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Thermoplastic materials in Orthodontics – A Narrative Review

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Trabalho apresentado à Universidade Fernando Pessoa como parte dos requisitos para obtenção do grau de Mestre em Medicina Dentária.

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ABSTRACT

This is the age of plastics. They possess several applications in day-to-day life. In Dental Medicine, thermoplastics have risen to overtake orthodontics, and share new light in this specific area of expertise. The aim of this paper is to compare, differentiate, and indicate the best use regarding different thermoplastics.

A bibliographic search was performed in order to collect the literature required to achieve a Narrative Review with merit and impertinent to the scientific community. Investigation articles within the theme of thermoplastics were chosen, likewise other relevant literature to the investigation.

Nowadays, the commercialization of clear aligners and its worldwide usage is a manifestation of the evolving market and the quality of the thermoplastic materials involved in the process. Further investigation is fundamental to understand, to improve and achieve the perfect material for movement performed by removable orthodontic appliances.

Keywords: Orthodontics, Orthodontic Removable Appliances, Dental Materials

RESUMO

Esta é a era dos plásticos. Estes possuem diversas aplicações no dia-a-dia. Na Medicina Dentária, os termoplásticos surgiram para renovar a prática clínica de Ortodontia e partilhar uma nova luz nesta área específica de atuação. O objetivo deste artigo é comparar, diferenciar e indicar o melhor uso em relação aos diferentes termoplásticos.

Foi efetuada uma pesquisa bibliográfica com o objetivo de reunir a literatura necessária para a realização de uma Revisão Narrativa com mérito e pertinência para a comunidade científica. Foram escolhidos artigos de investigação dentro da temática dos termoplásticos, bem como outras literaturas relevantes para o tema.

Atualmente, a comercialização de alinhadores e o seu uso mundial é uma manifestação do mercado em evolução e da qualidade dos materiais envolvidos no processo. Uma investigação mais aprofundada é fundamental para entender, melhorar e alcançar o material ideal para a movimentação dentária realizada por aparelhos ortodônticos removíveis.

Palavras chave: Ortodontia, Aparelhos ortodônticos removíveis, Materiais dentários

DEDICATÓRIA

Dedico este trabalho aos meus pais, avós e irmã

pelo apoio incondicional

e sabedoria.

Ao João, meu namorado,

por olhar sempre por mim.

Contigo tudo é possível.

AGRADECIMENTOS

Agradeço ao meu Orientador, o Prof. Doutor Ricardo Noschang, pela sua disponibilidade e interesse, tendo sido fundamental na conclusão deste capítulo da minha vida académica. Gostaria de o realçar como exemplo de inspiração pessoal, pela sua excelência no exercício da profissão e pela constante vontade de aprofundar o seu conhecimento.

Agradeço à Patrícia Silva, estimada amiga e colega de Curso a quem devo momentos inesquecíveis de partilha e amizade.

Um agradecimento a todos os docentes e funcionários da Universidade Fernando Pessoa que me acompanharam e que contribuíram para o meu desenvolvimento como Médica Dentista.

Por último, uma palavra de agradecimento a todos os doentes com quem tive a oportunidade de praticar a arte da Medicina Dentária.

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ABBREVIATIONS

BC	Before Christ
BPA	Bisphenol A
CAD/CAM	Computer-aided design/Computer-aided manufacturing
PET	Polyethylene terephthalate
PET- G	Polyethylene terephthalate glycol
PP	Polypropylene
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PU	Polyurethane
PVC	Polyvinyl chloride
Ri	Ratio of hydrogen bonded carboxyl groups to free ones

I – INTRODUCTION

The history of Orthodontics has come a long way since ancient Greece and Rome, dates as far back as 400 and 300 BC (Gemmi, C., 2018). Many developments were made throughout the centuries until we have reached the current definition. Orthodontics is defined as the branch of dentistry that deals with irregularities of the teeth, such as malocclusions and their correction. With all the advances in technology, the field of Orthodontics has grown in leaps and bounds over the last twenty years. Dentistry is largely a material science and orthodontics is no exception (Gupta, Tuli and Jain, 2020). The rise of a new technique in orthodontic movements alternative to conventional archwires and brackets, that combines esthetic and comfort, is accomplished with the use of different thermoplastics, therefore, Dental Medicine has seen an incremental growth in the clear aligner industry (Lombardo *et al.*, 2017).

Initially, the clear aligners were used to arrange mild malocclusions, such as anterior crowding and the generalized existence of spaces. In spite of the efficacy of treatment in these cases, there is disagreement on whether it is possible to treat more difficult cases (Cai *et al.*, 2015). The latest meta-analysis report on the efficacy of aligners compared to the gold standard of fixed appliances, revealed that clear aligner treatment cannot be considered equally effective to braces at present, while their use is associated with limited treatment outcome (Iliadi *et al.*, 2020). It is of public knowledge that exists contradictory studies regarding clear aligners, but firstly and entirely dependent, is the evaluation of the materials that enable this therapy to exist. There are several thermoplastics materials currently being used in the industry, each one with different components and therefore properties. Regardless of the existence of many studies that researched different treatment outcomes, the biomechanical mechanisms by which clear aligners exert its effects remain unknown, and it is extremely demanding to evaluate the force imparted by these clear aligners (Liu and Hu, 2018).

To choose the type of orthodontic appliance for each particular case, must be considered some important factors, taking into account the different characteristics of patients, assuming that orthodontic therapy will affect the periodontium (Chhibber *et al.*, 2018). Even so, if these removable appliances do not hamper oral hygiene maintenance, and if also, they reduce the risk of white spots, caries, gingivitis and periodontal disease (Lombardo *et al.*, 2015). However, salivary film can coat any solid surface that exists in oral environment, dental plaque also accumulates, for example in acrylic appliances (Shpack *et al.*, 2014). Pain is another important factor to account for when selecting an orthodontic treatment, and it is one of the reasons why there exists a discontinuance in orthodontic treatment (White *et al.*, 2017). Another problem that has been investigated in orthodontics is the potential BPA substitutes in aligners constitution (Eliades *et al.*, 2009). They present cytotoxic effects that include a cell cycle disturbance, an immune reaction to the material, cell apoptosis, induction of mutagenesis or carcinogenesis, however these side effects do not emerge promptly (Premaraj *et al.*, 2014). It must not be forgotten that the practice of dentistry itself also plays a role in biofilm formation through the introduction of a variety of foreign surfaces, which are ideal for colonization by oral microbes (Low *et al.*, 2011). Nevertheless, it has been investigated that aligners have less plaque accumulation and gingival inflammation compared to fixed appliances (Suter *et al.*, 2020).

The advances in technology have played an extremely important part in the clear aligner industry. The Computer-aided design/Computer-aided manufacturing (CAD/CAM) procedure is based on the digitalization of various steps of the procedure: from the creation of the anatomy of each patient to the fabrication of reference models (Barone *et al.*, 2017). The Invisalign system (Align Technology) uses CAD/CAM stereolithographic technology to forecast treatment and fabricate many custom-made aligners from a single impression (Kravitz *et al.*, 2009). Notwithstanding, CAD/CAM software was used before in dentistry in the 1980s, but it was considered a cumbersome novelty, requiring a distraught amount of time to produce a viable product. This limitation prevented its use within dental offices and limited it to being used in dental laboratories. With the improvement of techniques, software and materials (thermoplastics) the chairside use of CAD/CAM increased.

It is common knowledge that Orthodontics is the area of Dental Medicine where thermoplastics are gaining an important part in therapy. The mechanical properties of thermoplastic materials used in manufacturing of clear aligners for tooth movement change depending on the processing history and intraoral environment of use (Ryokawa *et al.*, 2006). Understanding their manufacturing procedure is key to obtaining the best results as well as their construction material. This can affect their mechanical properties and therefore their performance. In an ideal world, to provide physiological movement of the teeth with clear aligners, they should be able to exert constant and well distributed light forces throughout their use, but in reality, it is extremely difficult to obtain that performance. The principle of aligner therapy is based on the discrepancy between the actual tooth position and the ‘‘programmed’’ setup position reflected as negative shape by the aligner (Elkholy *et al.*, 2017).

Thermoplastic elastomers are polymeric materials, which exhibit elasticity at ambient temperatures and can be processed as plastics by melt processing techniques. They are essentially two-phase systems. The phase separation is the result of restricted compatibility of the two phases involved. When the material is heated above the melting point or melting range of the hard phase, its melt becomes homogeneous and can be shaped into desired shapes and/or products.

These aligners are fabricated via a thermoforming process, using accurate models of patients' malocclusions (Gracco *et al.*, 2009). Thermoformed orthodontic thin overlay appliances have been used for tooth movement (Kwon *et al.*, 2008). The unique material properties of plastics and versatile processing methods are attributed to their molecular structure. The facility with which polymers are processed and with which one can consolidate several parts into a single part, as well as their high strength - to - weight ratio, make them the most sought-after materials today (Osswald *et al*., 2006a).

Vacuum formers used in the dental industry are able to imprint opposing bite and fabricate other dental appliances, for example orthodontic appliances. Clear aligners also come in a range of different thicknesses, from 0.50 mm to 1.5 mm. These formers can use a variety of thermoplastics depending on the thickness and flexibility needed. High quality materials are a necessary starting point to achieve the best possible outcome.

The aim of this review is to compare, differentiate, and indicate the best use regarding different thermoplastic materials used in Orthodontics.

1.1 Materials and methods

An electronic search was done in the online search engines like *Pubmed*, *GoogleScholar* and *ScienceDirect*, in the English language using the following expressions with the respective Boolean markers: ((Invisalign) OR (Orthodontic aligners) AND (Physical properties)); ((Invisalign) AND (Physical Properties) AND (Vacuum-formed));

((Invisalign) OR (Orthodontic aligners) AND (Thermoplastic material)); ((Invisalign) AND (Thermoplastic polymers)); ((Orthodontic aligners) AND (Thermoplastic material)); ((Orthodontic aligners) AND (Vacuum-formed)); ((Orthodontic aligners) AND (Physical properties) AND (Chemical properties)); ((Orthodontic aligners) AND (Thermoplastic polymers) AND (Chemical Properties) AND (Mechanical Properties)); ((Clear aligner) AND (Thermoplastic polymers) AND (Cytotoxicity)); ((Orthodontic aligners) AND (Thermoplastic polymers) AND (Cytotoxicity)); ((Orthodontic aligners) AND (Thermoplastic polymers)); ((Orthodontic aligners) AND (Thermoforming)); ((Orthodontic aligners) AND (Dimensional stability)); ((Orthodontic aligners) AND (Intraoral ageing)); ((Invisalign) AND (Thermoforming)).

It was also utilized as a complement to research, the book *International Plastics Handbook* and *The Handbook of Thermoplastic Elastomers*. Other sources and hand searching reference sections of potential studies were also performed. Unpublished/ grey literature was not included.

II - DEVELOPMENT

Dental aligners are the new commented treatment modality in Orthodontics. This appliance is one of the best use of plastics in dentistry with the focus in dental movement associated with patient comfort and hygiene. In 1998, Align Technology (Santa Clara, Calif) introduced Invisalign, a series of removable polyurethane aligners, as an esthetic alternative to fixed conventional braces. However, the idea of a removable appliance to move teeth was not new, but never was commercialized (Baldwin *et al.*, 2008). This company managed to introduce a new light in orthodontics, which involved more adults to partake in the treatment. The first marketed aligners, commercialized by this multinational were made out of a single-layer rigid polyurethane obtained from methylene diphenyl diisocyanate and 1,6-hexanediol. Subsequent materials used were formed from a new material called "Exceed-30" (Align Technology), designed for its improved flexibility, breakage resistance, and transparency. In 2012 it was substituted by another material called "SmartTrack" (Align Technology), a thermoplastic polyurethane that should be able to meet the need for lighter, more constant forces, as well as a greater elasticity, which should make orthodontic movements more predictable (Lombardo *et al.*, 2017).

In this research, only the scientific name of the plastics will be referred, and only the most cited were investigated: Polyurethane; Polyethylene terephthalate glycol (PET-G); Copolyester and Polypropylene. The majority of current aligner manufacturers use modified PET-G, although polypropylene, polycarbonate, thermoplastic polyurethanes, copolyester, and many other plastics are also known to be used.

2.1 PET-G

Polyethylene terephthalate glycol, known as PETG or PET-G, is a thermoplastic polyester that delivers significant chemical resistance, durability, and formability for manufacturing. PET-G is an adaptation of PET (Polyethylene terephthalate) where the 'G' stands for glycol, which is added at a molecular level to offer different chemical properties. PET uses the same monomers as the glycol modified PET-G, but PET-G has greater strength and durability, as well as being more impact resistant and better suited to higher temperatures (TWI, 2021).

Due to the low forming temperatures of PET-G, it is easily vacuum and pressure formed or heat bent, making it popular for a variety of consumer and commercial applications, for example in the clear aligner industry. These properties also make PET-G one of the most widely used materials for 3D printing and other heat-forming processes (vacuum-formed). PET-G is also well suited for techniques including bending.

Properties of PET-G applied to Orthodontics

One of the most studied properties is the resistance that thermoplastics possess when exposed to the oral environment, as it is known, the clear aligners need to support several days within the oral environment. The force produced by a thermoplastic material is strongly correlated with its initial mechanical properties and especially stiffness. Therefore, any significant changes among different systems or over time in the mouth may have an impact on what aligner system the practitioner chooses to use (Gerard Bradley *et al.*, 2016).

It must be accounted for that the biomechanics and force delivery features of clear aligners depend on the appliance's geometry, its setup, staging and more importantly in the physical characteristics of the material it is made of (Ihssen *et al.*, 2019).

Via the three-point bending test (Lombardo *et al.*, 2017), it was shown that the single-layer materials (PET-G) were more than four times stiffer than their double-layer counterparts. This characteristic should be considered because at the thicknesses marketed today, some aligners may not be able to exert sufficient force to guide the teeth into their programmed positions, or the clinical protocol should be adjusted specifically for this feature (Lombardo *et al.*, 2017).

In the study of Ercoli *et al.* (2014), it was compared PET-G aligners to PVC aligners, the thickness of the latter varies with the desired type of tooth movement but never exceeds 1 mm. A material with interesting elastic characteristics after a deformation with moderate loads. This characteristic allows reducing the optimal wear time to 14h per day (Ercoli *et al.*, 2014).

The PET-G aligners are a light, resistant, and very clear material. It is resistant to time and wear, and its elasticity allows for a gradual tooth movement. They possess a thickness that changes throughout the different treatment phases: 0.75 mm at the beginning of treatment, 0.85 mm during the intermediate phase, and 1 mm at the end of treatment. (Ercoli *et al.*, 2014).

The force combination applied by an aligner to individual teeth is highly dependent on the location and orientation of the contact forces exerted by the aligner and, also, on the morphology of the corresponding teeth. The results of Elkholy *et al.* (2017) revealed that when the same aligner material and thickness are used, mesiodistal rotation of a lower canine leads to a rotational moment about 71% lower than that determined for rotation of a maxillary central incisor. It is supposed that this difference is related to the different shape between the two teeth involved. It can be hypothesized that such morphological variations apply not only to different types of tooth but also to the same type of tooth in different individuals, not forgetting the thermoplastic used (Elkholy *et al.*, 2017).

2.2 Polyurethane

Polyurethanes (PUs) were developed in the year 1937 by Otto Bayer's laboratory as they were seeking out an alternative source to rubber. Nowadays, PUs have been incorporated into consumer goods, toys, mattresses, biomedical equipment, houses, shoes, and others. PUs have a wide array of applications because of their strong, yet flexible qualities (Tang *et al*., 2011).

The properties of PU resins are mostly determined by none other than the urethane structural characteristics. This fact constitutes their unique variety among polymers: polyurethanes are primarily known as foams, elastomers, and solid parts (Osswald *et al*., 2006b).

Polyurethane possesses a myriad of favorable properties: chemical resistance, abrasion resistance, adhesion characteristics, and ease of processing (Gupta, Tuli and Jain, 2020). High elasticity, flexibility, chemical resistance, oxidation resistance, mechanical strength and ease of processing are more examples of important properties of PUs (Bernard *et al.*, 2020).

PUs show histocompatibility, low toxicity, blood compatibility, and better biodegradability. Their ability to have different properties allows them to be used in medical applications that need both strength and flexibility. These important properties mimic body tissues (Condo' *et al.*, 2018). Polyurethane, is one of the most versatile engineering thermoplastics, with excellent physical properties, chemical resistance, abrasion resistance, and ease of processing. However, polyurethane is not an inert material and is affected by heat, moisture and prolonged contact with salivary enzymes (Condo' *et al.*, 2018).

Properties of Polyurethane applied to Orthodontics

When Polyurethane stress relaxation properties were studied by Lombardo *et al.* (2017), and compared with four different thermoplastic aligner materials, in the stress relaxation test, the PU presented the greatest absolute initial stress, but also the greatest decay during the 24-hour period. PUs presented the greatest absolute initial stress value (23.7 MPa), but 40.5% of this was lost during the first 8 hours, and 54.5% during the entire 24 hours, reaching a plateau at 13 MPa (Lombardo *et al.*, 2017). These results confirm that the aligners on the market will perform differently in strict relation to their thickness and construction material.

In the study of Fang *et al.* (2020), they investigated the property changes of a polyurethane based material, before and after 2-week use in the intraoral condition. For the mechanical properties, although it was not found significant differences, there seems to be a trend of reduction in elastic modulus and acceleration in stress relaxation after the clinical use. Creep strain of these aligners was stable after 2 weeks of clinical use, implying that there was good material ductility to allow the aligner material to envelop the teeth and deliver designated force to move teeth. However, the aging effect of the oral environment on the material was not significant, which is consistent with other studies (Fang *et al.*, 2020), that concluded that material fatigue did not play a significant role in the rate or amount of tooth movement.

In the study of Gerard Bradley *et al.* (2016), it was not identified significant chemical changes in the appliances after intraoral aging, when testing a polyurethane based material. However, the mechanical properties showed significant differences in comparison with the reference material, that has no history of intraoral exposure (Gerard Bradley *et al.*, 2016). Based on the experimental outcome of this study, all the mechanical properties tested were adversely affected following intraoral aging. From a mechanical standpoint, the decrease implies attenuation of the force delivery capacity by the appliance during intraoral use. The results of creep measurements clearly showed that constant forces developed by opposite dentition and the deformation of the intraorally aged material increased, weakening the orthodontic forces exerted (Gerard Bradley *et al.*, 2016).

Under clinical conditions, these aligners suffer from a polyurethane softening mechanism. The two-phase microstructure of thermoplastic polyurethane consists of hard and soft segments, where the soft tends to be oriented perpendicular to the applied stresses, and then breaks into smaller pieces to manage receiving further deformation. The relief of the residual stresses made by the manufacturing process and the leaching of matrix plasticizers have also been said to explain the degradation of mechanical properties during intra-oral use of the aligner (One- *et al.*, 2019).

2.3 Copolyester

Copolyester is synthesized, for example, from dimethyl terephtalate, poly(tetramethylene ether glycol), and tetramethylene glycol via a transesterification reaction in the melt using titanium catalysts. During the final stage of polymerization, excess short-chain diol is removed by distillation. Other monomers are also used to produce a family of materials having a multi-block structure (Drobny, J. G., 2007).

This material is elastic, but their recoverable elasticity is limited to low strains. Copolyester thermoplastic elastomers exhibit exceptional dynamic performance. When they are operating within their elastic range, they are very resistant to creep and can endure high loads for extended periods of time without noticeable stress relaxation. Plus, their dynamic response is exceptional: copolyesters can be subjected to repeated cycles of tension and compression without any significant loss of mechanical strength (Drobny, J. G., 2007).

Copolyester elastomers are generally superior to polyester thermoplastic polyurethanes because they manage to retain flexibility better at low temperatures, and display smaller changes in properties with temperature. Chemical resistance depends of the composition of the copolymer, that is, the ratio of hard and soft segments. This material also exhibits outstanding impact resistance (Drobny, J. G. 2007).

Properties of Copolyester applied to Orthodontics

It was investigated by Fang *et al*. (2013), the dynamic stress relaxation of five thermoplastics, being two of them copolyester based materials from different manufacturers and the other three polyethylene terephthalate based materials. It was concluded that one of the copolyesters had a slower stress relaxation than three of the other thermoplastics. However, a comparative research has to be done to the chemical composition and molecular structure of the materials, in order to explain and prove the relation of these results with their chemicophysical features (Fang *et al.*, 2013).

In a recent study by Jaggy *et al*. (2020), the stress relaxation of four materials (similar composition to PET-G), was investigated being one of them a copolyester. Despite the similarity of the materials tested, the ratio of hydrogen bonded carboxyl groups to free ones (Ri) shows that the copolyester has a higher intermolecular bonding than all the others. No major differences were identified for the reduction of applied stress after one week, implicit that the different materials sustain equal degradation despite their differences in Ri (Jaggy *et al.*, 2020).

2.4 Polypropylene

Polypropylene, is a thermoplastic polymer used in a wide variety of applications. It is produced via chain-growth polymerization from the monomer propylene (Reddy *et al.*, 2013).
Polypropylene is partially crystalline and non-polar. Its properties are similar to polyethylene, but it is slightly harder and more heat resistant. It is a white, mechanically rugged material and has a high chemical resistance. Polypropylene is a bioplastic. They are either synthesized naturally from plants and animals, or entirely synthesized from renewable resources (Reddy *et al.*, 2013). Polypropylene is one of the most widely produced commodity plastics.

Properties of Polypropylene applied to Orthodontics

Five thermoplastics materials were studied by Kwon et al. (2008), for their force delivery properties, four of them were polyethylene and one was a polypropylene based material. It was proven that there were significant differences in force and energy delivery between the thermoplastics. After thermocycling, the amount of force delivered generally decreased. Deflections of optimal force in polypropylene (PP) for a maxillary central incisor tipping movement was 0.25 to 0.5 mm (16.8-118.1 g). The amounts of energy exerted by deflection of optimal force for tipping movement of a maxillary central incisor was 0.8 to 16.7 g per square millimeter for PP. Thermocycling did not influence the force delivery properties, but repeated load cycling did (Kwon *et al.*, 2008).

Seeing that the elastic modulus of the thermoplastic materials was significantly correlated with the orthodontic force, the influence of water absorption and strain on the elastic modulus was studied to clarify the reasons that affect the orthodontic force transmitted by the thermoplastic materials. Polypropylene had a significantly smaller water absorption than the other three. X-ray diffraction analysis revealed that the other thermoplastics had an amorphous phase while PP had a crystalline phase. Crystalline plastic has low water absorption, therefore the low water absorption of PP was likely due to its high crystallinity (Inoue *et al.*, 2020).

Polypropylene is composed by parts which are regularly and irregularly arranged, these were mixed in the molecular chains with a helical structure. For that matter, the absolute amount of molecular chains enabling those rearrangements is small even in the strain loading, confirming that PP was less affected by strain (Inoue *et al.*, 2020). Reflecting these properties of PP, a crystalline plastic may have a constant elastic modulus under constant strain loading. However, a large amount of wear in abrasion testing has been reported for PP compared with other thermoplastic materials, and it is easy to perforate and crack while using PP as an aligner material. Investigation of thermoplastic materials with a crystalline phase and lower elastic modulus than PP is necessary (Inoue *et al.*, 2020).

Three thermoplastics were investigated by Schuster *et al.* (2004), two of these were polypropylene based materials. PP is the lightest of the thermoplastics and has a Rockwell R hardness between 85 and 102. In this study, PET-G copolyester material exhibited less wear than did either of the softer PP thermoplastics. The results of this study validate the increased wear resistance of thermoplastic polymers as hardness increases. There was no difference in mean wear between the two PP thermoplastic materials.

III - DISCUSSION

The aim of this paper was to compare, differentiate, and indicate the best use regarding different thermoplastics. PET-G, PP, Copolyester and PU are the four thermoplastic materials studied in this investigation. They were selected based on the most cited materials during bibliographic research.

PET-G was the thermoplastic with a wholesome of experimentation and analysis. It is known for its resistance to temperature, which is a great advantage to the clear aligner industry in terms of the vacuum-formed procedure. In a study of Skaik *et al.* (2019), higher modulus of elasticity and abrasion resistance are two properties that improved the force management with the regular removal of the appliances by the patients. Nonetheless, it has to be taken into account that in this study several operating errors occurred and the system utilized did not show 100% precision, so the conclusions reached might not be completely correct.

A study by Lombardo *et al.* (2017) concluded that the force performance of an aligner material should not only be evaluated in the insertion but also 15 to 20 hours later. In the stress relaxation test the PU presented the greatest absolute initial stress, but also the greatest decay during the 24-hour period, so the authors concluded that stress relaxation releases during a prolonged period of time, not only in the initial use of the clear aligner. In spite of the insightful conclusions of this study, it is an *in-vitro* study and therefore, does not reproduce the oral environment and the specimens are not equal in surface conformation or thickness, which has been proved to be an important part that can differ the performance of the thermoplastic materials.

For the mechanical properties Fang *et al.* (2020), did not find significant differences between the material before and after a two week use in the intraoral condition, there was a reduction in elastic modulus and acceleration in stress relaxation after the clinical use of PU aligners. The fact that this study is based on the premise that different patients use the orthodontic removable appliances for the same number of hours is not directly transferred to a clinical situation and this fact can be relevant, because the mechanical properties will change according to the regularity of usage.

From a mechanical standpoint, a decrease in modulus of elasticity implies attenuation of the force delivery capacity by the appliance during intraoral use of PU thermoplastic

(Gerard Bradley *et al.*, 2016). This explained by the microstructure of the polyurethane material (One *et al.*, 2019).

Regarding the thickness of the materials, single-layered materials like PET-G were stiffer, which means that some of the materials usually used in aligner could not exert enough force to guide the teeth into the correct planned position (Lombardo *et al.*, 2017). The hardness of the copolyester materials tested in a particular study (Ryu *et al.*, 2018), changed after thermoforming. With an increase in the thickness of the materials, the force also increased while the elastic modulus decreased. The copolyesters also express a slower stress relaxation than the others thermoplastics, but regarding this characteristic, further investigation is necessary in order to understand the origin of these results (Fang *et al.*, 2013).

The morphological variations of the teeth can also influence the force applied by the aligner material, in this case, some materials like PET-G can be more sensitive to morphological variations and that applies not only to different types of tooth but also to the same type of tooth in different individuals (Elkholy *et al.*, 2017).

Correlation was also found between the composition of the thermoplastics and its properties (Inoue *et al.*, 2020). The crystalline plastic has low water absorption, leading to the low water absorption of PP due to its high crystallinity. Reflecting these properties of PP, a crystalline plastic may have a constant elastic modulus under constant strain loading (Inoue *et al.*, 2020).

In a fairly recent article, Skaik *et al.* (2019), compared two different PET-G materials. One of them was conventional PET-G, and the second was modified PET-G with a higher modulus of elasticity and greater abrasion resistance. The force change that occurred with varying appliance removal frequency were observed for both PET-G materials. Therefore, the data showed that patients treated with clear thermoplastic aligners must wear the appliance for at least 20 hours per day and should not remove it because this affects treatment efficiency and leads to prolonged treatment time. However, the modified PET-G material showed fewer force changes than did the conventional PET-G material, indicating that, compared with materials with inferior elasticity and resistance, materials with a higher modulus of elasticity and greater abrasion resistance are less affected by removal frequency. Although, not every aligner is equal, and those currently on the market differ in terms of their construction material, thickness, and clinical protocol (Lombardo *et al.*, 2017).

Clear aligners are viscoelastic materials, having intermediate properties between those of viscous and elastic materials. This means that under loading their behavior may vary considerably over time, even when first inserted and before any tooth movement is achieved. In materials science, stress relaxation is the observed decrease in stress in response to strain generated in the structure. In a recent study, stress relaxation was tested in several thermoplastics including PET-G (Lombardo *et al.*, 2017). In this stress relaxation test the PET-G released 44% of the initial stress during the first 8 hours, and 62% during 24 hours. This common pattern indicates that the performance of an aligner should be evaluated not only in terms of the force exerted upon insertion but also that expressed 15 to 20 hours later (Lombardo *et al.*, 2017). Nevertheless, it is mandatory to make a correct diagnosis and to choose a treatment objective that is achievable with the limited biomechanics offered by clear aligners (Ercoli *et al.*, 2014).

In the study of Ryu *et al.* (2018), several thermoplastics were evaluated, two of them consisted of copolyester based materials and the other two were PET-G based materials. The hardness of the thermoplastic materials tested in this study changed after thermoforming. Vickers hardness was measured to compare the transfer of force and energy according to the type and thickness of the thermoplastic material, and it was found that the hardness affected the orthodontics force. In this study the surface hardness of both the copolyester increases after thermoforming. In a three-point bending test, with an increase in the thickness of the thermoplastic materials, the force increases but the flexural modulus decreases. A tensile test was performed after thermoforming in order to evaluate the durability of the tested thermoplastic materials. The results showed that the force and elastic modulus of all materials decreased after thermoforming. With an increase in the thickness of the materials, the force increased while the elastic modulus decreased (Ryu *et al.*, 2018). One of the many obstacles to overcome in this investigation is the lack of regulation towards the testing of the materials. It is extremely important to be able to compare the research, and it is almost impossible to find the same tests with common characteristics that provide the opportunity to do so. A base line of rules and detriments should exist to guide all research and build a common ground in this particular field.

The majority of the studies published in this topic are *in-vitro*. That limits the conclusions drawn from these, because the intraoral condition cannot be replicated fully in *in-vitro* studies.

With the results reached by the cited authors, all of the thermoplastics have advantages and disadvantages. The PET-G material showed satisfactory results regarding its higher modulus of elasticity and greater abrasion resistance. Polypropylene has a high crystallinity that enables it to have a constant elastic modulus under constant strain loading. The surface hardness of copolyester increases after thermoforming, which can be useful in orthodontic movements. PU has a softening system, caused by its microstructure, that can alter the outcome of the treatment. These thermoplastics materials presented are all different, so whilst the perfect one is yet to be manufactured, the characteristics of the current materials must be taken into account when indicating a treatment and the personalization regarding the patient’s orthodontic needs should exist.

Further studies should be performed, more importantly, in the intraoral environment, only then we can fully understand our own implications and which properties should prevail in a thermoplastic material.

IV – CONCLUSION

- The morphology of different teeth influences the force delivery and treatment outcome;
- Thickness of the thermoplastic material should be taken in account throughout the treatment;
- Composition of the thermoplastics must be properly investigated, seeing that exerts impact in all characteristics, mechanical and chemical, of the material and its performance;
- Regulation in testing thermoplastic materials should be implemented;
- Different thermoplastics should the chosen for each particular case, taking into account their characteristics;
- Further investigation on thermoplastic materials is essential, the perfect plastic is yet to be manufactured and Orthodontics with the use of clear aligner is just beginning.

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APPENDIX 1

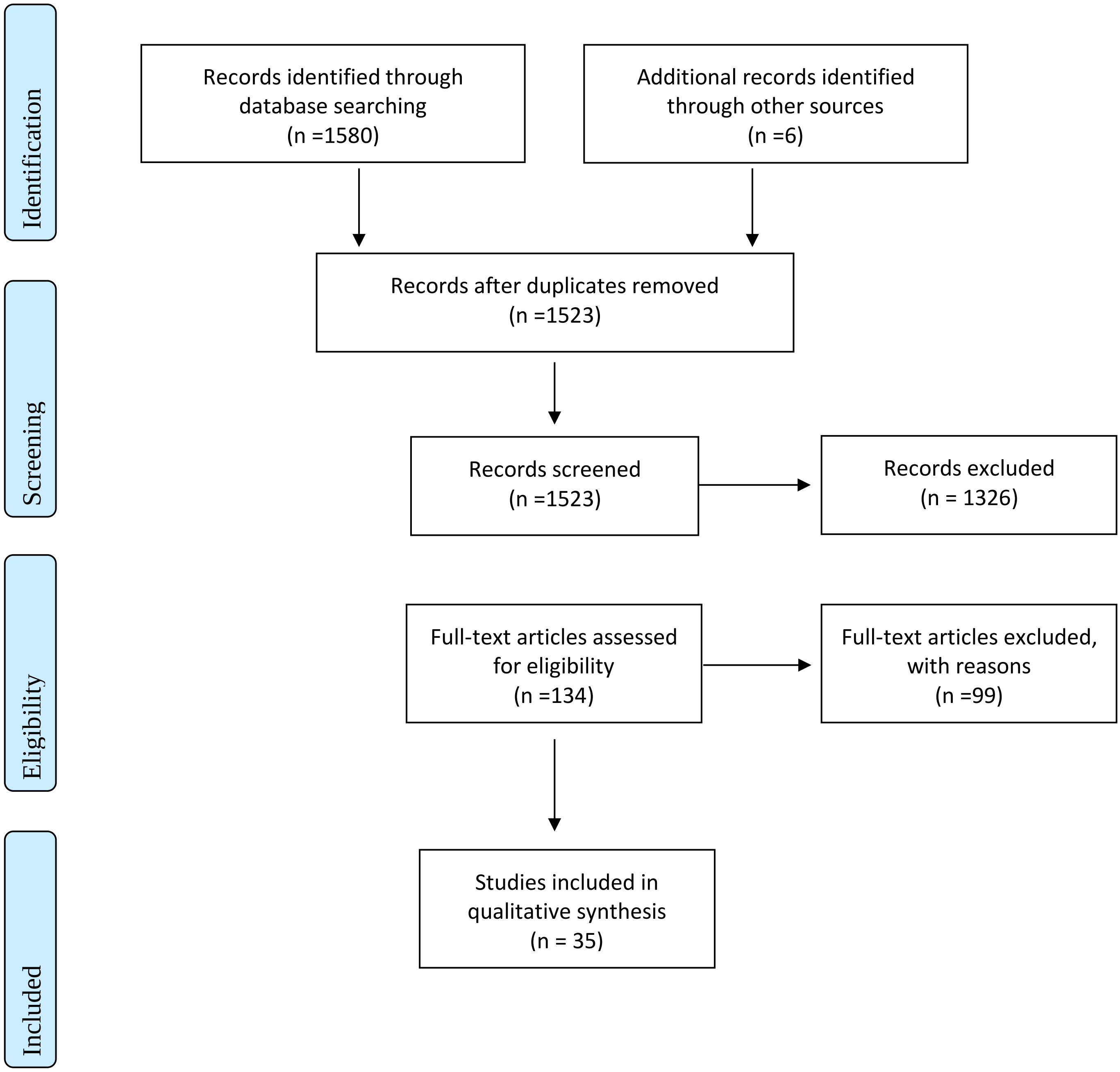

Figure 1. Prisma flow chart

APPENDIX 2

Table 1. Inclusion and exclusion criteria for selection and eligibility of articles included for review

Inclusion Criteria	*Exclusion Criteria*
• Papers relevant to the Narrative Review • Publication date over the last 10 years • Studies regarding one or multiple of the following parameters: PET-G; PU; Copolyester; PP	• Language used • Do not address the chosen topic • Non published literature • Articles which the complete text was not available