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Dependence of Lower Molding Temperature Limit and Molding Time on Molding Mechanism in Dental Thermoforming

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Abstract

Effectiveness and safety of a sports mouthguard depend on its thickness and material, and the thermoforming process affects these. The purpose of this study was to clarify the effects of differences in molding mechanisms on the lower molding temperature limit and molding time in dental thermoforming. Ethylene vinyl acetate resin mouthguard sheet and two thermoforming machines; vacuum blower molding machine and vacuum ejector/pressure molding machine were used. The molding pressures for suction molding were −0.018 MPa for vacuum blower molding and −0.090 MPa for vacuum ejector molding, and for pressure molding was set to 0.090 MPa or 0.450 MPa. Based on the manufacturer's standard molding temperature of 95˚C, the molding temperature was lowered in 2.5˚C increments to determine the lower molding temperature limit at which no molding defects occurred. In order to investigate the difference in molding time depending on the molding mechanism, the duration of molding pressure was adjusted in each molding machine, and the molding time required to obtain a sample without molding defects was measured. The molding time of each molding machine were compared using one-way analysis of variance. The lower molding temperature limit was 90.0˚C for the vacuum blower machine, 77.5˚C for the vacuum ejector machine, 77.5˚C for the pressure molding machine at 0.090 MPa, and 67.5˚C for the pressure molding machine at 0.45 MPa. The lower molding temperature limit was higher for lower absolute values of molding pressure. The molding time was shorter for pressure molding than for suction molding. Significant differences were observed between all conditions except between the pressure molding machine at 0.090 MPa and 0.45 MPa ($P < 0.01$). A comparison of the differences in lower molding temperature limit and molding time due to molding mechanisms in dental thermoforming revealed that the lower molding temperature limit depends on the molding pressure and that the molding time is longer for suction molding than for pressure molding.

Keywords

Thermoforming, Suction Molding, Pressure Molding, Lower Molding Temperature Limit, Molding Time

1. Introduction

Sports mouthguards are generally fabricated by thermoforming thermoplastic elastomer sheets. Depending on the molding method, molding machines can be roughly classified as either suction molding machines, which use the negative pressure created by a vacuum generator as the molding force, and pressure molding machines, which use compressed air (positive pressure) from a compressor as the molding force [1]. Suction molding machines use the breathability of the working model to suction the sheet against the contact surface of the model. Suction molding machines can be categorized according to the vacuum generator that creates the negative pressure into vacuum blower machines, which use the suction pressure of a blower, and vacuum ejector machines, which create negative pressure with a vacuum ejector using the Venturi effect. Vacuum blower machines achieve a low pressure of −0.010 to −0.025 MPa but a high flow rate, whereas vacuum ejector machines have a high pressure of −0.075 to −0.095 MPa but a low flow rate. The suction pressure produced by the vacuum generator cannot generate a molding pressure higher than atmospheric pressure, and the molding pressure cannot be adjusted because the level of vacuum achieved is fixed. In contrast, pressure molding machines use compressed air from a compressor as the molding force to apply molding pressure from above to press the sheet against the model. Many pressure molding machines use compressed air at a pressure of around 0.4 MPa [1].

In dental thermoforming, the differences in breathability and porosity of working model materials depend on the type of plaster [2] and the effect of surface treatment agents on the breathability of plaster models [3]. In addition, the thickness of the mouthguard is affected by the molding method [1] [4] [5], the softening state of the sheet [6]-[8], and the shape of the model [9]-[12]. However, it is not known to what extent differences in molding mechanisms, such as the molding method of the molding machine and molding pressure [13], affect the molding operation or the molded product.

The purpose of this study was to clarify the effects of differences in molding mechanisms on the minimum forming temperature and molding time in dental thermoforming. The null hypothesis was that the lower molding temperature limit and molding time were not affected by the molding mechanism.

2. Materials and Methods

2.1. Experiment 1: Comparison of the Lower Molding Temperature Limit for Suction and Pressure Molding Machines

The working model was prepared by pouring ordinary plaster (Ci Value Plaster;

Ci Medical. Co., Tokyo, Japan) into a rubber mold for standard dental plaster models (H1-500AU Nissin. Co. Kyoto, Japan) (Figure 1).

The material was an ethylene vinyl acetate resin mouthguard sheet (120 × 120 × 3 mm, yellow; Micro Tec Co., Tokyo, Japan). A vacuum blower molding machine (Vacuum Former EV2; 3A Medis Co., Goyang, South Korea) and a vacuum ejector/pressure molding machine (Model Capture Try; Shofu Inc., Kyoto, Japan) were used (Figure 2). The vacuum ejector molding and pressure molding were performed independently on the vacuum ejector/pressure molding machine. The molding pressures for suction molding were −0.018 MPa for vacuum blower molding and −0.090 MPa for vacuum ejector molding. Because the molding pressure for pressure molding could be adjusted freely, it was set to 0.090 MPa (positive pressure equal to the absolute value of the vacuum ejector molding negative pressure) or 0.450 MPa (recommended supply pressure).

Figure 1. Working model.

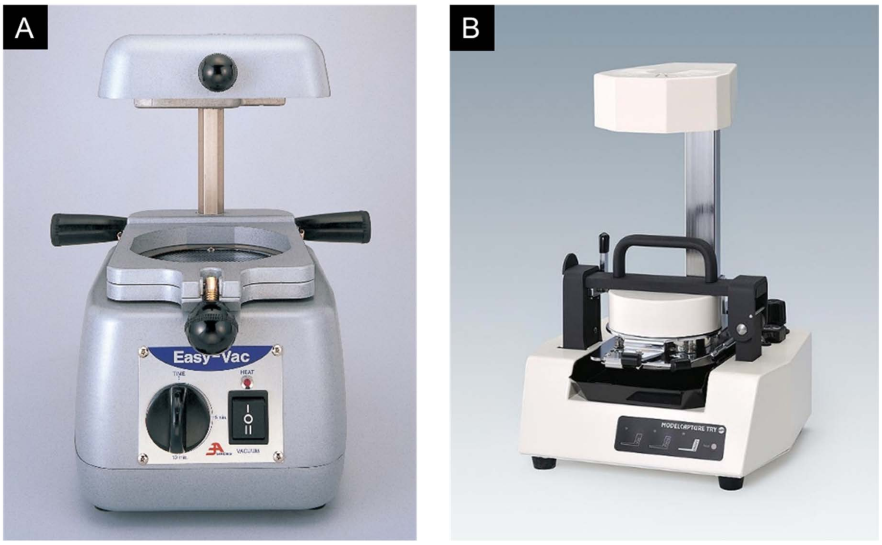

Figure 2. Molding machine. A: vacuum blower molding machine (Vacuum Former EV2). B: vacuum ejector/pressure molding machine (Model Capture Try).

Molding was performed according to the manufacturer's instructions for each molding machine. When the underside of the sheet hung down 15 mm from the sheet frame (*i.e.*, sheet temperature: 95˚C), the sheet frame was lowered and the sheet was pressed against the model [14]. The sheet temperature was measured using a non-contact infrared thermometer. Starting from the molding timing when the sheet temperature was 95˚C, samples were molded at temperatures that were decreased in steps of 2.5˚C. Five samples were prepared at each temperature. The temperature at which five samples without molding defects were obtained (*i.e.*, the lower limit molding temperature) was determined. In this study, when a glossy surface due to residual air on the sheet contact surface was visually observed, it was judged to be a molding defect (**Figure 3**).

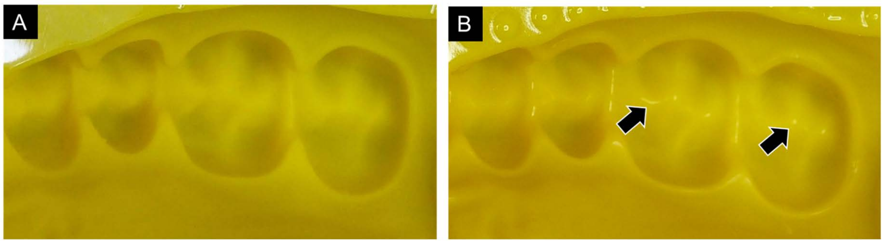

Figure 3. Example of the inner surface of a molded body. (A) Completely thermoformed sheet. (B) Incompletely thermoformed sheet. Arrows indicate glossy areas (insufficient formation) caused by residual air.

2.2. Experiment 2: Comparison of Molding Time between Suction and Pressure Molding Machines

The working model was made from hard gypsum (Hydro gypsum FS; Shofu Inc.) and injecting it into a cylindrical rubber mold (**Figure 4**). The molding method was the same as in Experiment 1, and the sheet was pressed against the model when the underside of the sheet had sagged 15 mm. The duration of the molding pressure was adjusted by operating the switch on the molding machine, and the molding time required to obtain a sample without molding defects was determined. The molding operation and equipment operation status were recorded on video (30 fps) using a digital camera (Coolpix P600; Nikon Corp., Tokyo, Japan) and the molding time was calculated.

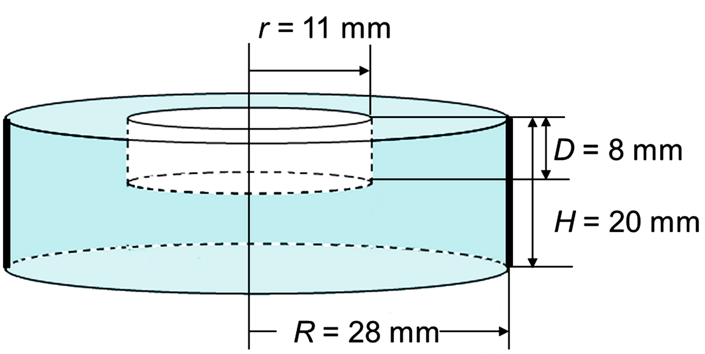

Figure 4. Schematic of the cylindrical working model.

2.3. Statistical Analysis

Statistical analysis software (IBM SPSS 24.0; SPSS Japan Inc., Tokyo, Japan) was used for statistical processing. The Shapiro-Wilk test for normality and Levene's test for homoscedasticity were used for all measurements. Normality and homoscedasticity were observed at each level when comparing the molding times using molding machines. Therefore, a one-way analysis of variance was performed, followed by multiple comparison testing using Bonferroni's multiple comparison test. The significance level was set to $P < 0.05$ in all analyses.

3. Results and Discussion

The lower molding temperature limit was about 90.0˚C for the vacuum blower machine, about 77.5˚C for the vacuum ejector machine, about 77.5˚C for the pressure molding machine at 0.090 MPa, and about 67.5˚C for the pressure molding machine at 0.45 MPa. The lower molding temperature limit was higher for lower absolute values of molding pressure.

The molding time was approximately 15.63 s for the vacuum blower machine, approximately 5.27 s for the vacuum ejector machine, approximately 1.78 s for the pressure molding machine at 0.090 MPa, and approximately 1.05 s for the pressure molding machine at 0.45 MPa. The molding time was shorter for pressure molding than for suction molding. Significant differences were observed between all conditions except between the pressure molding machine at 0.090 MPa and 0.45 MPa ($P < 0.01$) (Figure 5).

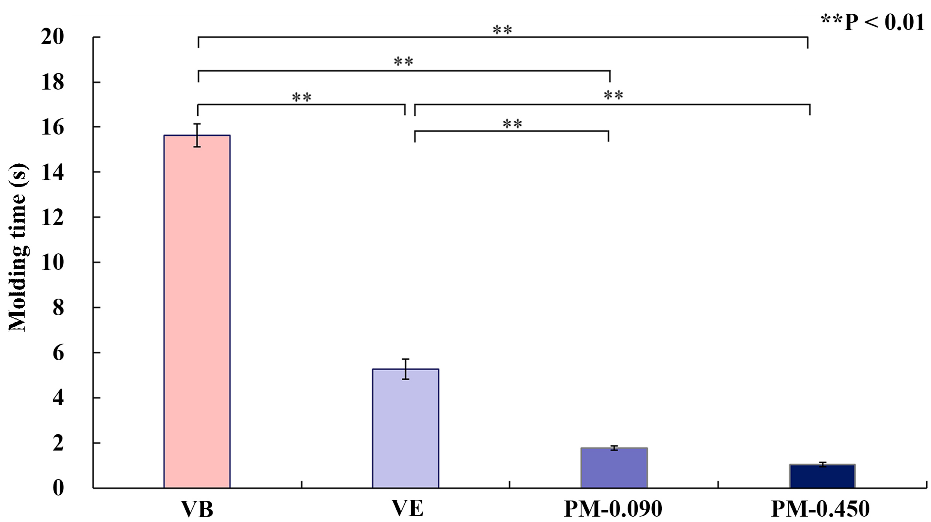

Figure 5. Molding time for each thermoforming machine. VB: vacuum blower molding machine; VE: vacuum ejector molding machine; PM-0.090: pressure molding machine at 0.090 Mpa; PM-0.450: pressure molding machine at 0.450 MPa.

The results of this study showed that the lower molding temperature limit and molding time depended on the forming mechanism. Therefore, the null hypothesis was rejected.

Mouthguard sheets are thermoplastic elastomers with rubber elasticity. In order for a sports mouthguard to exhibit these material properties, it is important to understand that rubber elasticity decreases when the moldable temperature is exceeded and to carry out the molding operation accordingly [1]. The ratio of the molding pressures of the vacuum blower, vacuum ejector, and pressure molding machines is 1:5:25, and thus it is assumed that there are large differences in molding capacity. However, in mouthguard thermoforming, optimal molding temperatures at different molding forces have not been determined. The moldable temperature of ethylene vinyl acetate sheet has been reported to be 80˚C - 120˚C [14], but in the present study, the lower molding temperature limit of the pressure molding machine (0.45 MPa) was 67.5˚C, suggesting that molding at low temperatures may be possible at high molding pressures. In addition, because the lower molding temperature limit for the vacuum ejector machine (−0.090 MPa) and the pressure machine (0.090 MPa) was the same at 77.5˚C, it was inferred that the molding force depends on the absolute pressure value regardless of whether positive or negative molding pressure is used.

Because the molding time may be affected by the area of the suction and exhaust holes on the molding table, a cylindrical model was used in Experiment 2. The molding time was significantly longer for suction molding than for pressure molding. This may be due to the time required for each molding machine to exert the necessary molding pressure [14]. In a preliminary experiment, a time of 1.1 s was required to exert molding pressure with the suction molding machine and 0.1 s with the pressure molding machine. A significant difference in molding time was observed between the vacuum ejector machine and the pressure molding machine with the same absolute molding pressures, indicating that it was the difference in the molding mechanism that affected the molding time. The difference in molding time between the vacuum blower and vacuum ejector machines was due to the difference in molding pressure. In other words, a molding machine with a lower molding pressure may require longer molding time.

In order for sports mouthguards to be effective in preventing or reducing injuries, the thickness and material of the mouthguard are important [15]-[17]. If the sheet is heated for a long time, the mouthguard becomes thinner and its physical properties deteriorate [6]-[8]. In other words, mouthguard performance is affected by the thermoforming process. In order to fully utilize the material properties of a mouthguard, it is important to carry out molding operations that take into account differences in molding mechanisms. This study revealed that the formable sheet temperature and molding time differ depending on the type of molding machines. This is a matter that directly affects the thickness and material properties of the mouthguard, so it is necessary knowledge for those who perform dental thermoforming.

4. Conclusions

A comparison of the differences in lower molding temperature limit and molding time due to molding mechanisms in dental thermoforming revealed that the lower molding temperature limit depends on the molding pressure and that the molding time is longer for suction molding than for pressure molding. These results suggest that the lower molding temperature limit and molding time may affect the thickness and material properties of the mouthguard. In the future, we plan to investigate the effects of the lower molding temperature limit and molding time on the thickness of the mouthguard.

This study has two main limitations. The first is that only one type of ethylene vinyl acetate resin was investigated. The softening temperature may vary depending on the vinyl acetate content and type of resin, and further investigation is required. Second, the study was limited to specific molding equipment. If the molding pressure is known, there is a high possibility that the results of this study can be applied, but more detailed investigation will be required as it may be affected by the shape of the heater and molding table.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Takeuchi, M. and Togaya, N. (2006) Effectiveness of Thermoforming Process for Fabricating of Intraoral Apparatus. Sunashobo, 23-44, 62-67.

[2] Takeuchi, M. and Takahashi, M. (2017) Air Permeability of Gypsum Working Model in Dental Thermoforming Process. *Journal of Sports dentistry*, **20**, 27-33.

[3] Takahashi, M. and Takeuchi, M. (2017) Influence of Surface Treatment Agents on Air Permeability of Plaster Model for Thermoforming. *Journal of Sports dentistry*, **21**, 11-16.

[4] Takahashi, M. and Bando, Y. (2019) Movement of Model Position Just before Vacuum Forming to Ensure Mouthguard Thickness: Part 2 Effect of Model Moving Distance. *Dental Traumatology*, **35**, 291-295. https://doi.org/10.1111/edt.12499

[5] Takahashi, M. and Bando, Y. (2022) Examination of Thermoforming Techniques to Secure Mouthguard Thickness of the Labial and Buccal Sides with a Single Sheet: An *in Vitro* Study. *Dental Traumatology*, **38**, 332-339. https://doi.org/10.1111/edt.12739

[6] Takahashi, M. and Koide, K. (2015) Optimal Heating Condition of Mouthguard Sheet in Vacuum-Pressure Formation: Part 2 Olefin-Based Thermoplastic Elastomer. *Dental Traumatology*, **32**, 90-94. https://doi.org/10.1111/edt.12206

[7] Takahashi, M., Koide, K., Satoh, Y. and Iwasaki, S. (2015) Heating Methods for Reducing Unevenness Softening of Mouthguard Sheets in Vacuum-Pressure Formation. *Dental Traumatology*, **32**, 316-320. https://doi.org/10.1111/edt.12254

[8] Takahashi, M. and Bando, Y. (2020) Controlling Softened State of Mouthguard Sheet during Thermoforming to Ensure Thickness. *Materials Sciences and Applications*, **11**, 431-440. https://doi.org/10.4236/msa.2020.117029

[9] Takahashi, M. and Bando, Y. (2020) Thermoforming Technique for Suppressing Reduction in Mouthguard Thickness: Part 2 Effect of Model Height and Model Moving Distance. *Dental Traumatology*, **36**, 543-550. https://doi.org/10.1111/edt.12554

[10] Takahashi, M. and Bando, Y. (2020) Fabrication Method to Maintain Mouthguard Thickness Regardless of the Model Angle. *Dental Traumatology*, **37**, 131-137.

https://doi.org/10.1111/edt.12584

[11] Takahashi, M. and Bando, Y. (2022) Dependence of Thermoformed Mouthguard Thickness on Model Height in Single-Layer and Laminated Mouthguards. *Materials Sciences and Applications*, **13**, 469-478. https://doi.org/10.4236/msa.2022.138028

[12] Takahashi, M. and Bando, Y. (2023) *In Vitro* Study of How the Undercut Amount on the Model Labial Side Affects the Reduction Rate of Laminated Mouthguard Thickness. *Dental Traumatology*, **39**, 206-213. https://doi.org/10.1111/edt.12820

[13] Maeda, Y. and Matsuda, S. (2006) Forming Machine Usage Manual. Quintessence Publishing, 15-17.

[14] Yamada, J. and Maeda, Y. (2007) Thermoforming Process for Fabricating Oral Appliances: Influence of Heating and Pressure Application Timing on Formability. *Journal of Prosthodontics*, **16**, 452-456. https://doi.org/10.1111/j.1532-849x.2007.00222.x

[15] Gawlak, D., Mańka-Malara, K., Mierzwińska-Nastalska, E., Gieleta, R., Kamiński, T. and Łuniewska, M. (2017) A Comparison of Impact Force Reduction by Polymer Materials used for Mouthguard Fabrication. *Acta of Bioengineering and Biomechanics*, **19**, 89-95.

[16] Bochnig, M.S., Oh, M., Nagel, T., Ziegler, F. and Jost-Brinkmann, P. (2017) Comparison of the Shock Absorption Capacities of Different Mouthguards. *Dental Traumatology*, **33**, 205-213. https://doi.org/10.1111/edt.12324

[17] Tribst, J.P.M., de Oliveira Dal Piva, A.M., Borges, A.L.S. and Bottino, M.A. (2018) Influence of Custom-Made and Stock Mouthguard Thickness on Biomechanical Response to a Simulated Impact. *Dental Traumatology*, **34**, 429-437. https://doi.org/10.1111/edt.12432