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Factors Affecting Thermal Shrinkage of Mouthguard Sheet during Thermoforming: Model Shape and Sheet Material Thickness

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Abstract

The effectiveness and safety of the mouthguard depend on the sheet material thickness. The thickness of the thermoformed mouthguard is affected by the model undercut and the thermal shrinkage that occurs when the extruded-molded sheet is reheated. The aim of this study was to clarify the influence of the undercut amount of the model and the thickness of the sheet material on the thermal shrinkage of the extruded sheet. The mouthguard sheet used ethylene-vinyl acetate resin with a thickness of 4.0 mm (4M) and 3.0 mm (3M) and was manufactured by extrusion molding. The working models were three hard gypsum models with the undercut amount on the labial side trimmed to 0˚ (U0), 10˚ (U10), and 20˚ (U20). Mouthguard thickness after vacuum formation was compared between the conditions formed so that the extrusion direction was vertical (condition V) or parallel (condition P) to the model midline. Differences in the reduction rate of the mouthguard thicknesses of the labial and buccal side depending on the sheet extrusion direction, model angle, and sheet material thickness were analyzed by three-way ANOVA and Bonferroni method. The reduction rate of the thickness in condition P was significantly greater than in condition V under all conditions except U0-4M on the labial side and U0-4M and U10-4M on the buccal side. In all models, the reduction rate of the thicknesses was significantly greater in 3M than in 4M in the same extrusion direction. In both 4M and 3M, the reduction rate of the thicknesses tended to increase as the amount of undercut increased in each extrusion direction. This study suggested that a model with a large amount of undercut on the labial side or a thin sheet had a significant effect on the thermal shrinkage of the mouthguard sheet during thermoforming, which leads to the thinning of the mouthguard.

Keywords

Mouthguard, Thermoforming, Thermal Shrinkage, Model Shape, Thickness

1. Introduction

Shock absorption and dispersibility of mouthguards largely depend on the material and thickness of the sheet, which determines the effectiveness and safety of the mouthguard [1] [2] [3] [4]. Thermoforming is a mouthguard fabricating method that many clinicians choose because of its simplicity. However, the mouthguard thickness after formation is greatly reduced compared with the original sheet [3] [5] [6] [7]. Consequently, it is difficult to achieve the mouthguard the thickness (3 - 4 mm) required for shock absorption with a single sheet, and this is the subject of many researches.

There are various factors that affect the thickness of thermoformed mouthguards, including the working model form [5] [6] [8] [9] [10] [11], the sheet material [12], sheet color [13], and sheet thickness [14] [15]. In addition, sheets manufactured by extrusion molding undergo thermal shrinkage when the sheet is reheated, which also affects the mouthguard thickness [16] [17] [18] [19]. This thermal shrinkage is a characteristic of sheets manufactured by extrusion molding and does not occur in sheets manufactured by injection molding [16]. In extruded sheets, strain remains because the molecular chains of the resin are oriented in a certain direction during manufacturing. When the sheet is thermoformed, the strain is released as the sheet temperature increases, which causes thermal shrinkage in the orientation direction [16]. Sheets of ethylene-vinyl acetate resin (EVA), which is one of the common mouthguard materials, are manufactured mainly by extrusion molding. The influence of thermal shrinkage of the extruded sheet on the mouthguard thickness has been clarified by examining the heating conditions of the sheet and the sheet shape [18]. However, it has not been verified to what extent the thermal shrinkage is affected by the model form and the thickness of the sheet material.

The aim of this study was to clarify the influence of the undercut amount of the model and the thickness of the sheet material on the thermal shrinkage of the extruded sheet. The null hypothesis was that the thermal shrinkage of the sheet was not affected by the model undercut amount and the sheet material thickness.

2. Materials and Methods

The working model was made by injecting dental gypsum (New Plastone; GC Co., Tokyo, Japan) after taking an impression of a maxillary dental model (D16FE-500A-QF; Nissin Dental Products Inc., Kyoto, Japan) with a silicone rubber impression material (Correcsil; Yamahachi Dental Mfg. Co., Aichi, Japan) for duplication [20]. Three working models were prepared, in which the following angles were formed between the labial surface of the central incisor and the basal plane of the model: 1) U0, where the undercut on the labial side was 0˚ (height of 25 mm at the incisal edge of the maxillary central incisor and 20 mm at the mesiobuccal cusp of the maxillary first molar); 2) U10, where the undercut amount on the labial side was 10˚ (height of 25 mm at the incisal edge of the maxillary central incisor and 25 mm at the mesiobuccal cusp of the maxillary first molar); and 3) U20, where the undercut amount on the labial side was 20˚ (height of 25 mm at the incisal edge of the maxillary central incisor and 30 mm at the mesiobuccal cusp of the maxillary first molar) (**Figure 1**). The model angle was calculated from the heights of the anterior teeth and molars and adjusted by trimming the basal plane of the model. The model was left at room temperature for 48 h or more and was sufficiently dried.

The mouthguard sheet was an EVA sheet manufactured by extrusion molding (Sports Mouthguard; Keystone Dental Inc., Cherry Hill, NJ; 127 × 127 mm, clear). The thickness of the sheet material was 4.0 mm (4M) and 3.0 mm (3M). A vacuum forming machine (Pro-form, T&S Dental & Plastics Co., Inc., Myerstown, PA) was used for formation. The mouthguard sheet was placed so that the model midline and the sheet extrusion direction were vertical (condition V) or parallel (condition P). The sheet was heated until it reached 100˚C, after which

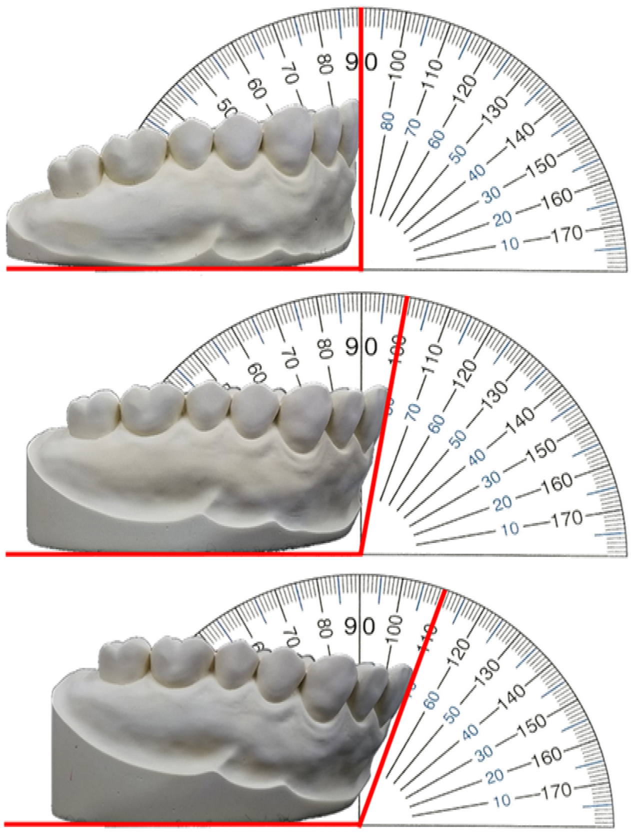

Figure 1. Working models. (A), the undercut on the labial side was 0˚ (U0); (B), the undercut on the labial side was 10˚ (U10); and (C), the undercut on the labial side was 20˚ (U20).

suction was continued for 30 s [20]. A radiation thermometer (CT-2000N, Custom Co., Tokyo, Japan) was used to measure the sheet temperature. Six samples were prepared for each condition, giving a total of 72 mouthguards (2 extrusion directions × 3 model angles × 2 sheet thicknesses × 6 repetitions).

A spring-free measuring caliper (21-111; YDM Co., Tokyo, Japan), which can measure up to 0.1 mm, was used to measure the mouthguard thickness [11] [20]. The mouthguard was sectioned, and each section was measured. For each sample, the labial and buccal thicknesses were measured once (**Figure 2**).

Statistical analysis software (IBM SPSS 24.0, SPSS Japan Inc., Tokyo, Japan) was used for statistical processing. For all the measured values, the differences in the reduction rate of the thickness after formation depending on the extrusion direction of the sheet, the model angle, and the thickness of the sheet material were compared. The Shapiro–Wilk test for normality of distribution and Levene's test for homogeneity of variance was also performed. Because normality and homoscedasticity were found for each item, analysis was performed by a three-way analysis of variance (ANOVA). For the factors in which the interaction was observed, the multiple comparison method (simple main effect test) was applied using the Bonferroni method for each level of each factor. All analyses were performed with a significance level of 5% and a detection power of 80%, and differences were considered significant when both were satisfied.

3. Results and Discussion

Table 1 shows the results of three-way ANOVA for the reduction rate of the mouthguard thickness. At both measurement points, the main effects of the sheet extrusion direction, model angle, and sheet thickness were significant, and their interaction was also significant. Based on the results, simple main effect tests were performed by the Bonferroni method.

Table 2 and **Figure 3** show the results of simple main effect tests of the reduction rates of the labial thickness of the mouthguard under each condition.

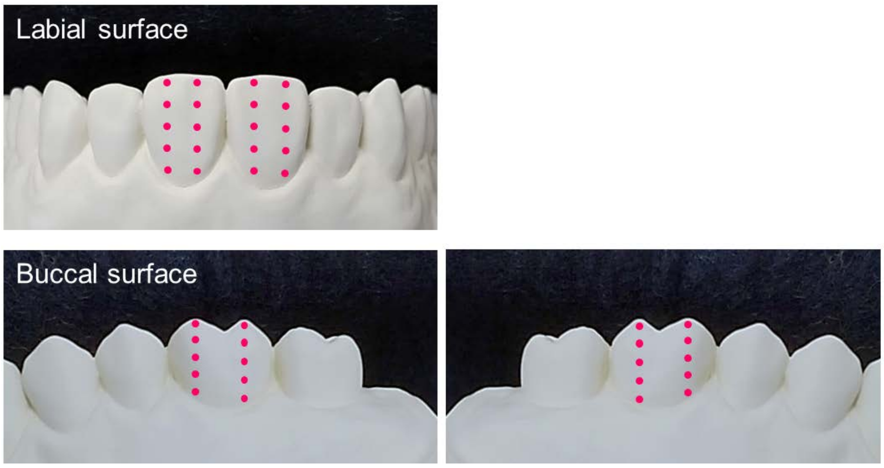

Figure 2. Measurement points on the labial and buccal surfaces for the mouthguard thickness corresponding to the model (20 measurement points each).

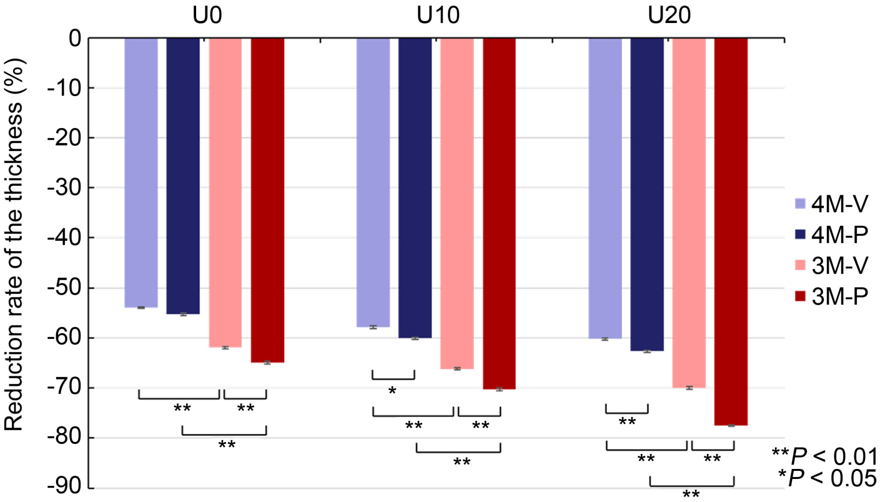

Figure 3. Reduction rate of the labial thickness according to the sheet extrusion direction, model angle, and sheet thickness. Measurements are expressed as mean value ± SD. **P < 0.01, *P < 0.05: denotes statistically significant difference by simple main effect tests.

Table 1. Results of two-way ANOVA for thickness after formation.

Source	*df*	SS	MS	*F*-value	*P*-value
Labial surface					
Sheet extrusion direction (A)	1	201.670	201.670	3180.081	<0.001**
Model angle (B)	2	888.691	444.345	7006.761	<0.001**
Sheet thickness (C)	1	1823.073	1823.073	28,747.545	<0.001**
A*B	2	25.900	12.950	204.207	<0.001**
A*C	1	41.253	41.253	650.515	<0.001**
B*C	2	46.505	23.253	366.664	<0.001**
A*B*C	2	9.510	4.755	74.982	<0.001**
Error	60	3.805	0.063		
Buccal surface					
Sheet extrusion direction (A)	1	169.894	169.894	1641.487	<0.001**
Model angle (B)	2	862.870	431.435	4168.455	<0.001**
Sheet thickness (C)	1	6086.722	6086.722	58,808.910	<0.001**
A*B	2	9.429	4.714	45.549	<0.001**
A*C	1	7.867	7.867	76.012	<0.001**
B*C	2	17.467	8.733	84.381	<0.001**
A*B*C	2	2.292	1.146	11.072	<0.001**
Error	60	6.210	0.104		

df: degree of freedom. SS: sum of squares. MS: mean square. **$P < 0.01$: denotes statistically significant difference.

Table 2. Results of simple main effect tests in the reduction rate of the labial thickness according to the model angle.

4M-V	U0	U10	U20
U0			
U10	**		
U20	**	*	
**$P < 0.01$; *$P < 0.05$			

4M-P	U0	U10	U20
U0			
U10	**		
U20	**	**	
**$P < 0.01$			

3M-V	U0	U10	U20
U0			
U10	**		
U20	**	**	
**$P < 0.01$			

3M-P	U0	U10	U20
U0			
U10	**		
U20	**	**	
**$P < 0.01$			

Differences due to the sheet extrusion direction were observed in U0-3M, U10-3M, U20-4M and U20-3M (P < 0.01), and in U10-4M (P < 0.05), and the reduction rate of the thicknesses were significantly greater in condition P than in condition V. In all models, the differences due to the thickness of the sheet material were observed between 4M-V and 3M-V, and 4M-P and 3M-P (P < 0.01), and the reduction rate of the thicknesses were significantly greater in 3M than in 4M. Differences due to the model angle were observed in 4M-V, 4M-P, 3M-V, and 3M-P, and the reduction rate of the thicknesses was U0 < U10 < U20 (P < 0.01, P < 0.05).

Table 3 and Figure 4 show the results of simple main effect tests of the reduction rates of the buccal thickness of the mouthguard under each condition. Differences due to the sheet extrusion direction were observed in U0-3M, U10-3M, U20-4M and U20-3M (P < 0.01), and the reduction rate of the thicknesses were significantly greater in condition P than in condition V. In all models, the differences due to the thickness of the sheet material were observed between 4M-V and 3M-V, and between 4M-P and 3M-P (P < 0.01), and the reduction rate of the thicknesses were significantly greater in 3M than in 4M. Differences due to the model angle were observed in 4M-V, 4M-P, 3M-V, and 3M-P, and the reduction rate of the thicknesses was U0 < U10 < U20 (P < 0.01, P < 0.05).

There are three factors that affect how the mouthguard sheet behaves when it is heated by the forming machine: thermal expansion, thermal contraction, and elongation due to the sheet's own weight [16]. As a result of these three antagonisms, the sheet expansion, contraction, and sagging occur as visually recognizable phenomena. These phenomena affect the elongation of the sheet [16]. The sheet elongation also affects the thermal shrinkage of the extruded sheet, which, in turn, affects the sheet thickness after formation. Because thermal shrinkage occurs along the orientation direction of the sheet, the sheet expands uniformly in the direction orthogonal to the extrusion direction, but the expansion rate increases toward the center of the sheet in the direction parallel to the extrusion direction [16]. When the softened sheet is pressed against the model, the sheet is affected by the model morphology, and there are parts that extend and parts that shrink, causing non-uniform shape changes [7] [16]. Because the mouthguard thickness is affected by the model form, and the sheet material thickness [5] [11] [14], the thermal shrinkage that occurs in the extruded sheet will be affected by these factors. In addition, the reduction rate of the mouthguard

Table 3. Results of simple main effect tests in the reduction rate of the buccal thickness according to the model angle.

4M-V	U0	U10	U20
U0			
U10	**		
U20	**	**	

**$P < 0.01$

4M-P	U0	U10	U20
U0			
U10	**		
U20	**	**	

**$P < 0.01$

3M-V	U0	U10	U20
U0			
U10	**		
U20	**	**	

**$P < 0.01$

3M-P	U0	U10	U20
U0			
U10	**		
U20	**	**	

**$P < 0.01$

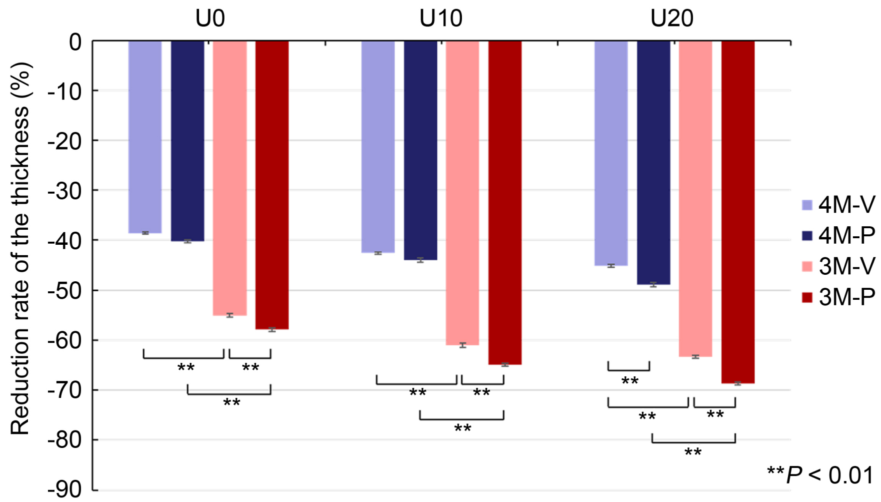

Figure 4. Reduction rate of the buccal thickness according to the sheet extrusion direction, model angle, and sheet thickness. Measurements are expressed as mean value ± SD. **P < 0.01: denotes statistically significant difference by simple main effect tests.

thickness is smaller when the sheet is formed by placing the sheet in the extrusion direction vertical to the model midline than when it is placed parallel [16] [17] [18] [19]. From these, it was predicted that the degree of influence of the sheet extrusion direction on the mouthguard thickness may depend on the working model conditions and sheet conditions. Therefore, in this study, the effects of the model undercut and the thickness of the sheet material on the thermal shrinkage of the mouthguard sheet were investigated.

The influence of model angle on the mouthguard thickness has been reported previously [8] [9] [10]. These studies showed that the presence of an undercut on the model labial side causes sheet elongation during pressure contacts and reduces the labial thickness of the mouthguard. For mouthguard users with maxillary anterior teeth tilted to the labial side, trimming the model so that there is no undercut on the labial side tends to increase the model height. However, as the height of the model increases, the mouthguard becomes thinner [5] [6] [11]. The model form in the present study used the minimum height possible without an undercut on the labial side, based on previous studies [11] [20], and model U0, with an anterior height of 25 mm and molar height of 20 mm, was used as a standard. Models U10 and U20 were prepared by adjusting the height of the molars so that the central incisor tooth axis was tilted 10˚ and 20˚ from that in

U0, respectively. Therefore, the effect of the model anterior height was eliminated and the effect of the undercut amount on the mouthguard thickness was verified. However, the molar height increased by 5 mm each with the increase in the amount of undercut.

As a result of this study, a model with a large amount of undercut on the labial side or a thin sheet had a significant influence on the thermal shrinkage of the mouthguard sheet during thermoforming. Therefore, the null hypothesis was rejected.

The reduction rate of the labial mouthguard thickness depending on the sheet extrusion direction was significantly different between all conditions, except U0-4M. For all models and both sheet material thicknesses, the reduction rate of the thickness was larger for condition P than for condition V. In addition, the decrease in thickness increased with the increase in the amount of undercut, as previously reported [8] [9] [10]. Under the condition that the model angle and the thickness of the sheet material were the same, the difference between conditions V and P increased with the amount of undercut of the model or as the sheet material became thinner. Thus, the influence of the thermal shrinkage of the sheet on the labial thickness depends on the undercut amount of the model and the thickness of the sheet material.

Because the anterior teeth in the model have a narrow anterior-posterior width and are sharp, the sheet is stretched greatly in the anteroposterior direction when the softened sheet is pressed against the model [21]. In the direction vertical to the extrusion direction, the reduction rate of the thickness with the elongation of the material is small, whereas it is largely parallel to the extrusion direction [16] [17]. Therefore, the thickness for condition P would be decreased significantly with a slight extension, and the reduction rate of the thickness would have been larger than that for condition V.

The reduction rate of the buccal thickness of the mouthguard increased as the model height increased in the order of U0 < U10 < U20, similar to previous studies showing that the mouthguard becomes thinner as the model height increases [5] [6] [11]. The difference between conditions V and P was larger for 3M than for 4M under the same model angle and was in the order U0 < U10 < U20 under the same sheet thickness. Thus, the thermal shrinkage of the sheet had a greater effect on the buccal mouthguard thickness when the model was higher and the sheet was thinner. The molar part of the model slopes gently in the anterior-posterior and left-right directions compared with the anterior part because there is an occlusal surface. Therefore, the influence of the extrusion direction on the thickness may have been smaller than that on the labial side. If the model is high or the sheet is thin, the sheet tends to stretch more [11] [14] [15], so these factors may have affected the thermal shrinkage of the sheet, causing a difference in the buccal thickness.

From the above, in the equipment and forming environment used in this study, the influence of thermal shrinkage of the extruded sheet on the mouthguard thickness was remarkable when the amount of undercut on the labial side of the model was large or the sheet material was thin. In other words, it was clarified that the difference in the mouthguard thickness caused by the extrusion direction of the sheet depends on the amount of undercut on the labial side of the model and the thickness of the sheet material. However, in the model without an undercut, the extrusion direction of the sheet did not make a significant difference to the mouthguard thickness. The limitation of this study was that the thickness required for shock absorption could not be achieved even if the mouthguard was formed considering the effect of the thermal shrinkage of the sheet.

4. Conclusion

In the equipment and forming environment used in this study, the influence of thermal shrinkage of the extruded sheet on the mouthguard thickness was remarkable when the amount of undercut on the labial side of the model was large or the sheet material was thin. In other words, it was clarified that the difference in the mouthguard thickness caused by the extrusion direction of the sheet depends on the amount of undercut on the labial side of the model and the thickness of the sheet material. In future research, it will be necessary to investigate the design of laminated mouthguards considering the effect of the undercut amount of the model, the model height, and the sheet material thickness on the thermal shrinkage of the extruded sheet.

Conflict of Interest Statement

The authors report no conflict of interest. This study was supported by Nippon Dental University Intramural Research Fund.

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