

Mechanical properties of orthodontic aligners: A review of the literature

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Abstract

Background: The purpose of this study is to identify the mechanical properties of orthodontic aligners and the effect produced by thermoforming and aging in vitro.

Material and Methods: A review of the literature was carried out at the end of 2022 in different search engines (PubMed, Scielo, UNAM), using the search strategy: (aligners), (transparent) and (orthodontics) to identify articles that present information on the mechanical properties and the effect of humidity and temperature on orthodontic aligners.

Results: Of a total of 17,130 articles found in search engines, only 21 articles met the inclusion and exclusion criteria. For this systematic review, the most frequent criteria were: aligners, mechanical, and thermoplastic.

Conclusions: With the review of the literature carried out, it was concluded that aging due to the effect of water absorption and temperature does not affect the thermomechanical properties and the molecular composition as much as the thermoforming process does.

Keywords: Aligners; Mechanical tests; Thermoformed; Thickness

1. Introduction

In daily dental practice, especially in the area of orthodontics, there are many common side effects such as pain, discomfort and poor patient cooperation that affect the success of orthodontic treatment with removable appliances [1]. Therefore, with the technological development in oral health care, new ways have been created to promote treatments that are adapted to the needs of patients, thus avoiding these unwanted effects [2]. The term tooth movement using sequential removable appliances was introduced in 1945 by Dr. Harold Dean Kesling [3], who said that "these appliances allow the teeth to be placed in their most ideal position without the need for brackets, bands or wires and that it is also more effective against functional forces".

Currently, esthetics is one of the most important factors when it comes to accepting treatment. It has been proven that adult patients tend to prefer clear aligners over conventional brackets [4,5,6], since the latter are often the main cause of bacterial plaque accumulation which causes a higher risk of caries, gingivitis and even periodontitis, which obviously alters and affects oral health. To avoid this problem and others such as root resorption [7], clear orthodontic aligners (TOA) have been introduced as an alternative to fixed treatments [8] as these, in addition to improving esthetics, provide comfort and better oral hygiene for the patient [9].

In any orthodontic treatment the application of continuous force is indispensable, however this is not the case with removable appliances. The main difference between fixed and removable appliances is the time of application of the

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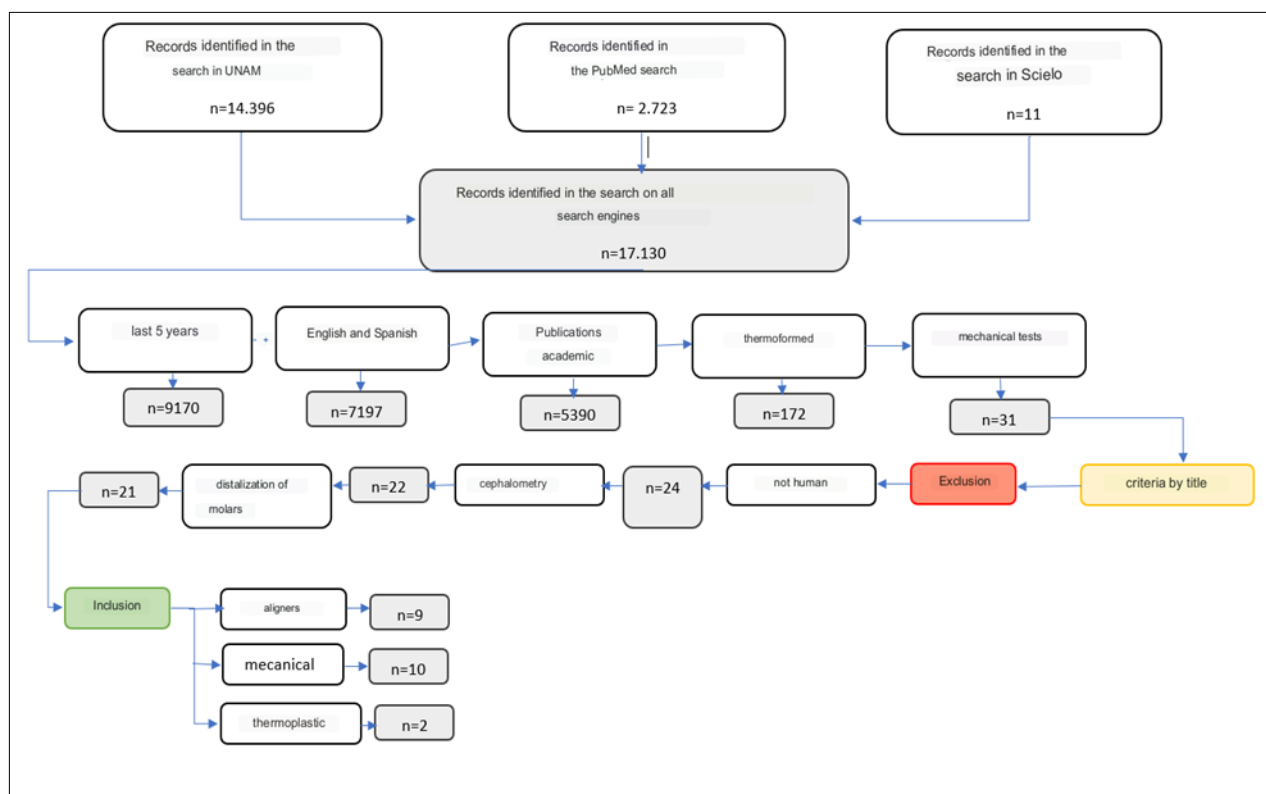
force. In the former, a constant force is maintained for 24 hours, which is the most propitious for adequate dental movement. On the contrary, because of the need to remove the appliance for cleaning and feeding, the maximum time of use of removable appliances is 12 hours since it coincides with the time to sleep [4].

For effective treatment with aligners, thermoplastic materials that generate a constant and adequate force for tooth movement are required. [10]. For the fabrication of aligners it is necessary to obtain a dental impression of the patient and then thermoform a transparent biocompatible thermoplastic sheet using a vacuum thermoforming machine [11, 12]. Both the thickness (0.50mm to 1.5mm) and the thermoforming process influence the magnitude of the force exerted by the aligner on the teeth [13, 14]. In addition, these materials have important physical, chemical and mechanical properties such as low stiffness, dimensional stability and good deformability [15]. Different studies have shown that aligners release small amounts of trace elements such as aluminum, nickel and zinc [16] however they show a low level of cytotoxicity, which is lower or equal compared to metal brackets, bands, mini-screws or bonding materials, so their clinical use is safe [17].

The forces applied to individual teeth by aligners are affected by some material-dependent variables, such as the initial stiffness of the aligner and the behavior of the material during its intraoral application period [18, 19] so the aim of this study is to identify the mechanical properties of aligners and to know if these are affected by variables such as thermoforming and the medium that simulates the oral cavity.

2. Material and methods

In November 2022, a literature review was initiated to identify articles presenting information on orthodontic aligners. To obtain the articles, a search was performed in PubMed, Scielo, UNAM, using the search strategy (aligners), (clear) and (orthodontics). The articles were selected according to the inclusion and exclusion criteria. The inclusion criteria were: articles from the last 5 years, language in English and Spanish, academic publications, thermoformed aligners, mechanical tests. The exclusion criteria were non-human, cephalometry, molar distalization. The article selection procedure was described in Figure 1.



Source: Durán, B; Lema, B; Bravo, M

Figure 1 Flowchart for search and selection of articles

3. Results

Of the 17,130 articles found in the search, only 21 articles were selected that met the inclusion and exclusion criteria. The list of articles and their most important characteristics are described in Table 1.

Table 1 Final list of articles with their main characteristics

	Article title	Characteristics
1	Comparative mechanical testing for different orthodontic aligner materials over time - in vitro study	The material of the aligners tested (PET-G) does not maintain a constant mechanical force over time, so it was concluded that the material does not have sufficient mechanical properties for use in orthodontics.
2	Mechanical and geometric properties of thermoformed and 3D printed clear dental aligners	The material and manufacturing methods influence the properties of the aligners. The material must be rigid with high yield strength and the stress relaxation curve must remain flat to exert a constant and continuous force.
3	In vitro cytotoxicity of different thermoplastic materials for clear aligners	During clinical use, the aligners are exposed to the oral environment that generates the release of molecules; however, these have low cytotoxicity, so their clinical use is safe. The thermoforming process was shown to increase the cytotoxicity of the materials.
4	Mechanical Properties of Thermoplastic Polymers for Aligner Manufacturing: In Vitro Study	The mechanical properties of different polymers (PETG, PET and TPU) used in different brands of aligners are affected to a greater or lesser extent by the manufacturing process and exposure to the oral environment.
5	Clear aligners in orthodontic treatment	Depending on the type of manufacturing used for the aligner, it can acquire greater strength and more precision to generate movements.
6	Stress relaxation properties of four orthodontic aligner materials: A 24-hour in vitro study	The aligners, regardless of their polymer (TPU, PET-G, PET-G/TPU, TPU/PC) must present a flat relaxation curve that demonstrates their ability to exert a constant and continuous force over time. All aligners showed a significant decrease in tension over a 24-hour period.
7	Dynamic mechanical and thermal properties of clear aligners after thermoforming and aging	The flexural modulus (tendency to resist bending) decreases after the thermoforming and thermocycling process. The thermoforming process plays an important role in weakening the aligner material. If the hardness of the material decreases, so will the application of force.
8	Biomechanics of clear aligners: hidden truths & first principles	Aligners are known for: -applying light forces, -working better with fewer activations, -showing little flexibility, -suffering a rapid decay of force. The thickness of the material influences: -thin: light forces good for tipping; -gross: forces that generate translation or movement of the root.
9	Visualization of orthodontic forces generated by aligner-type appliances	Photoelastic stress analysis is a new technique that can be used to measure the force exerted by aligners.
10	Orthodontic clear aligner treatment	Aligner materials and accessories will continue to improve, allowing clear aligners to fit better and for longer periods of time, leading to better results.
11	Clear aligner: invisalign: A review	The Smart Track polymer is composed mainly of thermoplastic polyurethane (PU), this material helps improve elasticity and are programmed to produce a precise movement of 0.15-0.25 mm.
12	Effects of thermoforming on the physical and mechanical properties of thermoplastic materials for transparent orthodontic aligners	The thermoplastic materials (Duran, Essix A, Essix ACE and eClinger) showed higher water absorption, a decrease in strength and elastic modulus after thermoforming, so it is advisable to evaluate the physical and mechanical properties of thermoplastic materials after

		thermoforming. In addition, the selection of transparent aligners must be careful and depending on the treatment required.
13	Influence of constant strain on the elasticity of thermoplastic orthodontic materials	There is a significant correlation between the elastic modulus of thermoplastic materials (EA, DU, ER and EC) with orthodontic strength, which allowed establishing the influence of water absorption and determining the factors that affect orthodontic strength. EC had a lower water absorption than EA, DU and ER, due to the presence of a crystalline phase in EC, which suggests advantages in the use of EC as a material in orthodontic aligners.
14	Mechanical properties of "two generations" of teeth aligners: Change analysis during oral permanence	Smart Track, the latest generation of Invisalign showed greater translucency, flexibility, conformability and consistency in the application of orthodontic forces than those produced with Exceed 30 polymer.
15	Compliance with removable orthodontic appliances	The success of orthodontic treatment with removable appliances depends on many factors, especially patient compliance, which can increase when patients are aware of professional monitoring; however, more research is required to identify possible barriers to improve compliance. removable orthodontic appliances.
16	Mechanical Characterization of Thermoplastic Aligner Materials: Recommendations for Test Parameter Standardization	Among the parameters to standardize the flexion tests of the PET-G samples is that samples must be made after thermoforming, in addition the influence of long-term storage of water under load (24h) reduces the strength of the aligner, therefore it is reduces the strength of the material.
17	A comparison of treatment effectiveness between clear aligner and fixed appliance therapies	Clear aligners and braces were effective in treating malocclusion. The advantage of aligners in segmented movement and reduction in treatment duration was significant, however orthopedic appliances were more effective in achieving a great improvement, so the characteristics of the two appliances should be considered when taking a decision.
18	Changes in mechanical properties, surface morphology, structure, and composition of Invisalign material in the oral environment	The mechanical properties, surface molecular structure, and internal structure of the Smart Track material were not affected by the oral environment, so material fatigue does not play a significant role in speed or amount of tooth movement.
19	Effect of in vitro aging by water immersion and thermocycling on the mechanical properties of PETG aligner material	Aligners can be influenced by the intraoral environment, heating up to intraoral temperature (37°C) and water absorption instantly reduces the Young's modulus and maximum tensile strength of PETG, this leads to physical aging of the material. which contributes to a decrease in orthodontic forces and movement.
20	Force decay of polyethylene terephthalate glycol aligner materials during simulation of typical clinical loading/unloading scenarios	PET-G samples have a high initial stiffness, but the transmission of excessive forces is attenuated after the first loading cycle, promoting a decrease in material-related force after contact with the oral cavity.
21	Changes in Roughness and Mechanical Properties of Invisalign® Appliances after One- and Two-Weeks Use	Aging has a detrimental effect on the surface roughness and the mechanical properties of Invisalign appliances, especially within the first week, which influences the retention and orthodontic forces of the aligners during orthodontic treatment, so the use of aligners is not recommended for two weeks.

Source: Durán, B; Lema, B; Bravo, M

4. Discussion

As esthetics has become indispensable for the development of people's social relationships, more and more people are looking for treatments that suit the patient and increase their confidence as a result of a superior dentofacial appearance. Thus, clear dental aligners have become a solution to tooth misalignment through the use of various aligners [13, 20]. TOAs are produced with a computerized treatment plan with different types of attachments to generate the different movements without losing aesthetics as they are made of resin [21, 22, 23].

The modulus of elasticity of thermoplastic materials was significantly correlated with orthodontic strength, the influence of water absorption and strain on the modulus of elasticity was investigated to clarify the factors affecting the orthodontic strength expressed by thermoplastic materials [24, 25]. There are different types of polymers that are used for the production of aligners, among these we find polyester, polyurethane, polypropylene. The polymers used in aligners can be affected by the heat, humidity and salivary enzymes to which they are exposed in the oral cavity [26].

Transparent thermoplastic removable appliances are produced by CAD/CAM technology, thus, it is possible to produce the movements required for comprehensive orthodontic treatment and, at the same time, create more esthetic appeal than traditional stainless steel or esthetic brackets and wires [24]. In this regard, it is necessary to consider that a thermoplastic material is viscoelastic in nature, which means that the force generated by the planned movement decreases with time [25]. Jindal et al [16] in their study "Mechanical and geometric properties of thermoformed and 3D printed clear dental aligners" measured the modulus of elasticity and yield strength of thermoformed materials before and after thermoforming, in addition to aging under human saliva, obtaining the following results. The tensile yield strength (49.49 MPa) and elastic modulus (1368 MPa) with aging under saliva are lower compared to the thermoformed sample (53.52 MPa and 1693 MPa), which is in contrast to the study by Drake et al. who concluded that material fatigue did not play a significant role in the speed or amount of tooth movement. . They also performed a compression test and found that the irreversible plastic deformation of the thermoformed aligners was 8.6 mm with a maximum load of 584 N as opposed to 3D printed aligners whose test results were 2.93 mm with a maximum load of 531 N [13].

Lombardo et al [14] in "Stress relaxation properties of four orthodontic aligner materials: A 24-hour in vitro study" demonstrated that the aligners present a significant decrease in stress during a 24h period, where the first 8 hours there is a higher stress.

Polymers are not only exposed to temperature changes and water immersion, but are also subject to other environmental effects within the oral cavity, such as calcification, lipid absorption, chewing, and the effect of plaque metabolites [27]. In addition, it has been found that aligner materials undergo changes in mechanical and optical properties during the manufacturing process and exposure to the oral cavity, these being greater or lesser depending on the type of polymer as demonstrated in the article Mechanical Properties of Thermoplastic Polymers for Aligner Manufacturing: In Vitro Study by Tamburrino et al [28]. and this was confirmed in the article "Dynamic mechanical and thermal properties of clear aligners after thermoforming and aging" by Dalaie et al. and in "Do the mechanical and chemical properties of Invisalign™ appliances change after use? A retrieval analysis" concluded that aging does not affect thermomechanical properties and molecular composition as much as the thermoforming process does [29, 30].

Food and beverage consumption should be avoided during aligner use to prevent alteration of the physical properties of the aligner material and to increase the predictability of the resulting force systems [27].

To advance our understanding of the mechanical properties of aligner materials, more standardized testing protocols that result in reliable information are needed. In addition, advances in engineering, chemistry, and production protocols for aligner materials are still in flux and need to be studied [31].

5. Conclusion

With the literature review carried out, it was concluded that aging by the effect of water absorption and temperature does not affect the thermo-mechanical properties and molecular composition as much as the thermoforming process does. Influencing both physically and chemically. In addition, it is imperative the need for more studies to test the aligners due to the continuous advancement of the polymers used.

Compliance with ethical standards

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Disclosure of conflict of interest

There were no major conflicts of interest during the performing of this article.

Statement of ethical approval

The present research work does not contain any studies performed on animals/humans subjects by any of the authors.

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