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Impact of plasticization temperature on the mechanical properties of sports mouthguards

Impacto da temperatura de plastificação nas propriedades mecânicas de protetores bucais esportivos

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ABSTRACT

Objective: Mouthguards can reduce or even prevent orofacial injuries. These devices are responsible for absorbing part of the energy of an impact force, while the remaining part is dissipated. The present study aimed to evaluate how the plasticization temperature of the sports mouthguards' manufacturing process influences their mechanical properties and protective potential. **Material and Methods:** Specimens were made according to different plasticization temperatures (85°C, 103°C, 121°C and 128°C) and different dental brands of EVA sheets (Bio-art and FGM). Plasticization temperatures were measured using a culinary thermometer (Term; TP300). The mechanical properties evaluated were: energy absorption capacity, deformation, and modulus of elasticity. Compression testing was carried out in the Emic universal testing machine with a speed of 600 mm/min to simulate a punch. **Results:** EVA sheets submitted to the highest temperatures (121°C and 128°C) had their energy absorption capacity reduced. In addition, the samples that plasticized at the lowest temperature (85°C) showed higher absorption capacity, lower elastic modulus, and less variation in its dimensions. It proved to be the most effective in protection and with greater durability. **Conclusion:** The plasticization temperature proved to be an influential factor in the absorption capacity of mouthguards, so the increase in temperature led to a reduction in this property, especially when higher than 120°C. In addition, the plasticization temperature may vary depending on the sheet brand used. Finally, the kitchen thermometer used proved to be efficient and practical, thanks to its easy-to-read display and wide availability on the market.

KEYWORDS

Modulus of elasticity; Mouthguards; Physicochemical absorption; Polyethylene vinyl acetate; Temperature.

RESUMO

Objetivo: Os protetores bucais são capazes de reduzir ou mesmo prevenir lesões orofaciais. Esses dispositivos são responsáveis por absorver parte da energia de uma força de impacto, enquanto a parte restante é dissipada. Este estudo teve como objetivo avaliar como a temperatura de plastificação de protetores bucais esportivos influencia em suas propriedades mecânicas e no seu potencial protetivo. **Material e Métodos**: Foram confeccionados modelos de trabalho segundo diferentes temperaturas de plastificação (85°C, 103°C, 121°C e 128°C) e distintas marcas odontológicas de placas de EVA (Bio-art e FGM). As temperaturas de plastificação foram medidas com termômetro culinário da marca Term/TP300. As propriedades mecânicas avaliadas foram capacidade de absorção de energia, deformação e módulo de elasticidade. O teste de compressão foi realizado na máquina de ensaios universal Emic com velocidade de 600 mm/min, a fim de simular um soco. **Resultados**: As placas de EVA submetidas às mais altas temperaturas (121°C e 128°C) tiveram sua capacidade de absorção de energia reduzida. Além disso, as amostras que plastificaram na temperatura mais baixa (85°C) apresentaram maior capacidade de absorção, menor módulo de elasticidade e menor variação em suas dimensões. Assim, mostraram-se a mais eficaz na proteção e com maior durabilidade. **Conclusão:** A temperatura de plastificação demonstrou ser um fator influente na capacidade de absorção dos protetores bucais, de modo que o aumento da temperatura levou a uma redução desta propriedade, principalmente quando superior a 120°C. Além disso, a temperatura de plastificação pode variar dependendo da marca comercial utilizada. Por fim, o termômetro culinário utilizado mostrou-se eficiente e prático, pela facilidade de leitura e por ser facilmente encontrado no mercado.

PALAVRAS-CHAVE

Módulo de elasticidade; Protetores bucais; Absorção físico-química; Polietileno vinil acetato; Temperatura.

INTRODUCTION

Several studies point out how sports practice is closely related to orofacial injuries and brain concussions. Among the sports, the most affected are those of contact, such as football, basketball, handball, and, mainly, martial arts [1-5].

Mouthguards are devices crafted to cover both the teeth and gums, aiming to prevent trauma. Their key objectives involve safeguarding soft tissues like the tongue, cheeks, and lips, along with providing protection to teeth and their associated structures. Additionally, it prevents the occurrence of brain concussions and injuries to the temporomandibular joint [6-8].

Mouthguards work by absorbing part of the energy of an impact force, while the remaining part is dissipated. Thus, it must have a high power of energy absorption in addition to the ability to dissipate forces along its entire length [6,8,9].

There are 3 types of mouthguards: prefabricated (Type I), thermoplastic (Type II), known as “boils and bites,” and customized (Type III). Type IIIs are manufactured in the laboratory by a dentist from plaster models of the patient’s dental arches. Since they ensure greater proportionality with the dental arch, these present greater adaptation and retention, being the gold standard [6,8,10].

Nowadays, a new variant classification of type III has been developed, the personalized multilaminate mouth guards (Type IV), which are made from several layers of EVA sheets [11,12].

EVA (ethylene-vinyl acetate), a material known for its exceptional qualities, stands out as the optimal choice for crafting sports mouthguards. Its remarkable damping capacity, coupled with a reduced hardness, ensures superior energy absorption and steadfast product quality. These attributes make EVA particularly favorable for the construction of reliable and stable mouthguards [8,9,13]

The manufacturing of mouthguards is carried out by EVA sheets and the vacuum process is composed of different stages that can be summarized as placing the model in the center of the vacuum former machine and then pressing the heated sheet onto it with negative pressure. Several factors can influence the result, such as the final thickness of the mouthguard, the residual humidity of a previous process, the height and positioning of the sheet in the former, and the forming temperature are some of the variables described in the literature. Therefore, the variation in the production process can directly influence its impact on energy absorption capacity [14-16].

Beyond the fabrication process, Haddad and Borro et al. [17], argue that the surface treatment of the mouthguard during its cleaning and storage also influences the maintenance of its properties. Their study evaluated the interference in the wettability and roughness properties of the mouthguard, according to different cleaning methods. The investigation revealed that immersion of EVA in an effervescent solution of sodium bicarbonate induced notable surface alterations. In contrast, employing a toothbrush, water, and neutral soap for mouthguard cleaning exhibited superior efficacy, thus indicating their superiority as the more appropriate method. In parallel with this study, there is a clear need to investigate and standardize the fabrication and maintenance methods of sports mouthguards in order to preserve their comfort and protective capabilities.

Furthermore, a narrative literature review conducted by de Queiroz et al. [8], concludes that there is a need to develop mouthguards with higher stress-absorption efficiency. There exists a vast range of research opportunities in the field of mouthguards, mainly regarding force dissipation, reinforcement incorporation, and additive manufacturing. It is imperative to undertake studies to explore the possibility of using different reinforcing materials and new fabrication methodologies for these devices

Bearing in mind the necessity to elevate the stress-absorption capacity of these devices, the present work aims to investigate the influence of temperature in the manufacturing process of a mouthguard on its energy absorption capacity.

MATERIAL AND METHODS

Specimens

Two different groups of dental brands of soft sheet for mouthguards, Group B (EVA soft plate; Bio-art Dental Equipment Ltd; São Paulo, Brazil) and Group F (EVA soft plate; FGM Whiteners - Whiteness do Brasil Industry Ltd; Santa Catarina, Brazil), based on ethylene and vinyl acetate copolymer (EVA) with 3mm thicknesses, were thermoplasticized onto a plateau-shaped working model. In order to guarantee two different temperatures of plasticization, two different vacuum-forming machines were used: No. 1 with ceramic resistance (Vacuum forming machine with motor; Essence Dental Import and Export Ltd; São Paulo, Brazil) and No. 2 with carbon resistance (Plastvac P7; Bio-art Dental Equipment Ltd; São Paulo, Brazil).

Each dental brand EVA sheet was assigned to a type of vacuum forming machine, with Groups B1, B2, F1, and F2 referring to the specimens resulting from Groups B and F submitted to vacuum forming machines 1 and 2, as shown in Table I.

Around 40 specimens for each group were obtained by manually cutting four sheets of each brand. On average, each specimen exhibited initial diameters and thicknesses of 9.23 mm and 2.72 mm, respectively.

During the heating process, a culinary thermometer (Term TP300; Knup Import and Export Ltd., China) was used, positioned in the vacuum forming machine between the thermal source and the base where the sheet is attached to measure the temperature. The sheet was considered ready to use by visual observation based on the parameters of changes in translucency and the lowering of the sheet in relation to the base level in the form of a bubble. Once these properties were achieved, the plasticization temperature was determined, and the heated sheet was pressed on the working model.

Table I - Plasticization temperature

Groups	Temperature
B1	103°C
B2	128°C
F1	85°C
F2	121°C

Compression test

The compression test was carried out on the Emic DL2000 (Instron Brazil Scientific Equipment Ltd.; Parana, Brazil) universal testing machine with the Tesc program version 3.04. A speed of 600 mm/min was determined for all 4 groups. For each group, the elasticity modulus was determined and is illustrated in Figure 1, while the average absorbed energy is presented in Table II.

Specimens' measurement

A digital caliper (Digimess, Precision Instruments Ltd; São Paulo, Brazil) with an accuracy of 0.01mm was used to measure the final and initial thicknesses (mm) and diameters (mm) of

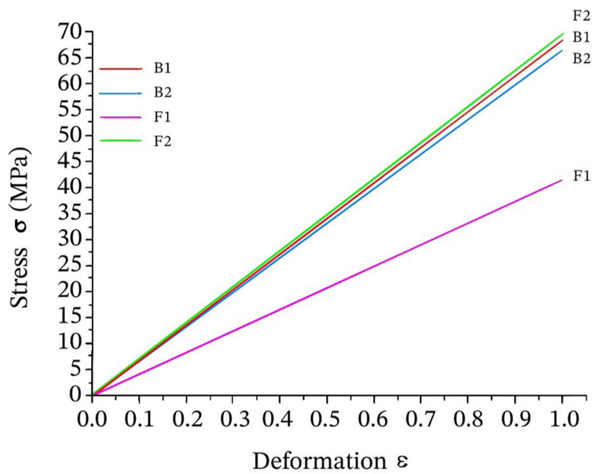

Figure 1 - Elastic modulus graph.

Table II - The average energy absorbed standard deviation is in parentheses. The same letter means statistical equality

	Average energy absorbed (N.mm/mm³)
Group B1 (*a*)	13.19 (0.84)
Group B2 (*a*)	10.96 (2.32)
Group F1 (*b*)	15.55 (1.68)
Group F2 (*a*)	12.52 (2.042)

Table III - Deformation and variation in thickness and diameter. The same letter represents statistical equality

	Deformation average (mm/mm)	Thickness variation (%)	Diameter variation (%)
Group B1 (*a*)	0.7440	8.3%	6.63%
Group B2 *(a)*	0.7069	13%	5.6%
Group F1(*b*)	0.1599	5%	4.6%
Group F2 *(a)*	0.7247	8%	6.63%

the specimens from the 4 groups. The variations in these measurements and the average deformation for each group are presented in Table III.

Results analysis

Data analysis was carried out according to the following parameters:

- Absorbed energy ($N.mm/mm^3$): Obtained with the Tesc program version 3.04
- Average deformation (mm/mm): Obtained with the Tesc program version 3.04
- Percentage of thickness variation (%), with the formula:

$$\left(Ef - Ei\right) / Ef) \ *100 \quad (1)$$

Ef: Average thickness after the compression test

Ei: Average thickness before the compression test

- Percentage of diameter variation with the formula:

$$\left(Df - Di\right) / Df) \ *100 \quad (2)$$

Df: Average diameter after the compression test

Di: Average diameter before the compression test

- Modulus of elasticity obtained by Hooke's law:

$$\sigma = E * \varepsilon \quad (3)$$

σ: Stress (MPa)

E: Modulus of elasticity (MPa)

ε: Deformation (dimensionless)

The analysis was carried out with 40 sample units per group using ANOVA followed by Tukey's test for multiple comparisons. The test power was calculated Post Hoc, showing a test power of 0.998 (G*Power 3.1.9.7). The confidence interval adopted was 95% and $p<0.05$ (5%) was considered statistically significant.

RESULTS

Comparison of means

Statistical analysis of the comparison of means was performed using Tukey`s test with $p=0.05$. It was found that Group F1 obtained the best results with statistical significance, while the other groups proved to be statistically equal.

Absorbed energy determined in the compression test

Concerning the average energy absorbed, as shown in Table II, Groups F1 and B1 reveal the highest absolute values, respectively, followed by Groups F2 and B2. Furthermore, Group B1 presents the lowest standard deviation among all, revealing a lower rate of failures when using this device material.

Although Groups B1 and B2 are from the same brand, Group B2 was plasticized at a higher temperature (128°C) compared to Group B1 (103°C), thus the average energy absorbed in Group B2 was lower than Group B1.

Likewise, despite Groups F1 and F2 being of the same brand, Group F2 was plasticized at a higher temperature (121°C) than Group F1 (85°C), so the average energy absorbed in Group F2 was lower compared to Group F1.

When comparing the groups of each dental brand in general, the average values of absorbed energy for Brand F are higher than for Brand B.

Deformation and percentages of variation in thickness and diameter

Table III reveals that groups B1, B2, and F2 recorded very close deformation averages, however, the average in Group F1 proved to be around 5 times lower than the others. The percentage of thickness variation in Group F1 proved to be the smallest, while that in Group B2 was the largest. The diameter variation in Group F1 presented the lowest percentage, however, the greatest variation was observed in Groups B1 and F2, which presented the same values.

Group F2, plasticized at a higher temperature, showed an increase in the percentages of variation in thickness and diameter. In Brand B, the greatest variation in thickness was noted in Group B2, which was in agreement with what was observed in Brand F, also plasticized at a higher temperature. However, the opposite occurred with the diameter, where Group B1 with the lowest plasticization temperature expressed the greatest variation.

Modulus of elasticity

As illustrated in Figure 1, and according to Hooke's Law, where the angle under the stress-strain curve indicates the modulus of elasticity, Group F1 showed the lowest modulus of elasticity.

DISCUSSION

Even though there is a consensus that the type III protector is considered the gold standard, there is no standardization of its manufacturing method in the literature, which allows for different variations that are likely to decrease its protective capacity [10].

The mechanical behavior of EVA was analyzed by Coto et al. [9], who observed that the thickness of the material had a great influence on the protection potential, so that the greater the thickness of the mouthguard, the better the dissipation and redirection of forces.

In 2016, Mizuhashi et al. [18], evaluated the variation in mouthguard thickness according to different heating conditions. To accomplish this, the EVA sheet was heated until the center was displaced by 10, 15, and 20 mm from the baseline of the vacuum-pressure former. Thus, the greater the distance from the center, the greater its heating. It was found that among the 3 evaluated conditions, 20 mm, corresponding to the highest temperature reached, obtained the best result since it adopted a greater thickness to the mouthguard.

Yamada and Maeda [14] conducted a study on the influence of temperature and pressure application time on the mouthguard formation. As a result, the ideal temperature for plasticization of the EVA sheet was determined in the range of 80°C – 120°C through the observation of an evaluator regarding the change in the characteristics of thickness, texture, and shape of the working models.

In the present study, working models were made similarly to the study by Yamada and Maeda [14], since it had a single evaluator to determine the moment of vacuum plasticization by changes in shape, texture, and translucency. Mizuhashi et al. [18], used dental arch models for plasticization and found that in the incisor region, the thickness of the incisal portion was smaller than the cervical portion of the tooth. In the present study, however, it was stipulated that working models were plasticized on a plateau in order to isolate the variance in thicknesses resulting from the different dental anatomical regions. According to Takahashi et al. [19], the continuous use of the same former machine could change the properties of the mouthguard, so a minimum interval of 10 minutes should be applied between each lamination. To maintain a pattern and avoid interference, the current research respected this interval.

Tribst et al. [5] carried out a comparative study where the stress caused by different types of punches was measured in models of human skulls with and without a mouthguard. The results showed that the highest tensile stress peaks were observed in the upper central incisors and that the closer the impact region is to the dental structures, the greater the stress dissipation capacity of the protector.

A good performance in boxing depends on the combination of strength and speed in applying punches in a fight. A comparative study sought to analyze these kinematic parameters between 2 groups of boxers, one composed of Olympic medalists and the other of well-trained young people. Punch speed and impact force were higher in the Elite group, however, it was possible to identify an average equivalent to 10 m/s or 600,000 mm/min between the two groups [20].

Considering the above study, the present research established a speed of 600 mm/min for analysis of energy absorption in type III mouthguards to simulate the average impact speed of a punch.

The comparative analysis of plasticization temperatures showed that the groups subjected to the highest temperatures, corresponding to 128°C in Group B2 and 121°C in Group F2, had their energy absorption capacity reduced. This finding reaffirms the study by Yamada and Maeda [13] since both temperatures are higher than the ideal EVA plasticization range (> 120°C) and present a lower performance of the material. Groups B1 and F1, plasticized within the ideal range between 80°C and 120°C, showed better energy absorption.

The physical and mechanical properties of the sheets vary with the chemical composition of the material, and even commercial brands made of the same material can also vary in terms of these properties [13,21]. Likewise, when comparing Groups B1 and F1, composed of EVA and plasticized within the ideal temperature range, the last one showed that it reached the plasticization point at a lower temperature and also presented a better capacity to absorb energy.

The modulus of elasticity refers to a fundamental mechanical property of the material that can be measured through the slope coefficient of a straight line and a stress-strain graph obtained in the elastic regime. In the elastic regime, when removing the force causing deformation, all absorbed energy must be fully returned. Flexible materials undergo greater deformation within their elasticity range, while rigid materials do not flex and, when absorbing energy, can reach their fracture limit. Therefore, the modulus of elasticity is higher in rigid materials and lower in flexible materials such as EVA [22].

The graphs referring to the modulus of elasticity show that Group F1 plasticized at the lowest temperature and with the highest absorption capacity, presented the lowest modulus of elasticity among the others. At first, considering the plasticized groups within the ideal temperature range, Brand F proved to be superior to Brand B in terms of energy absorption capacity. However, with the increase in temperature, the performance of the Brand F test specimens became similar to that presented by Brand B, which can be possibly attributed to the change in the microstructure of the Brand F material and, consequently, its change in elastic modulus. As a result, it is possible to establish as a preliminary result that, depending on the commercial brand, the plasticization temperature can in fact influence the modulus of elasticity of the material and, consequently, its ability to absorb energy.

Furthermore, Group F1, which was plasticized at the lowest temperature, showed greater absorption capacity, and lower modulus of elasticity, in addition to less variation in its dimensions. As a result, it proved to be the most effective in protection and with the greatest durability. However, in Brand B, the different plasticization temperatures showed little interference in the change in the elastic modulus, expressing a tolerable difference. Furthermore, Group B2 exhibited the lowest standard deviation during compression tests, which may be an indication that this is a more reliable material for experiments since it had a lower failure rate.

Finally, the present study highlighted the possibility of measuring the temperature of a vacuum laminator using a culinary thermometer, an accessible tool in terms of value and availability on the market. Thus, the dentist can check and control the plasticization temperature in his own office in order to promote better properties for the sports mouthguard.

CONCLUSION

The plasticization temperature of EVA sheets significantly influences the absorption capacity of mouthguards. An increase in temperature led to a reduction in this property, especially when higher than 120°C. However, the influence of the plasticization temperature on the process of manufacturing a mouthguard may vary depending on the commercial brand used.

The culinary thermometer can be easily used to check the plasticization temperature by the dentist in his office in order to provide better properties to the mouthguard.

Author's Contributions

ESRS: Conceptualization, Methodology, Investigation, Resources, Data Curation, Writing – Original Draft Preparation. TRMG: Conceptualization, Methodology, Resources, Writing – Review & Editing, Visualization, Supervision. SSIO: Validation, Formal Analysis, Writing – Review & Editing, Visualization, Supervision. KMW: Validation, Formal Analysis, Visualization, Supervision. LGM: Validation, Formal Analysis, Visualization. JNSMDM: Validation, Formal Analysis, Visualization.

Conflict of Interest

The authors have no conflicts of interest to declare.

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Regulatory Statement

Not applicable.

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