

Evaluation of mechanical changes to clear aligners caused by exposure to different liquids

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Introduction: The purpose of this study was to compare the mechanical changes of clear aligners manufactured using either the direct method (Graphy Tc-85) or the indirect method (CA Pro or Invisalign) following an exposure to different liquids.

Material and Method: The clear aligners were produced using a single patient's digital maxillary model. CA Pro aligners were produced indirectly using the Ministar S device, while Graphy Tc-85 resin aligners were produced directly using a three-dimensional printer (Ackuretta, Taipei, Taiwan). Invisalign appliances were produced by Align Technology, Inc. The appliances were randomly divided into seven groups: a control group and six experimental groups. The control group appliances were not immersed in any liquid. The appliances in the experimental groups were immersed in six different liquids (orange juice, soy sauce, cola, red wine, tea, and coffee) for 24 hr at 37°C. Following immersion, the upper right first molar section of each appliance was separated using an abrasive disc and embedded in a 2 mm thick acrylic layer. A cyclic loading test was conducted using a specialised mechanism (a combination of a dynamometer and a deformation depth measuring instrument) and each sample was subjected to varying cyclical forces until a deformation depth of 1 mm was reached. The force magnitude required to achieve the 1 mm material deformation at the 1st, 5th, 10th, and 50th cycles of loading was recorded for each sample.

Results: As a result of repeated loads, the indenting force values decreased in the three sample groups, regardless of the liquid in which the appliances had been stored. However, soy sauce and orange juice had a greater detrimental effect on the mechanical properties of the aligners compared to the other liquids. On comparing the force values required for the material to reach a 1 mm depth during the 1st and 50th loadings, the decreases were recorded as 0.4% for Graphy Tc-85, 26.3% for CA Pro, and 42.1% for Invisalign.

Conclusions: Of the tested aligners, Graphy Tc-85 was the most resistant to repetitive loads, while Invisalign was the least resistant. It is inherently difficult to predict how different liquids will affect aligners made of different materials.

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Introduction

Clear aligners, which have become increasingly popular in line with the increasing aesthetic demands of orthodontic patients, have led to the market involvement of many manufacturing companies. The majority of aligner producers use an indirect fabrication method in which digital models are first created by a 3D printer.¹ The aligners are subsequently thermo-formed on the printed models using polymers which include polyethylene terephthalate glycol (PET-G), polypropylene, polyurethane

(PU), polycarbonate (PC), thermoplastic urethanes (TPU), and ethylene vinyl. The desired properties of the polymer combinations are high flexibility, transparency and the capacity to maintain flexibility under repeated loads.² Each company's unique viscoelastic aligner composition has an impact on the product's mechanical qualities.

Recent advancements in technology have made it possible to produce clear aligners directly using three-dimensional printers and liquid resins of which Graphy Tc-85 (Graphy, Seoul, South Korea)

is commonly-used.³ The direct production of aligners from resins reduces expense and saves time. The mechanical qualities of aligners made using the new manufacturing technique and those made using the indirect method, have not been extensively studied.⁴

CA Pro aligners (Henry Schein, Langen, Germany) feature a rigid, elastic, three-layered material structure made from a polyethylene glycol terephthalate (PETG)-based polymer. The design increases force absorption and enhances patient comfort due to a flexible elastomeric layer. CA Pro aligners can apply a constant force, with minimal power loss, while also exhibiting high fracture resistance. The odourless, transparent and solid material has a density of 1.27 g/cm³ and includes a 0.25 mm thick softer thermoplastic elastomeric (TPE) layer between two 0.25 mm thick hard copolyester layers. The dimensions of CA Pro aligners are 0.75 mm in thickness and 125 mm in diameter.^{5,6}

Medical-grade, high molecular weight thermoplastic polymers are used in the manufacture of Invisalign aligners. High-precision stereolithography (STL) and milling technologies are used to produce sequential removable aligners from a polyurethane-based thermoplastic material.⁷

‘Creep’ and ‘stress relaxation’ are two terms that are used to describe the mechanical characteristics of viscoelastic materials. Creep may be defined as plastic deformation that occurs over time in a material under constant stress.⁸ Stress relaxation (SR) is defined as the change of stress in a material under a constant load over time. A viscoelastic material deforms more under repeated loads, thereby decreasing an aligner’s force-applying capacity during the treatment process. Therefore, it is desirable that aligners have a low SR value to maintain its viscoelastic structure and elasticity under repetitive loads.²

Water absorption is a factor that can influence the stress relaxation values of clear aligners.^{9,10} This phenomenon causes the thermoplastic material to expand, resulting in irreversible degradation of the material’s mechanical properties. In addition to water, it is highly likely that other liquids, consumed on a daily basis, will affect the material properties of aligners. Previous studies have investigated the effect of various liquids on the discolouration of aligners but not on their mechanical properties.^{11,12} Room temperature water is the only liquid manufacturers recommend while the aligners are being worn.

Most patients drink liquids without removing their aligners¹³ and it is uncertain whether other liquids alter the mechanical properties of the appliances.

Timm et al. showed that, of 2,644 aligner patients, a total of 953 (36.0%) exhibited full compliance, 1,012 (38.3%) showed fair compliance, and 679 (25.7%) demonstrated poor compliance. Low patient compliance indicates that patients do not adhere to instructions delivered by providers. Consequently, patients are likely to repeatedly insert and remove their aligners throughout the day¹⁴ which means that the aligners are subjected to repetitive loads.

Therefore, the purpose of the present study was to investigate the mechanical strength of different aligner materials (Graphy Tc-85, CA Pro, and Invisalign) by applying repetitive forces and determine the mechanical changes following exposure to various liquids. The study’s null hypothesis was that there would be no differences in the mechanical properties between the aligners.

Materials and method

The research protocol of this in vitro study was approved by the Afyonkarahisar Health Science University Clinical Research Ethics Committee (ID:2023/411). A power analysis using the Gx power 3.1.9.2 program ($\alpha = 0.05$, $1-\beta = 0.80$, effect size = 0.25) indicated that a total of 210 samples were required, incorporating 10 in the various subgroups.

The printed aligner Graphy Tc-85, vacuum-formed CA Pro, and Invisalign were the three main material groups examined. Each main group was divided into 7 subgroups according to the liquid media immersion identified by a control group (dry condition, no liquid exposure), and additional orange juice, soy sauce, red wine, cola, tea, and coffee groups.

Preparation of the samples

All of the aligner samples were prepared using a digital model of the same individual’s upper dentition. There was no decay nor restorations in the patient’s upper molars. For each material brand, the following production process was applied:

Graphy Tc-85 aligners were adjusted to a thickness of 0.75 mm in Blue Sky Plan software (Libertyville, IL, USA) and produced directly by a 3D printer (Ackuretta [SOL], Ackuretta, Taipei City, Taiwan).

The layer thickness was 100 µm. Trimming was not required for the Graphy aligners because the gingival line was digitally designed prior to printing. After generation, the samples were washed with 97% isopropyl alcohol and allowed to air dry to ensure that neither surplus resin nor isopropyl alcohol remained.¹⁵ The samples (CureM U102H, Graphy Inc., Korea) were then cured twice for 25 minutes each under UV light using a wavelength in the range of 385 to 405 nm.^{16,17}

For the production of CA Pro samples (Henry Schein, Langen, Germany), three-dimensional (3D) models of the upper dentition were first produced using the Phrozen Sonic Mini 8k printer. Using the Ministar S device, CA Pro plates were thermoformed on the 3D-printed models at 70°C and 4 bars of pressure.¹⁸ Straight trimming was then performed along the gingival line.

Invisalign samples were produced by the Align company (Santa Clara, CA, USA) using the digital model of the same patient and whose gingival line was set by the company. Instructions were provided to produce aligners with zero tooth movement. All group samples were immersed in six different liquids (coffee, orange juice, coke, tea, red wine, and soy sauce)^{12,19–23} (Table I) and were left in an oven at 37°C for 24 hours.^{12,19,24} The upper right first molar sections of each aligner sample were separated using an abrasive disc following the mesial and distal proximal contact lines (marked with a pencil before cutting). The right first molar sections were embedded in 2 mm thick acrylic resin in square moulds produced using a 3D printer (height = 12 mm, base length = 12 mm × 12 mm) (Figure 1). The molar samples were placed in the containers with their occlusal surfaces parallel to the horizontal plane. All stages of the experimental procedure were performed by a single researcher (T.S.).

Cyclic loading test

A special instrument (a combination of a dynamometer [force-measuring device] and a deformation depth measuring instrument) was constructed for the study. To measure a force applied to the samples, a Kistler 9272A dynamometer (Kistler Group, Winterthur, Switzerland) with a measurement upper limit of 400 Newtons (N) and a sensitivity of 0.001 N was attached to a perpendicular table of the

Table I. Content and pH values of the liquids

Liquids	Content	pH values
Coffee (Nescafe Classic®, Nestle, Switzerland)	Instant coffee	5.0
Coke (The Coca Cola Company, USA)	Water, sugar, cola extract, carbon dioxide, colorant, caffeine, phosphoric acid	2.53
Red wine (Sava, Denizli, Türkiye)	Fresh grape juice, sulfur dioxide	3.60
Tea (Yellow Label® tea, Lipton, Kenya)	Black tea	5.5
Soy sauce (Carl Kühne Fermentation, İzmir, Türkiye)	Water, soy protein, wheat flour, sodium benzoate	5.1
Orange juice (Dimes company, Izmir, Türkiye)	Orange juice	3.93

instrument. The experimental setup also included a Thorlabs LTS150/M (Thorlabs, Inc., Newton, New Jersey, USA) device which could move precisely in the x, y, and z axes to determine deformation depth.²⁵ This part of the mechanism consisted of an 0.8 mm diameter loading piece with a blunt tip (Figure 2).

The first molar samples were placed into the instrument perpendicular to the horizontal plane. The tip of the loading piece was adjusted to align with the tooth's central fossa. A force was applied to the samples at a speed of 0.1 mm/sec in order to ultimately reach a deformation depth of 1 mm.^{26,27} The force was applied to each sample 50 times and the force magnitude required to achieve the 1 mm deformation in the material at the 1st, 5th, 10th, and 50th cycles of loading was recorded for each sample.

Statistical analysis

Statistical analyses were carried out using SPSS Version 25.0 (IBM Corp., Armonk, NY, USA) software. The Kolmogorov-Smirnov test was used to determine whether the data were normally



Figure 1. A schematic illustration of the process involving embedding the upper right first molar tooth in containers using acrylic.

distributed. The Kruskal-Wallis test was applied to compare inter-groups, while the Friedman test was used for intra-group comparison. The p value was set at 0.05.

Results

An aligner material reaching a 1 mm deformation depth with a lower force means that the flexibility of that material is greater. A low stress relaxation (SR) value is indicated by a decrease in force with repeated loading. According to the data obtained during the first loading applied to the control group, the flexibility of the materials, from highest to lowest, were: CA Pro (34.15 ± 3.20), Graphy (43.40 ± 0.38), and Invisalign (46.02 ± 1.00). The difference between the aligners in the control groups was statistically significant ($p = 0.016$) (Table II).

Samples from the three aligner groups showed a decrease in force values regardless of the liquid in which they were immersed due to an increase in the number of repetitive loads. Soy sauce and orange juice generally had a greater negative impact on the material's structure compared to the other liquids.

After the initial, 5th, 10th, and 50th loadings of the CA Pro samples, there was no statistically significant difference between the experimental and control groups. However, there was a statistically significant difference between the experimental and control groups at the end of the 1st, 5th, 10th, and 50th loadings of the Graphy and Invisalign samples (Tables II–V).

When the 1st and 50th loading values were compared, the Invisalign samples exhibited the greatest decrease in force (42.1%), while the Graphy Tc-85 resin aligner samples showed the least change (0.4%). The decrease in force values in the CA Pro samples was 26.3%.

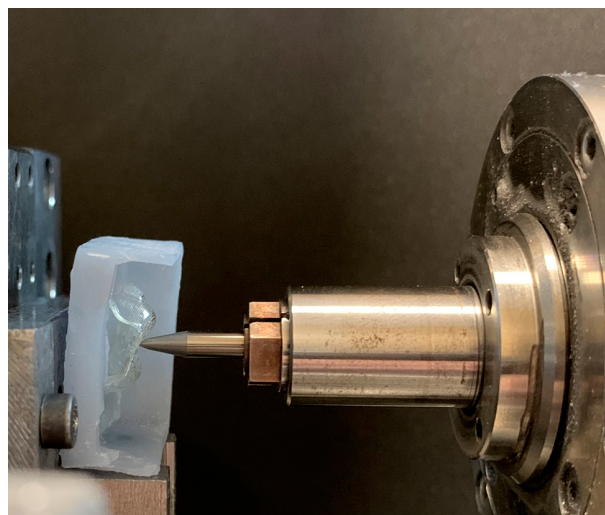


Figure 2. Cyclic loading mechanism.

Discussion

Clear aligners are widely preferred by patients due to their aesthetic appearance and ease of use. However, for the appliances to be effective, strict patient compliance is required. To prevent discolouration and ensure adequate hygiene, aligners should be removed while eating and drinking and replaced immediately after a meal has been consumed.²⁸ However, the mechanical qualities of the viscoelastic aligner material may deteriorate with repeated removal and reinsertion of the aligners, particularly in patients who have a habit of frequently eating snacks. This prevents the aligners from consistently applying the intended force on the teeth.^{29,30} The concept known as 'stress relaxation' (SR) determines whether an aligner material maintains its initial mechanical properties throughout use. An aligner material should have a low SR value³¹ which is related, not only to the material's mechanical effects such as removal and reinsertion, but also to factors that alter the polymer structure, such as water absorption. Disinfectants and cleaning solutions, for example, have been shown to have a negative effect on aligner material properties.⁴ The impact of frequently consumed liquids (tea, coffee, cola, red wine, etc.) on the colour of aligners has been previously studied,^{12,19} but their effect on mechanical properties has not been investigated.

Thermoplastic materials such as polyethylene terephthalate glycol (PETG), polypropylene, polycarbonate, thermoplastic polyurethanes (TPU),

Table II. 1st Loading force values

Subgroups Aligner Brands	Control		Orange juice		Soy sauce		Red wine		Coke		Coffee	
	Mean ± Sd. (n=10)		Mean ± Sd. (n=10)		Mean ± Sd. (n=10)		Mean ± Sd. (n=10)		Mean ± Sd. (n=10)		Mean ± Sd. (n=10)	p (Ω)
CA PRO	34.15 ± 3.20 ^{Aa}		31.33 ± 0.62 ^{Aa}		31.37 ± 0.77 ^{Aa}		31.35 ± 0.72 ^{Aa}		31.34 ± 0.71 ^{Aa}		31.29 ± 0.44 ^{Aa}	0.167
INVISALIGN	46.02 ± 1.00 ^{Ab}		39.7 ± 0.84 ^{Bb}		39.9 ± 0.33 ^{Bb}		40.53 ± 1.27 ^{Ba}		41.85 ± 0.84 ^{BCb}		44.34 ± 0.92 ^{ACb}	0.019*
GRAPHY TC-85	43.4 ± 0.38 ^{Ab}		38.69 ± 0.41 ^{Bb}		38.75 ± 0.20 ^{Bb}		41.26 ± 0.77 ^{ABa}		42.04 ± 0.22 ^{Ab}		39.55 ± 0.16 ^{Bc}	0.024*
p(θ)	0.016*		0.018*		0.014*		0.012*		0.013*		0.010*	0.011*

*p < 0.05.
Different capital letters show statistical differences between groups on the same line.
Different lowercase letters represent statistical differences between groups in the same column.
Ω, Friedman Test; θ, Kruskal Wallis Test; SD, standard deviation.

Table III. 5th Loading force values

Subgroups	Control	Orange juice	Soy sauce	Red wine	Coke	Tea	Coffee
Aligner Brands	Mean $\pm$ Sd. (n=10)	Mean $\pm$ Sd. (n=10)	Mean $\pm$ Sd. (n=10)	Mean $\pm$ Sd. (n=10)	Mean $\pm$ Sd. (n=10)	Mean $\pm$ Sd. (n=10)	Mean $\pm$ Sd. (n=10)
CA PRO	31.60 $\pm$ 2.18 ^{Aa}	29.01 $\pm$ 0.66 ^{Aa}	29.09 $\pm$ 0.34 ^{Aa}	29.04 $\pm$ 0.47 ^{Aa}	29.03 $\pm$ 0.62 ^{Aa}	28.99 $\pm$ 0.51 ^{Aa}	29.02 $\pm$ 0.10 ^{Aa}
INVISALIGN	42.66 $\pm$ 0.93 ^{Ab}	36.7 $\pm$ 0.77 ^{Bb}	36.8 $\pm$ 0.61 ^{Bb}	39.23 $\pm$ 0.50 ^{ABb}	38.79 $\pm$ 0.78 ^{ABa}	41.69 $\pm$ 0.43 ^{Ab}	41.1 $\pm$ 0.85 ^{ABb}
GRAPHY TC-85	42.84 $\pm$ 0.37 ^{Ab}	38.22 $\pm$ 0.45 ^{Bb}	38.25 $\pm$ 0.20 ^{Bb}	40.73 $\pm$ 0.76 ^{ABb}	41.49 $\pm$ 0.22 ^{ABa}	41.39 $\pm$ 0.16 ^{ABb}	39.03 $\pm$ 0.16 ^{Bb}
p(θ)	0.010*	0.012*	0.011*	0.012*	0.013*	0.008*	0.009*

*p < 0.05.

Different capital letters show statistical differences between groups on the same line.

Different lowercase letters represent statistical differences between groups in the same column.

 Ω , Friedman Test; θ , Kruskal Wallis Test; SD, standard deviation

Table IV. 10th Loading force values

Subgroups Aligner Brands	Control		Orange juice		Soy sauce		Red wine		Coke		Coffee	
	Mean ± Sd. (n=10)		Mean ± Sd. (n=10)		Mean ± Sd. (n=10)		Mean ± Sd. (n=10)		Mean ± Sd. (n=10)		Mean ± Sd. (n=10)	p (Ω)
CA PRO	29 ± 2.17 ^{Aa}		26.64 ± 0.61 ^{Aa}		26.55 ± 0.76 ^{Aa}		26.63 ± 0.60 ^{Aa}		26.57 ± 0.37 ^{Aa}		26.58 ± 0.83 ^{Aa}	0.169
INVISALIGN	40.48 ± 0.88 ^{Ab}		34.72 ± 0.74 ^{Bb}		35.01 ± 0.58 ^{Bb}		37.23 ± 0.49 ^{ABb}		36.82 ± 0.74 ^{Bb}		39.00 ± 0.81 ^{ABb}	0.029*
GRAPHY TC-85	42.12 ± 0.36 ^{Ab}		37.53 ± 0.28 ^{Bc}		37.61 ± 0.19 ^{Bc}		40.04 ± 0.75 ^{Ac}		40.8 ± 0.22 ^{Ac}		38.38 ± 0.15 ^{Bb}	0.033*
p(θ)	0.009*		0.010*		0.009*		0.007*		0.007*		0.011*	

* p < 0.05.

Different capital letters show statistical differences between groups on the same line.

Different lowercase letters represent statistical differences between groups in the same column.

Ω, Friedman Test; θ, Kruskal Wallis Test; SD, standard deviation

Table V. 50th Loading force values

Subgroups	Control		Orange juice		Soy sauce		Red wine		Coke		Tea		Coffee	
	Mean ± Sd.	(n = 10)	Mean ± Sd.	(n = 10)	Mean ± Sd.	(n = 10)	Mean ± Sd.	(n = 10)	Mean ± Sd.	(n = 10)	Mean ± Sd.	(n = 10)	Mean ± Sd.	(n = 10)
Aligner rands														
CA PRO	26.44 ± 0.15 ^{Aa}		24.29 ± 0.55 ^{Aa}		24.21 ± 0.44 ^{Aa}		24.28 ± 0.56 ^{Aa}		24.20 ± 0.48 ^{Aa}		24.24 ± 0.56 ^{Aa}		24.25 ± 0.36 ^{aAa}	0.166
INVISALIGN	26.75 ± 0.8 ^{Aa}		23.12 ± 0.49 ^{Ba}		23.08 ± 0.64 ^{Ba}		24.6 ± 0.32 ^{Ba}		24.33 ± 0.49 ^{Ba}		26.14 ± 0.27 ^{Aa}		25.77 ± 0.53 ^{ABab}	0.027*
GRAPHY TC-85	41.35 ± 0.36 ^{Ab}		36.92 ± 0.19 ^{Bb}		36.88 ± 0.35 ^{Bb}		39.32 ± 0.74 ^{ABa}		40.06 ± 0.21 ^{Ab}		39.96 ± 0.15 ^{Abb}		37.68 ± 0.15 ^{Bb}	0.018*
p(θ)	0.006*		0.008*		0.007*		0.005*		0.004*		0.006*		0.007*	

*p < 0.05.

Different capital letters show statistical differences between groups on the same line.

Different lowercase letters represent statistical differences between groups in the same column.

Ω, Friedman Test; θ, Kruskal Wallis Test; SD, standard deviation

and copolyester are generally used in the production of aligners.^{31–33} Of these, PETG is preferred by more manufacturers due to its stronger mechanical properties.¹¹ However, in addition to mechanical durability, flexibility and its preservation are critical. For example, TPU with its greater flexibility is preferred by the Align company (Santa Clara, CA, USA) to achieve more predictable orthodontic movements by applying a lighter and more constant force.⁹ In addition, hybrid materials that combine the qualities of multiple materials, particularly flexibility and durability, are currently available.

In recent years, clear aligners have been produced directly by a 3D printer using special resins whose characteristics are undisclosed by the manufacturer due to patent rights. However, metallurgical analysis has revealed that the printed material is an aliphatic vinyl ester-urethane polymer, possibly cross-linked with methacrylate.¹⁶ A uniform thickness is typically achieved in aligner production using Graphy resin¹⁷ which may therefore enable more predictable tooth movement in the clinical application of Graphy TC-85 aligners.¹⁷ However, it remains unclear if these new cross-linked products of homogeneous thickness and standard thermoplastic materials have similar mechanical qualities. In addition to the material type, the widely used thermoforming vacuum production technique affects an aligner's thickness, compatibility, and ability to apply force.¹⁸ Because the material expands and contracts during the thermoforming process,³⁴ predicting the location and magnitude of the contraction and expansion throughout manufacture is challenging. Vacuum thermoforming has been shown to alter several physical characteristics, including surface hardness, water absorption capacity, transparency, and elastic modulus. It has also been reported to reduce the thermoplastic material's thickness from a maximum of 92.6% to 57.5%.^{35,36} Lombardo et al. revealed that the stress relaxation rates of thermoplastic materials varied within a 24-hr period, based on the material type and layer count. The rates ranged from 17.9% to 62%.⁹

Aligner thickness can be a factor affecting treatment results. Graphy aligners, being printed, can achieve a homogeneous thickness. However, CA Pro and Invisalign aligners, being thermoformed, exhibit regional thickness variations, thereby making standardisation uncertain.³⁷ Mantovani et al. reported that the SmartTrack thickness after thermoforming should be 0.03" (0.762 mm). However, according to

the study, the mean thickness of Invisalign aligners ranged from 0.582 mm to 0.639 mm in the incisor region, 0.569 mm to 0.644 mm in the canine region, and 0.566 mm to 0.634 mm in the molar region.³⁷ Lyu et al. reported that while manufacturers recommend an aligner thickness between 0.50 mm and 1.0 mm, they chose to model an aligner with a thickness of 0.75 mm in their finite element analysis study.³⁸ In the current study, the Graphy aligner had a thickness of 0.75 mm. While the initial thickness of the CA Pro plate was also 0.75 mm, it changed during the vacuum shaping phase. However, as Invisalign appliance production is managed by the company, there was no opportunity to gain information. The lack of standardisation regarding material thickness, which is not feasible with vacuum-shaped appliances, is a limitation of the present study.

The stress relaxation properties of aligners have been evaluated using a variety of mechanical methods.^{4,27} Iliadi et al. generated a force-indentation depth graph by applying a 2.9 N load with a two-second contact time to the upper first molars of various aligners.⁴ Additionally, the stress relaxation induced by the applied load over a 60-second period was monitored using an instrumented indentation test.⁴ Jindal et al. investigated the force-deformation characteristics by allowing samples to reach their final deformation under varying force and temperature conditions.¹⁸ Force-deformation graphs for both cured and uncured samples produced by the direct method from transparent aligner resins were obtained, as well as for samples produced by the indirect method. The aligners were placed in a force application unit capable of applying a 1000 N load and compressing the samples from both upper and lower directions.¹⁸ In a 2013 study by Kohda et al., 0.5 mm and 1 mm activations were applied to transparent aligners using a nano-indentation test. Approximately 1 cm² samples were cut from thermoplastic materials and affixed to a testing table with adhesive resin.²⁷ The nano-indentation tests were conducted at 28°C with a maximum load of 10 mN.²⁷ Each test consisted of three phases involving 10 seconds of loading to the maximum determined force, 1 second of holding at the peak load, and 10 seconds of unloading.²⁷ In the present study, it was aimed to acquire detailed information regarding the stress relaxation properties of clear aligners using the designed cyclic loading test setup. During the test, the 1 mm

activation required for tooth movement was used as a reference, as reported by Kohda et al.²⁷ The force-deformation depth of the samples under cyclic loads was comparatively examined. The dynamometer (Kistler Group, Winterthur, Switzerland) and the Thorlabs LTS150/M, which were employed in the current investigation, are reliable instruments utilised in metallurgical engineering.²⁵ It is clear that the very low level deviations of the obtained values indicated that the instruments performed repeated measurements accurately. It is further evident that the literature lacks a defined gold standard for evaluating the mechanical properties of aligner materials and therefore most researchers have developed their own methods. The current hypothesis is that, provided the same magnitude of load and duration are applied, and reliable instruments from reputable manufacturers are used, the specific method employed may not significantly impact the results largely because such studies are inherently comparative.

Orthodontists usually instruct their patients to wear each aligner for 10 days but can range between 7 and 14 days.³⁹ Assuming that patients eat three main meals and two snacks per day, appliance removal and repositioning may be done five times, daily. As a result, it was decided that the current study would have 50 repeated loads (10 days $\times$ 5 removal = 50). Noted findings have been reported in studies comparing the mechanical properties of clear aligners against various manufacturing methods and structural components. Jindal et al. found that Duran + (Scheu Dental, Iserlohn, Germany) aligners produced using the indirect method exhibited more irreversible plastic deformation at lower forces compared to Dental LT Clear (Formlabs, Somerville, MA, USA) aligners produced using the direct method.¹⁸ Lombardo et al. applied a specific force to samples of three different aligner materials for 24 hr and found that aligner stress decay exceeded 50%.⁹ Lee et al. found that Graphy Tc-85 aligners had lower stress relaxation values than PETG aligners.¹⁷ Sayahpour et al. reported that the mechanical strength of Graphy Tc-85 outperformed Invisalign material and PETG-based aligners from Scheu-Dental (Iserlohn, Germany).⁴⁰ The results obtained in the current study were consistent with those of previous studies. Furthermore, in the present study, no relationship was found between the pH level and a change in the mechanical properties of an aligner.

Low pH liquids do not appear to significantly degrade the aligner material, even though tooth enamel may be damaged. However, soy sauce and orange juice had the greatest effect on material properties compared to other liquids. This could be due to compositional factors other than the pH of these liquids.⁴¹ An additional reason could be that different liquid constituents interact differently with cross-linked aligner materials than non-cross-linked conventional aligners.

Graphy aligners have a shape memory feature, unlike CA Pro and Invisalign materials. It is unknown whether Graphy aligners are affected by the 37°C temperature of the liquids in which they were immersed. Lee and his colleagues reported that Graphy aligners maintained geometric stability at high temperatures¹⁷ which is supported by the data obtained in the present study. A further factor is the number of layers comprising the aligners. Graphy and Invisalign had a single-layer structure, whereas CA Pro had three layers. Lombardo et al. suggested that thermoplastic materials exhibited a stress relaxation of approximately 17.9% to 62% over 24 hr at 37°C, with the amount of relaxation varying depending on the type of material and the number of appliance layers.⁹ However, in the current study, no difference was observed between the control group and the experimental groups of CA Pro samples regardless of the number of loadings. While Lombardo et al. applied a constant load for 24 hours, the repetitive force application in the present study may explain the inconsistency of the findings obtained between the two studies.

The current study had limitations related to its *in vitro* nature. The samples were maintained at 37°C which was consistent with previous *in vitro* studies,^{11,42} but tea and coffee are typically consumed at a higher temperature. The current study's limitations relate to the inability to mimic the oral microbial flora, saliva's buffering effect, and intraoral occlusal forces. More research is needed to characterise and generalise the current findings.

Conclusion

In the present study, Invisalign aligner material showed the least resistance to repeated loading. Graphy was the aligner material that possessed the greatest resistance to repeated loads. CA pro was the

aligner least affected by the exposure to the various liquids. The other aligner brands were influenced to varying degrees by different fluid exposures. It is therefore a challenge to predict how different liquids will affect an aligner material.

Ethical approval

This study was approved by Afyonkarahisar Health Science University Clinical Research Ethics Committee (ID:2023/411).

Author's contribution

The authors contributed to this project equally and read and approved the final manuscript.

Data Availability

Data and materials are available from the Orthodontic Department in the Faculty of Dentistry, Afyonkarahisar Health Science University.

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Conflict of interest

The authors declare that there is no conflict of interest.

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