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Assessment of Mechanical Properties of Different Thermoplastic Orthodontic Retainers before and after Thermoforming

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ABSTRACT

Background and Objective: After orthodontic treatment, it is very important to maintain and preserve them and prevent them from returning to their original position. Given that the lifespan of different thermoplastic orthodontic aligners affects the durability of thermoplastic retainers, this study was conducted to compare the mechanical characteristics of three types of thermoplastic retainer materials before thermoforming (BT) and after thermoforming (AT).

Methods: In this in-vitro study, 120 sheets of three types of materials were used: Clear Advantage Series I, Clear Advantage Series II, and Leone, each material having a thickness of 1 mm. The elastic modulus and surface hardness were measured and compared for 60 thermoformed and 60 non-thermoformed samples. Each material was measured in two states of BT and AT.

Findings: The investigated materials' elastic modulus differed significantly BT (G1: 2172.13±64.78, G2: 2394.47±113.40, G3: 2557.69±159.90). In addition, it differed significantly AT (G1: 2062.97±66.79, G2: 1834.47±73.67, G3: 2432.79±71.52). All studied materials showed a significant decrease in elastic modulus AT ($p\leq0.05$). In the case of surface hardness, it differed significantly BT (G1: 9.815±0.465, G2: 7.915±0.251, G3: 10.948±0.873). In addition, it differed significantly AT (G1: 11.185±0.387, G2: 12.035±0.261, G3: 11.498±0.381). All studied materials showed a significant increase in hardness AT ($p\leq0.05$).

Conclusion: The results of this study showed that thermoforming can greatly affect thermoplastic materials' mechanical characteristics, making them less flexible and harder. In addition, these findings showed that PETG would be an appropriate choice for applications requiring a high degree of stiffness and that polypropylene could be more suitable for applications requiring a high degree of hardness making them more abrasion resistance. Copolyester does not have the most outstanding values in every characteristic, which offers average properties regarding stiffness and hardness.

Keywords: *Hardness, Mechanical Properties, Orthodontic Thermoplastic Retainers, Retainer Materials, Thermoforming.*

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Introduction

Retention is crucial after orthodontic treatment to maintain the alignment of teeth and prevent them from moving back to their original positions (1). It also enhances long-term patient satisfaction with the outcomes (2, 3). Studies have shown that, despite effective treatment, teeth often revert to their initial positions (4, 5). Typically, the choice of retainer is made by the orthodontist and the patient without specific guidelines (6). Thermoplastic retainers are popular due to their aesthetic design and clear appearance, leading to high usage rates and good patient compliance with these devices (7).

Heating the material during the vacuum or pressure-forming process, which is required to produce thermoplastic retainers, may irreversibly alter its morphological and mechanical characteristics. Moreover, thermoplastic materials may mechanically degrade during insertion and removal from the oral cavity (8). This degradation appears at the morphological level and may cause the properties of the materials to deteriorate (9, 10). In turn, their ability to maintain the teeth in place is impaired. Many restrictions are associated with using thermoplastic retainers in clinical settings. For example, they might wear out, break, and have a shorter life span (7, 11).

Generally, practitioners have little agreement on the most efficient retention strategy, and they often differ significantly (12, 13). However, most orthodontists now accept the need for lifetime retention (14, 15). According to various studies, long-term retention is the only way to maintain stability (16, 17). Retainer material is gradually worn off by the patient's mouth (9). In order to save expenses and maintain the results of orthodontic treatment, thermoplastic retainers must be made of stronger, more resilient materials (18). In addition, durability is a critical consideration in evaluating the cost-effectiveness of thermoplastic retainers because they have been designed to last a lifetime (19).

To the best of our knowledge, little research has evaluated how the mechanical properties of the following thermoplastic retainer materials are affected by thermoforming to predict potential clinical applications of Clear Advantage™ Series I, Clear Advantage™ Series II, and Leone materials. In the present investigation, we evaluated and compared the results of the elastic modulus and hardness tests conducted before and after thermoforming.

Methods

Specimen preparation: This study is an in-vitro investigation. After being approved by the ethics committee of the College of Dentistry, University of Baghdad with project NO. 762423, it was conducted with the following thermoplastic materials that were used for producing vacuum-formed retainers (VFRs): Copolyester Clear Advantage™ Series I Retainer Material (Ortho-Technology, Tampa, Florida, USA), Polypropylene Clear Advantage™ Series II Durable Retainer Material (Ortho-Technology, Tampa, Florida, USA), and Polyethylene Terephthalate modified with Glycol (PETG) Material of Leone® (Leone, Firenze, Italy). 120 sheets of three different thermoplastic materials with a consistent thickness of 1 mm are divided into:

Group 1: Copolyester (CP) thermoplastic sheets.
Group 2: Polypropylene (PP) thermoplastic sheets.
Group 3: Polyethylene Terephthalate modified with Glycol **(**PETG) thermoplastic sheets.

Each material was measured as not yet thermoformed (BT) and after the thermoforming process (AT). Using a Biostar® pressure-molding machine (Scheu Dental, Iserlohn, Germany), sheets of thermoplastic materials were thermoformed. The sheets were heated according to the manufacturer's recommendations,

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then vacuumed and pressed onto a 3D custom-made stone disk. This 80×12 mm disk resembled a mold for the thermoforming machine.

Tensile test: Twenty specimens of each material before and after thermoforming were subjected to the tensile test. Using a CNC machine (CNC Technology Co., Shandong, China), dumbbell-shaped specimens measuring 63.5 mm in length and 9.53 mm in width were created, following the EN ISO 527-2 guidelines (20). A universal testing machine (Laryee Technology Co., Beijing, China) was used for the tests, which were performed at 23±2°C, with an initial grip spacing of 20 mm. The elastic modulus was obtained by adjusting the crosshead speed to 12 mm/min. Thus, the elastic modulus values were calculated automatically by the stress-strain curve that appeared at the end of the tensile test (Figure 1) (21).

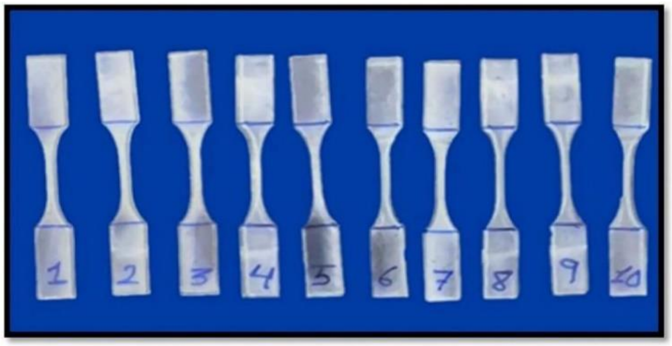

Figure 1. Sheets after cutting with CNC machine and encoded

Vicker's hardness test: The three thermoplastic materials' surface hardness values were determined using an HVS-1000 Vickers hardness tester (Laryee Technology Co, Beijing, China) (Figure 2). Twenty specimens from each material BT and AT measuring 9×13 mm were prepared. Three indentations were made in each specimen using a pyramid-shaped diamond indenter under a 10 N force for 10 s. The diameters of the generated squares were measured using a light microscope at 40 X magnification.

The Vickers number, or HV, was obtained using the following formula:

$$HV = 1.854 \frac{f}{d^2}$$

F is the loading force, and d is the mean of the indentation diameters. For each material, the mean and stranded deviation values of the specimens were calculated (22).

Figure 2. Vicker’s hardness device for measuring the surface hardness

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SPSS version 26 (SPSS Inc., Chicago, IL, USA) was utilized for statistical analysis. Mean and standard deviation (SD) were calculated for each data set. Shapiro-Wilk and Levene's tests assessed normality and homogeneity of values. Two Sample *T-tests* compared pre- and post-thermoforming data. One-way ANOVA and Tukey's post-hoc test analyzed the elastic modulus and hardness data. A p≤0.05 was regarded as statistically significant. G Power software (version 3.1.9.7; Franz Faul, Kiel University, Kiel, Germany) was used for sample size calculation. With a power of 85% and α error of 0.05%, the estimated sample size was 120 sheets of the three different thermoplastic materials. The data was acquired from research published by Ryu et al. (23). Moreover, the coding of samples aided the randomization during the study.

Results

Tensile test: The elastic modulus of all tested materials decreased after thermoforming (Table 1). The mean elastic modulus values for G1, G2, and G3, BT were 2172.13±64.78, 2394.47±113.40, and 2557.69±159.90, respectively. While AT, the mean elastic modulus values were for G1: 2062.97±66.79, G2: 1834.47±73.67, and G3: 2432.79±71.52. There were significant differences (p≤0.05) between BT and AT. The comparison of the mean difference of elastic modulus among all groups using One-way analysis of variance (ANOVA) BT and AT indicated significant differences (p≤0.05) between all groups. In addition, the Post-hoc Tukey's (HSD) test revealed that there were significant differences (p≤0.05) among all groups BT and AT.

Surface hardness test: All tested materials' hardness increased following thermoforming (Table 2). The mean hardness values for G1, G2, and G3, BT were 9.815±0.465, 7.915±0.251, and 10.948±0.873, respectively. While AT, the mean hardness values were for G1: 11.185±0.387, G2: 12.035±0.261, and G3: 11.498±0.381. There were significant differences (p≤0.05) between BT and AT. In addition, there were significant differences (p≤0.05) in the surface hardness values between all groups, BT and AT. The Post-hoc Tukey's (HSD) test revealed that there were significant differences (p≤0.05) between all groups BT. While AT, there were significant differences (p≤0.05) between the groups, except between the G1 and G3, which showed no significant difference.

Table 1. Descriptive and inferential statistics for comparisons of elastic modulus values between different groups before and after thermoforming

Groups	G1 (MPA) Mean±SD	G2 (MPA) Mean±SD	G3 (MPA) Mean±SD	Comparison F-test	Comparison p-value	Tukey's HSD test Between subgroups	Tukey's HSD test p-value
BT	2172.13±64.78	2394.47±113.40	2557.69±159.90	26.362	0.000*	G1-G2	0.000*
						G1-G3	0.000*
						G2-G3	0.001*
AT	2062.97±66.79	1834.47±73.67	2432.79±71.52	182.277	0.000*	G1-G2	0.000*
						G1-G3	0.000*
						G2-G3	0.000*
T-test	3.71	13.10	2.26				
p-value	0.002*	0.000*	0.037*				

***Indicates statistically significant differences at (p≤0.05)**

BT: before thermoforming, AT: after thermoforming

G1: Copolyester (CP), G2: Polypropylene (PP), G3: Polyethylene Terephthalate modified with Glycol (PETG)

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Table 2. Descriptive and inferential statistics for comparisons of surface hardness values between different groups before and after thermoforming

Groups	G1 Mean±SD	G2 Mean±SD	G3 Mean±SD	Comparison		Tukey's HSD test	
				F-test	p-value	Between subgroups	p-value
BT	9.815±0.465	7.915±0.251	10.948±0.873	100.401	0.000*	G1-G2	0.000*
						G1-G3	0.000*
						G2-G3	0.000*
AT	11.185±0.387	12.035±0.261	11.498±0.381	7.891	0.000*	G1-G2	0.001*
						G1-G3	0.465
						G2-G3	0.047*
T-test	7.148	35.816	2.532				
p-value	0.000*	0.000*	0.014*				

***Indicates statistically significant differences at $(p \leq 0.05)$**

BT: before thermoforming, AT: after thermoforming

G1: Copolyester (CP), G2: Polypropylene (PP), G3: Polyethylene Terephthalate modified with Glycol (PETG)

Discussion

The tensile test conducted in the present study was used to assess the durability of the tested thermoplastic materials. Based on the results of the elastic modulus, there were significant differences between all the materials before and after thermoforming. The elastic modulus values of all the materials decreased significantly after thermoforming.

Our study's findings are consistent with those of Dalaie et al., who demonstrated that thermoforming considerably lowered Erkodur sheets' flexural modulus, hardness, elastic modulus, and glass transition temperature (22). After the thermoforming process, Golkhani et al. examined the alterations in PET-G sheets and discovered a statistically significant decrease in elastic modulus (24). Similarly, PET-G trapezoidal prism specimens showed a significant decrease in elastic modulus, as noted by Ryu et al. (23). Furthermore, this is in line with the results of Staderini et al., who discovered a slight but non-significant decrease in the tested material's elastic modulus (25). Tamburrino et al. demonstrated a significant increase in the specimens' elastic modulus following thermoforming in contrast to the current data (21). They attributed this rise to a process called "drawing," which happens when the material becomes heated and pulled, causing the chains of polymers to slide over one another and orient some of the chains in the direction of the force.

Thermoplastic materials may thin and deform if temperatures exceed the glass transition point. By contrast, changes in mechanical characteristics accompany their shift from an amorphous to a crystalline form upon decreasing temperature, as reported by Hallmann et al. (26). The fundamental reason for the minor alterations in the material's mechanical characteristics may be this decrease in thickness during thermoforming (25), which happened in this study where there was a decrease in elastic modulus. The highest elastic modulus value was in the case of Leone material (PETG), an intermediate elastic modulus value was in the case of Clear Advantage™ Series I (CP), while the lowest elastic modulus value was for Clear Advantage™ Series II (PP). These findings appeared to be related to changes in the molecular arrangement within every specimen, as PETG and CP are amorphous polymers, while PP is a crystalline polymer (27). The polymers with low crystallinity often exhibit high elasticity (26).

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Vickers hardness was another mechanical property that we looked at in our investigation. Since hardness measures a substance's resistance to penetration, this property describes how a material responds upon contact. Consequently, appropriate thermoplastic materials should exhibit high wear resistance (high hardness) (28). Based on the results, there were significant differences between the materials pre- and post-thermoforming, except between the Clear Advantage™ Series I and Leone materials, which showed no significant differences after thermoforming. Following thermoforming, all of the materials' hardness evaluations increased significantly. Our study's findings are in line with those of Ryu et al., who observed that thermoforming did not change Duran's hardness but increased the hardness of the other materials tested (23). On the contrary, Dalaie et al. found that Duran and Erkodur materials become less hard following thermoforming (22). Furthermore, Albilali et al. discovered significant differences in the hardness values of several thermoplastic retainer materials after thermoforming (29).

Therefore, changes in molecular weight, chemical structure, density, ingredients, state of polymerization, and crystallization across the various thermoplastic polymers may account for the observed increase in hardness across different materials (29, 30). Furthermore, closer alignment of polymer chains and increased surface hardness result from stronger secondary bonding forces, as shown by Gerard Bradley et al. (31). The highest hardness value was in the case of Clear Advantage™ Series II (PP), while an intermediate hardness value was in the case of Leone material (PETG), in addition, the lowest hardness value was for Clear Advantage™ Series I (CP). The hardness of PP (crystalline polymer) was greater than that of CP and PETG (amorphous polymers) due to the elevated pressure and temperature exerted on the material during thermoforming, resulting in straight polymer chains tightly organized across a relatively long distance. Furthermore, the buildup of the secondary bonding force in the crystalline polymer results in a stronger bonding force than in an amorphous polymer (32, 33).

However, the research's conclusions should be further examined because clinical settings differ markedly from the oral circumstances used in this investigation. A limitation arose when specimens with an overall thickness of only 1 mm were used in this study. Subsequent research ought to compare specimens with varying thicknesses.

The present study’s findings showed that the thermoforming process alters the mechanical characteristics, resulting in a less stiff and tougher retainer material. Furthermore, it is shown that the maximum resistance to deformation under applied load was provided by the high stiffness of Leone materials (PETG). Conversely, the Clear Advantage Series II (PP), having the maximum hardness of all the materials evaluated, provides excellent resistance to surface indentation or abrasion. Thus, these results imply that PETG would be a good option for applications needing high stiffness, whereas Polypropylene might be better suited for those needing high hardness such as bruxism patients. Copolyester may compromise stiffness and hardness, although it does not have the highest possible values in every characteristic.

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