-0.14 (0.105)	0.044*	-0.16 (0.179)	0.119	-0.08 (0.131)	0.264

Paired t-test was performed for evaluate dimensional changes of printed models with acrylonitrile butadiene styrene (ABS) after one-time fabrication of the appliance. ABS, acrylonitrile butadiene styrene; SD, standard deviation; #11, maxillary right central incisor; #13, maxillary right canine; #16, maxillary right first molar.

*$p<0.05$, **$p<0.01$.

Table 5. Dimensional changes of models printed with polylactic acid (PLA) after one-time fabrication of thermoplastic orthodontic appliance

Variable		Models printed with PLA					
		20%		40%		60%	
		Mean (SD)	p-value	Mean (SD)	p-value	Mean (SD)	p-value
Mesiodistal width	#11	-0.09 (0.051)	0.016*	-0.05 (0.020)	0.005**	-0.02 (0.061)	0.543
	#13	-0.10 (0.061)	0.022*	-0.04 (0.093)	0.411	-0.04 (0.081)	0.354
	#16	-0.22 (0.050)	0.001**	-0.2 (0.086)	0.005**	-0.12 (0.068)	0.019*
Buccolingual thickness	#11	-0.05 (0.038)	0.049*	-0.02 (0.022)	0.178	-0.02 (0.032)	0.170
	#13	-0.07 (0.030)	0.005**	-0.05 (0.040)	0.061	-0.04 (0.063)	0.210
	#16	-0.05 (0.035)	0.032*	-0.01 (0.017)	0.266	-0.03 (0.021)	0.034*
Intercanine distance		-0.22 (0.135)	0.022*	-0.19 (0.131)	0.034*	-0.11 (0.118)	0.098
Intermolar distance		-0.24 (0.244)	0.091	-0.21 (0.051)	0.001**	-0.18 (0.036)	0.000***
Arch length		-0.06 (0.040)	0.031*	-0.07* (0.047)	0.025*	-0.08 (0.018)	0.001**

Paired t-test was performed for evaluate dimensional changes of models printed with polylactic acid (PLA) after one-time fabrication of the appliance. PLA, polylactic acid; SD, standard deviation; #11, maxillary right central incisor; #13, maxillary right canine; #16, maxillary right first molar.

*$p<0.05$, **$p<0.01$, ***$p<0.001$.

mesiodistal width of #11, #13 and arch length were significantly decreased by 0.14, 0.04 and 0.14 mm ($p<0.05$). In ABS models printed with 40%, only buccolingual thickness of #16 were significantly decreased by 0.04 mm ($p<0.05$). In ABS models printed with 60% density, there was no significance.

In PLA models printed with 20% density, all measurements were significantly decreased except for intermolar distance ($p<0.05$). In PLA models printed with 40% density, mesiodistal width of #11, #13 and all measurements in arch dimension were significantly decreased from 0.05 to 0.21 mm ($p<0.05$). In PLA models printed with 60% density, mesiodistal width and buccolingual thickness of #16 were significantly decreased by 0.12 and 0.03 mm, respectively ($p<0.05$). Intermolar distance and arch length were also significantly decreased by 0.18 and 0.08 mm, respectively ($p<0.01$).

3. Dimensional changes of printed models after three times fabrication of thermoplastic orthodontic appliances

Tables 6 and 7 show the changes in printed models after three times fabrication of thermoplastic orthodontic appliance. In ABS models printed with 20% density, mesiodistal width of #11 and #16, intermolar distance and arch length were significantly decreased from 0.19 to 0.27 mm ($p<0.05$). In ABS models printed with 40% density, mesiodistal width of #11 and buccolingual thickness of #13 were significantly decreased by 0.08 mm ($p<0.05$). In ABS models printed with 60% density, there was no significance ($p<0.05$).

In PLA models printed with 20% density, all measurements were significantly decreased except for intermolar distance. In PLA models printed with 40%, mesiodistal width of #16, buccolingual thickness of #11 and all arch dimension measurements were significantly decreased from 0.06 to 0.35 mm ($p<0.05$). In PLA models printed with 60%, mesiodistal width and buccolingual thickness of #16 and all arch dimension measurements were significantly decreased from 0.04 to 0.42 mm ($p<0.05$).

Discussion

The purpose of this study was evaluation of the dimensional changes in 3D printed models after fabrication of thermoplastic orthodontic appliances. In addition, the accuracy of the printed models by their materials and density was also investigated to determine the possibility of clinical use.

In our study, the accuracy of 3D printed models was accurate, regardless of the materials and printed density (Table 2, 3). Although differences in models printed with ABS ranged from -0.14 to 0.02 mm were not significantly different, most of the measurements were relatively small compared with those of the digital reference model (Table 2). These results were similar to the previous study (4, 5, 18, 21). Lee et al (18) who compared 3D printed teeth with FDM and Polyjet techniques reported that mean deviations of the replica teeth manufactured with FDM and Polyjet methods were 0.047 and 0.038 mm respectively, and it meant both 3D printing techniques can be used clinically with very high accuracy. They also found that most of measurements of the FDM replicas showed a decreasing tendency and assumed that it was caused by shrinkage of materials. In our study, ABS models also showed tendency that all measurements were decreased as the density increased. It might be assumed that the higher the density of printed models with ABS, the greater polymerization shrinkage occured. Differences in models with PLA ranged from -0.26 to 0.22 mm, which were not significantly different with the digital reference model.

To extend clinical indication of thermoplastic orthodontic appliance, it is essential to examine the

Table 6. Dimensional changes of models printed with acrylonitrile butadiene styrene (ABS) after three times fabrication of thermoplastic orthodontic appliances

Variable		Models printed with ABS					
		20%		40%		60%	
		Mean (SD)	p-value	Mean (SD)	p-value	Mean (SD)	p-value
Mesiodistal width	#11	-0.21 (0.125)	0.019*	-0.08 (0.054)	0.026*	0.00 (0.029)	1.0
	#13	-0.04 (0.053)	0.152	-0.05 (0.091)	0.303	-0.04 (0.060)	0.208
	#16	-0.19 (0.086)	0.008**	-0.05 (0.075)	0.197	-0.10 (0.152)	0.222
Buccolingual thickness	#11	-0.00 (0.065)	0.898	-0.06* (0.057)	0.067	-0.03 (0.062)	0.371
	#13	-0.01 (0.145)	0.862	-0.08 (0.055)	0.032*	-0.05 (0.100)	0.323
	#16	-0.26 (0.28)	0.099	-0.04 (0.093)	0.352	-0.02 (0.078)	0.633
Intercanine distance		-0.06 (0.157)	0.413	-0.12 (0.223)	0.302	-0.08 (0.280)	0.568
Intermolar distance		-0.27 (0.210)	0.045*	-0.12 (0.143)	0.145	-0.04 (0.234)	0.735
Arch length		-0.26 (0.098)	0.004**	-0.19 (0.194)	0.091	-0.11 (0.137)	0.137

Paired t-test was performed for evaluate dimensional changes of models printed with acrylonitrile butadiene styrene (ABS) after three times fabrication of the appliances. ABS, acrylonitrile butadiene styrene; SD, standard deviation; #11, maxillary right central incisor; #13, maxillary right canine; #16, maxillary right first molar.
*$p < 0.05$, **$p < 0.01$.

Table 7. Dimensional changes of models printed with polylactic acid (PLA) after three times fabrication of thermoplastic orthodontic appliances

Variable		Models printed with PLA					
		20%		40%		60%	
		Mean (SD)	p-value	Mean (SD)	p-value	Mean (SD)	p-value
Mesiodistal width	#11	-0.15 (0.104)	0.030*	-0.07 (0.094)	0.171	0.09 (0.076)	0.058
	#13	-0.14 (0.072)	0.011*	-0.09 (0.106)	0.118	-0.08 (0.101)	0.169
	#16	-0.27 (0.077)	0.001*	-0.21 (0.083)	0.005**	-0.15 (0.062)	0.006**
Buccolingual thickness	#11	-0.11 (0.073)	0.028*	-0.06 (0.025)	0.005**	-0.02 (0.036)	0.215
	#13	-0.13 (0.030)	0.001***	-0.09 (0.072)	0.055	-0.06 (0.068)	0.129
	#16	-0.13 (0.086)	0.026*	-0.02 (0.021)	0.061	-0.04 (0.030)	0.041*
Intercanine distance		-0.39 (0.104)	0.001**	-0.24 (0.194)	0.05*	-0.21 (0.127)	0.021*
Intermolar distance		-0.38 (0.587)	0.223	-0.35 (0.055)	0.000***	-0.42 (0.111)	0.001**
Arch length		-0.22 (0.103)	0.009**	-0.12 (0.077)	0.026*	-0.11 (0.033)	0.002**

Paired t-test was performed for evaluate dimensional changes of models printed with polylactic acid (PLA) after three times fabrication of the appliances. PLA, polylactic acid; SD, standard deviation; #11, maxillary right central incisor; #13, maxillary right canine; #16, maxillary right first molar.
*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

accuracy of procedures including fabrication of the appliance and determine whether errors from the procedures would prove to be clinically significant. The range of error (< 0.5 mm) was determined based on the clinical validity and the standard set by the American Board of Orthodontics' increments for grading plaster models (19). Stevens et al (22) determined that differences of measurements less than 0.16 mm were considered clinically insignificant. Other authors set the threshold for clinical significance at 0.25, 0.27, and 0.30 mm (3, 23, 24) From this point of view, printed models with ABS were assessed to have enough dimensional stability for clinical use in our study. Even when the strictest threshold of 0.16 mm was applied, one-time fabrication of thermoplastic orthodontic appliance seldom affected the dimensional stability of the models with ABS (Table 4). Only ABS models printed with 20% were affected in some tooth measurements and arch dimensions after three times of the fabrication (Table 6). Unlike the results of ABS models, a few measurements in models printed with PLA were changed over the acceptable clinical errors. One-time fabrication caused dimensional changes in some tooth measurements and arch dimensions of PLA models, regardless of the printed density (Table 5). After three times of the fabrication, some of tooth measurements and most of arch dimensions were also affected in all models printed with PLA (Table 7).

These results were probably related to the properties of the materials used to 3D printing. PLA is an environment-friendly material and its melting point is relatively low as 180 to 230℃. Printed models with PLA are more accurate than models with ABS because there is no polymerization shrinkage in PLA (9). However, deformation may occur at high temperature as its relatively low melting point. ABS is a kind of petroleum products and its melting point is about 210 to 250℃. This material is relatively heat resistant and has a high strength, but polymerization shrinkage occurs during the polymerization. During the fabrication process of thermoplastic orthodontic appliance, thermoplastic materials are heated to 220℃ for softening and then pressed over dental models (10). It may lead to dimensional changes in 3D printed dental models.

Many invisible orthodontic systems with thermoplastic appliance including Invisalign (Align Technology, San Jose, Calif) consist of several aligners with tooth movement in each aligner from 0.25 to 0.30 mm (25). Thus, the error of the accuracy of printed dental models and dimensional changes after the fabrication of thermoplastic appliance must be smaller than 0.25 to 0.30 mm for the fabricated appliance to deliver orthodontic force on the teeth. In this respect, our finding indicated that dental models printed with FDM technique using both ABS and PLA materials are considered to be available for fabricating thermoplastic orthodontic appliance once. However, repeatedly fabricated thermoplastic appliances in a single dental model printed with both materials might not work properly, especially in models printed with PLA. They can lead to prevent desired orthodontic tooth movement and increase the total treatment period.

To our knowledge, this study was the first study conducted to evaluate dimensional changes after thermoplastic orthodontic appliance in 3D printed dental models with FDM technology. One of the limitations of this study is that only ABS and PLA were included as FDM printing materials. This is because ABS and PLA are the only commercially available materials for dental FDM printers. Further studies should evaluate the clinical availability of thermoplastic orthodontic appliance with other 3D printing machines and materials.

Conclusion

The accuracy of 3D printed dental models and dimensional changes after fabrication of thermoplastic orthodontic appliances were evaluated in this study.

3D printed dental models with ABS and PLA were accurate compared with the digital reference model, regardless of the density. Dimensional stability of dental models printed with ABS after fabrication of thermoplastic orthodontic appliances was relatively good, but models printed with PLA showed significant dimensional changes even after one-time fabrication of the thermoplastic appliance. Dimensional changes of 3D printed dental models were increased after three times fabrication of thermoplastic orthodontic appliances, especially in models printed with PLA.

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Original Article

Effects of thermoplastic appliance fabrication on the dimensional stability of 3D printed dental models

Byung-Min Kang[1], *Sung-Kwon Choi*[2,*]

[1]*Department of Orthodontics, School of Dentistry, Wonkwang University, Iksan, Repbulic of Korea*
[2]*College of Dentistry, Graduate school of Wonkwang University, Iksan, Republic of Korea*

The purpose of this study was to evaluate effects of fabrication of thermoplastic appliance on the dimensional stability of 3D printed dental models. A digital reference model was printed by different printing materials and densities [acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA); 20, 40 and 60%]. Thermoplastic appliances were then fabricated with printed models for three times and models were scanned at three different stated; following the print out, following the fabrication for one time and three times. Tooth and arch measurements were performed to evaluate the accuracy and dimensional stability of printed models after fabrication of thermoplastic appliances. Printed models were not significantly different from the digital reference model regardless of different materials and densities. After the first fabrication of the appliance, most of measurements were decreased in PLA models ranged from 0.05 to 0.24 mm ($p<0.05$), whereas only a few measurements were decreased in ABS models ($p<0.05$). After fabrication for three times, measurements were more decreased in PLA models ranged from 0.04 to 0.42 mm ($p<0.05$) and some measurements were decreased in ABS models ranged from 0.08 to 0.27 mm ($p<0.05$). ABS models showed relatively good dimensional stability, but the PLA models showed significant dimensional changes even after initial fabrication of the appliance. Repeated fabrication of the appliances increased dimensional changes in printed models, especially printed with PLA.

Key Words : 3D printing, Dimensional stability, Fused deposition modeling (FDM), Acrylonitrile butadiene styrene (ABS), Polylactic acid (PLA).