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Mechanical properties of orthodontic aligners and limitations of its clinical applicability

A systematic review

Leticia Maria Dias da Costa Lawrence

Dissertação conducente ao Grau de Mestre em

Medicina Dentária (Ciclo Integrado)

Gandra, 10 de janeiro de 2020

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Trabalho realizado sob a Orientação de Mestre Aline Gonçalves

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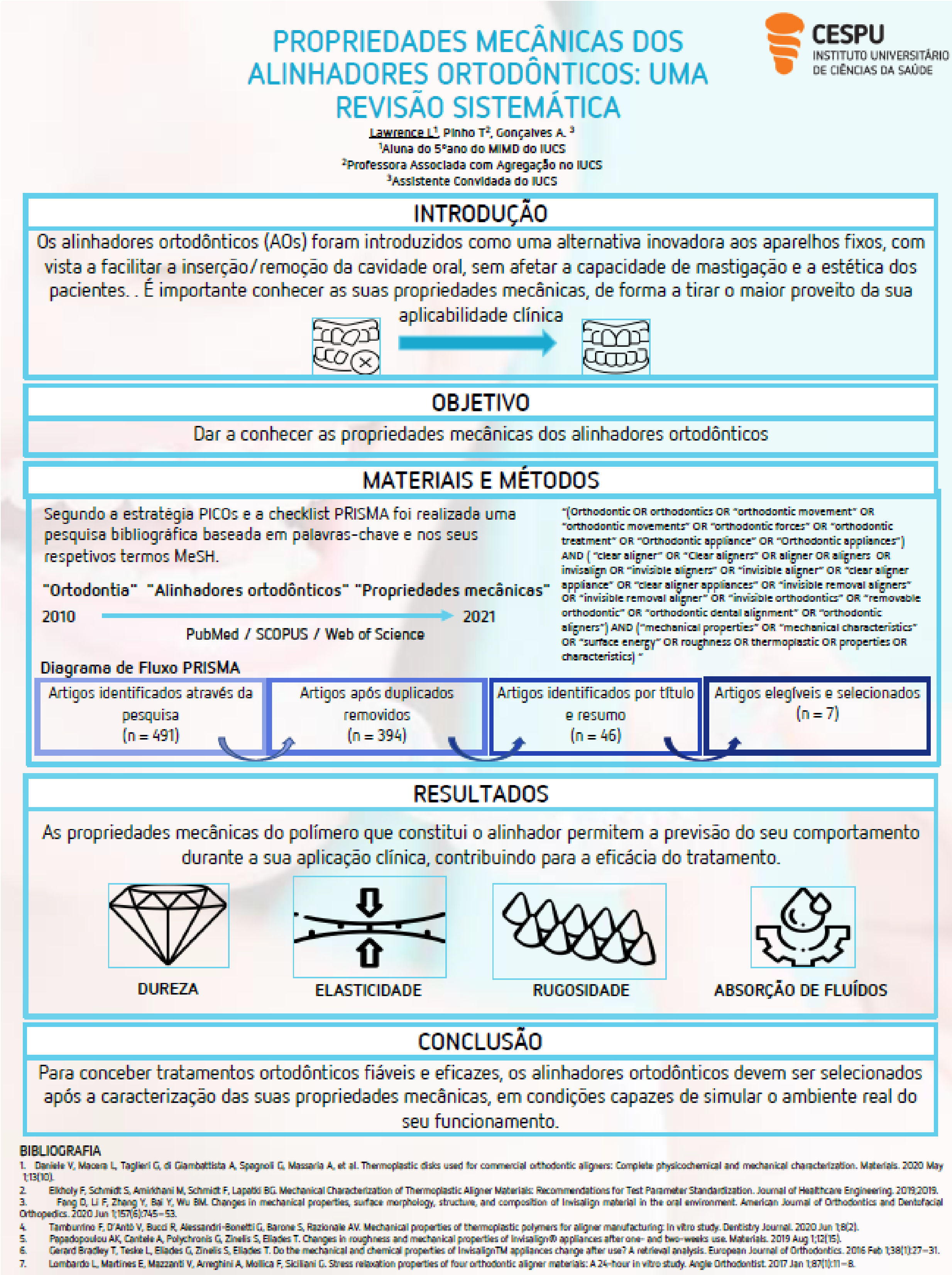

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PROPRIEDADES MECÂNICAS DOS ALINHADORES ORTODÔNTICOS: UMA REVISÃO SISTEMÁTICA

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INTRODUÇÃO

Os alinhadores ortodônticos (AOs) foram introduzidos como uma alternativa inovadora aos aparelhos fixos, com vista a facilitar a inserção/remoção da cavidade oral, sem afetar a capacidade de mastigação e a estética dos pacientes. . É importante conhecer as suas propriedades mecânicas, de forma a tirar o maior proveito da sua aplicabilidade clínica

OBJETIVO

Dar a conhecer as propriedades mecânicas dos alinhadores ortodônticos

MATERIAIS E MÉTODOS

Segundo a estratégia PICOs e a checklist PRISMA foi realizada uma pesquisa bibliográfica baseada em palavras-chave e nos seus respetivos termos MeSH.

"Ortodontia" "Alinhadores ortodônticos" "Propriedades mecânicas"

2010 → 2021

PubMed / SCOPUS / Web of Science

"(Orthodontic OR orthodontics OR "orthodontic movement" OR "orthodontic movements" OR "orthodontic forces" OR "orthodontic treatment" OR "Orthodontic appliance" OR "Orthodontic appliances") AND ("clear aligner" OR "Clear aligners" OR aligner OR aligners OR invisalign OR "invisible aligners" OR "invisible aligner" OR "clear aligner appliance" OR "clear aligner appliances" OR "invisible removal aligners" OR "invisible removal aligner" OR "invisible orthodontics" OR "removable orthodontic" OR "orthodontic dental alignment" OR "orthodontic aligners") AND ("mechanical properties" OR "mechanical characteristics" OR "surface energy" OR roughness OR thermoplastic OR properties OR characteristics) "

Diagrama de Fluxo PRISMA

Artigos identificados através da pesquisa (n = 491) → Artigos após duplicados removidos (n = 394) → Artigos identificados por título e resumo (n = 46) → Artigos elegíveis e selecionados (n = 7)

RESULTADOS

As propriedades mecânicas do polímero que constitui o alinhador permitem a previsão do seu comportamento durante a sua aplicação clínica, contribuindo para a eficácia do tratamento.

DUREZA

ELASTICIDADE

RUGOSIDADE

ABSORÇÃO DE FLUÍDOS

CONCLUSÃO

Para conceber tratamentos ortodônticos fiáveis e eficazes, os alinhadores ortodônticos devem ser selecionados após a caracterização das suas propriedades mecânicas, em condições capazes de simular o ambiente real do seu funcionamento.

BIBLIOGRAFIA

1. Daniele V, Macera L, Taglieri G, di Giambattista A, Spagnoli G, Massaria A, et al. Thermoplastic disks used for commercial orthodontic aligners: Complete physicochemical and mechanical characterization. Materials. 2020 May 1;13(10).
2. Elkholy F, Schmidt S, Amirkhani M, Schmidt F, Lapatki BG. Mechanical Characterization of Thermoplastic Aligner Materials: Recommendations for Test Parameter Standardization. Journal of Healthcare Engineering. 2019;2019.
3. Fang D, Li F, Zhang Y, Bai Y, Wu BM. Changes in mechanical properties, surface morphology, structure, and composition of Invisalign material in the oral environment. American Journal of Orthodontics and Dentofacial Orthopedics. 2020 Jun 1;157(6):745–53.
4. Tamburrino F, D'Antò V, Bucci R, Alessandri-Bonetti G, Barone S, Razionale AV. Mechanical properties of thermoplastic polymers for aligner manufacturing: In vitro study. Dentistry Journal. 2020 Jun 1;8(2).
5. Papadopoulou AK, Cantele A, Polychronis G, Zinelis S, Eliades T. Changes in roughness and mechanical properties of Invisalign® appliances after one- and two-weeks use. Materials. 2019 Aug 1;12(15).
6. Gerard Bradley T, Teske L, Eliades G, Zinelis S, Eliades T. Do the mechanical and chemical properties of InvisalignTM appliances change after use? A retrieval analysis. European Journal of Orthodontics. 2016 Feb 1;38(1):27–31.
7. Lombardo L, Martines E, Mazzanti V, Arreghini A, Mollica F, Siciliani G. Stress relaxation properties of four orthodontic aligner materials: A 24-hour in vitro study. Angle Orthodontist. 2017 Jan 1;87(1):11–8.

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Resumo

Introdução: Os alinhadores ortodônticos (AOs) foram introduzidos como uma alternativa inovadora aos aparelhos fixos, com vista a facilitar a inserção/remoção da cavidade oral, sem afetar a capacidade de mastigação e a estética dos pacientes.

Objetivos: Fornecer uma descrição e comparação das propriedades mecânicas dos AOs e a sua influência no desempenho clínico..

Materiais e Métodos: Uma pesquisa bibliográfica , com o uso das palavras-chave "ortodontia" "alinhador" e "propriedades mecânicas" e os respetivos termos MeSH , para artigos publicados entre Janeiro de 2010 e Fevereiro de 2021 em inglês e português foi conduzida nas bases de dados: PubMed e Web of Science. Um total de 513 artigos foram encontrados, apenas 10 artigos foram considerados relevantes e incluídos.

Resultados: As propriedades mecânicas permitem prever o comportamento do material durante a sua aplicação, contribuindo para a sua eficácia. O consenso entre os estudos é que o PET tem o módulo de elasticidade mais baixo, as amostras de TPU exibem o mais alto, PET-G dependendo de como é modificado tem um desempenho comparativamente médio ou similar. No que diz respeito ao stress, um estudo descobriu que a TPU tinha menos resistência e deforma-se plasticamente mais facilmente, em oposição a outros estudos, mas parece que o tamanho da amostra e a técnica de teste e o ambiente podem influenciar os resultados.

Conclusão: Enquanto PET, PET-G e CP são mais baratos permitindo um tratamento mais acessível a custos, a TPU tem melhores propriedades mecânicas, tais como maior elasticidade, melhor resistência, ponto de rendimento, bem como melhores propriedades de relaxamento do stress. É importante conhecer as suas propriedades mecânicas, de forma a tirar o maior proveito da sua aplicabilidade clínica. A mistura de diferentes polímeros nem sempre termina numa fusão das suas propriedades.

Palavras-chave: Ortodontia, Alinhador, Propriedades Mecânicas

Abstract

Introduction: Orthodontic aligners (OAs) were introduced as an innovative alternative to fixed appliances, with a view to facilitating insertion/removal in the oral cavity, without affecting patients' chewing ability and aesthetics. It is important to know their mechanical properties in order to make the most of their clinical applicability.

Objective: To provide description and comparison of the mechanical properties of OAs and their influence on performance.

Material and Methods: A bibliographic search, with the use of the keywords: "orthodontics", "aligner", " mechanical properties" and the respective MeSH terms, for articles published between January 2010 and February 2021 in English and Portuguese was conducted in the databases: PubMed and Web of Science. 511 articles were identified, only 9 articles were found relevant and included.

Results: The mechanical properties allow the prediction of the materials' behaviour during its application, contributing to its effectiveness. The consensus between studies is that PET has the lowest elasticity modulus, TPU samples exhibit the highest, PET-G depending on how it's modified has a comparatively average or similar performance. With regards to stress, one study found TPU to have less resistance and to deform plastically easier, in opposition to other studies, but it seems that sample size and testing technique and environment can influence results.

Conclusion: While PET, PET-G and CP are cheaper allowing more cost-accessible treatment, TPU has better mechanical properties such as higher elasticity, better strength, yield point as well as better stress relaxation properties. It is important to know their mechanical properties in order to make the most of their clinical applicability. Mixing different polymers doesn't always end in a merge of their properties.

Key words: Orthodontics, Aligner, Mechanical Properties

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General Index

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Figure Index

List of abbreviations

EM- Elastic modulus

IIT- Instrumented Indentation Test

IM- Indentation modulus

MH- Martens Hardness

OA- Orthodontic Aligner

PC- Polycarbonate

PET- Polyethylene terephthalate

PET-G - Polyethylene terephthalate glycol-modified

PP- Polypropylene

PU- Polyurethane

RI- Relaxation index

SR- Stress relaxation

TYS- Tensile yield strength

TPU- Thermoplastic polyurethane

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1- Introduction

The ever-growing call for esthetic, unobtrusive orthodontics has fueled an exponential boom within clear aligner industry. Patients tend to prefer them because of their superior comfort and aesthetics and their proven effectiveness.

Adolescent and adult patients privy to their malocclusion developments and disappointed with their dental appearance tend to have psychosocial concerns.(1)

Aesthetics play a significant role in patient's decisions to receive orthodontic treatment: a recent survey found that 33 per cent of young adults would be unwilling to wear visible braces if needed. Another study found that while traditional metal brackets were aesthetically acceptable to only 55 per cent of adults, clear aligners were acceptable to over 90 per cent.(2)

OAs can be easily inserted and removed and do not affect the patient's chewing ability. Tooth movement without the use of bands, brackets, or wires was described as early as 1945 by Kesling, who reported the use of a flexible tooth positioning appliance.(3)

The first mass-marketed aligners, commercialized by the multinational Align Technology (San Jose, California), were made out of a single-layer rigid polyurethane. (4)

However, each aligner is not created equal, and those presently available fluctuate in terms of their construction material, thickness, and scientific protocol. There are not a lot of articles that focus on the investigation and understanding of the mechanical properties that modern society craves.

For this task, the present review aims to provide, description and comparison of the mechanical properties of the thermoplastic disks utilized in fabrication of OAs, therefore permitting the deduction of their limitations in terms of clinical relevance.

2- Materials and methods

The review protocol used was the one described in the PRISMA recommendations (PRISMA Statement), using the PRISMA checklist available at http://www.prismastatement.org/PRISMAStatement/Checklist and the PRISMA Flowchart available at http://www.prisma-statement.org/PRISMAStatement/FlowDiagram.

2.1- Eligibility criteria

At the beginning of this integrative systematic review, a guiding question was formulated according to the PICOS strategy "Population, Intervention, Comparison, Outcomes and Study design" (Table 1)

Population	In vitro studies of Thermoplastic Aligners for Orthodontic Treatment.
Intervention	Understanding their Mechanical Properties and limitations
Comparison	Different Thermoplastic Manufacturing Disks
Results	Mechanical Properties
Study design	Randomized controlled studies, in vitro studies, observational studies and prospective and retrospective studies, test-tube lab research

Table 1- PICOs Strategy

Therefore, the focus question of the current systematic review was defined as: **How can the clinical effectivity of OAs be influenced by the mechanical properties of its constituent materials?**

The following inclusion criteria were considered:

- Articles published from 2010 to February 2021;
- Language: English and Portuguese;
- Availability: full articles that portray the theme and are not blocked;
- Randomized controlled studies, in vitro studies, observational studies, and prospective and retrospective studies, test-tube lab research .

The following exclusion criteria were considered:

- Meta-analyses, systematic reviews, case reports, case-control study;
- Theses and dissertations;
- Articles prior to 2010;
- Articles whose title and/or abstract do not fit the theme
- Full reading did not provide relevant information;
- Articles in languages other than English and Portuguese;
- Articles not available in the database referred in full text.

2.2- Information sources

A bibliographic search was conducted in PubMed and Web of Science databases. Articles published between January 2010 and February 2021 in English and Portuguese were analyzed.

The search used the following keywords and MeSH terms: (Orthodontic OR orthodontics OR "orthodontic movement" OR "orthodontic movements" OR "orthodontic forces" OR "orthodontic treatment" OR "Orthodontic appliance" OR "Orthodontic appliances") AND ("clear aligner" OR "Clear aligners" OR aligner OR aligners OR invisalign OR "invisible aligners" OR "invisible aligner" OR "clear aligner appliance" OR "clear aligner appliances" OR "invisible removal aligners" OR "invisible removal aligner" OR "invisible orthodontics" OR "removable orthodontic" OR "orthodontic dental alignment" OR "orthodontic aligners") AND ("mechanical properties" OR "mechanical characteristics" OR roughness OR thermoplastic OR properties OR characteristics)

The references of the included articles were analysed to identify and retrieve articles that did not appear in the initial search.

The search strategies are detailed in **Table 2.**

Databases	Search strategy	Total articles	Selected articles
PubMed	(Orthodontic OR orthodontics OR "orthodontic movement" OR "orthodontic movements" OR "orthodontic forces" OR "orthodontic treatment" OR "Orthodontic appliance" OR "Orthodontic appliances") AND ("clear aligner" OR "Clear aligners" OR aligner OR aligners OR invisalign OR "invisible aligners" OR "invisible aligner" OR "clear aligner appliance" OR	306	**52**

	"clear aligner appliances" OR "invisible removal aligners" OR "invisible removal aligner" OR "invisible orthodontics" OR "removable orthodontic" OR "orthodontic dental alignment" OR "orthodontic aligners") AND ("mechanical properties" OR "mechanical characteristics" OR roughness OR thermoplastic OR properties OR characteristics)		
Web of Science	(Orthodontic OR orthodontics OR "orthodontic movement" OR "orthodontic movements" OR "orthodontic forces" OR "orthodontic treatment" OR "Orthodontic appliance" OR "Orthodontic appliances") AND ("clear aligner" OR "Clear aligners" OR aligner OR aligners OR invisalign OR "invisible aligners" OR "invisible aligner" OR "clear aligner appliance" OR "clear aligner appliances" OR "invisible removal aligners" OR "invisible removal aligner" OR "invisible orthodontics" OR "removable orthodontic" OR "orthodontic dental alignment" OR "orthodontic aligners") AND ("mechanical properties" OR "mechanical characteristics" OR roughness OR thermoplastic OR properties OR characteristics)	205	47

Table 2- Search strategy

2.3- Article selection

First, an advanced search was performed using the keywords in the database and the respective MeSH terms. Duplicate articles were manually removed. The title and abstract of the identified potentially relevant articles were submitted to a preliminary assessment by two authors (A.G., L.L.) to determine whether they met the objective defined in this study.

Secondarily, the potentially eligible studies, which met the inclusion criteria, were read in full and assessed for eligibility.

Finally, the full assessment of the articles was completed. Data were extracted and organized in tabular form.

2.4- Data collection process

The following information was extracted from each article and organised in table form:

- Name of the first author;
- Study design
- Title of the article; Year of publication;
- Material characteristics;
- Intervention characteristics;
- Main results

3- Results

3.1- Article selection

Step I: Database results

From the bibliographic search databases and the manual search used in the present integrative systematic review, a total of 511 articles were found. Removal of duplicates (exclusion criteria) resulted in a total of 394 articles. After reading the titles and abstracts 21 articles were selected for further analysis, 14 articles were excluded because they were considered irrelevant or because they did not meet the inclusion criteria, thus making a total of 21 articles.

Step II: Review of the articles

The 21 articles were read in full and individually assessed for eligibility, from which 10 articles were selected.

Step III: Included articles

Finally, 10 articles were included in the present integrative systematic review. The article selection process is illustrated in the PRISMA flow diagram. (Figure 1)

The articles were evaluated in full, and the data were extracted and organized into a table. This was divided into the names of the authors of each study, the year of publication, the main objective, the type of study, and the main results found.

The following information were extracted from each article and organized in table form: Tensile/Yield test, Indentation modulus (IM), Martens Hardness (MH), Relaxation/stress test, Elastic modulus (EM).

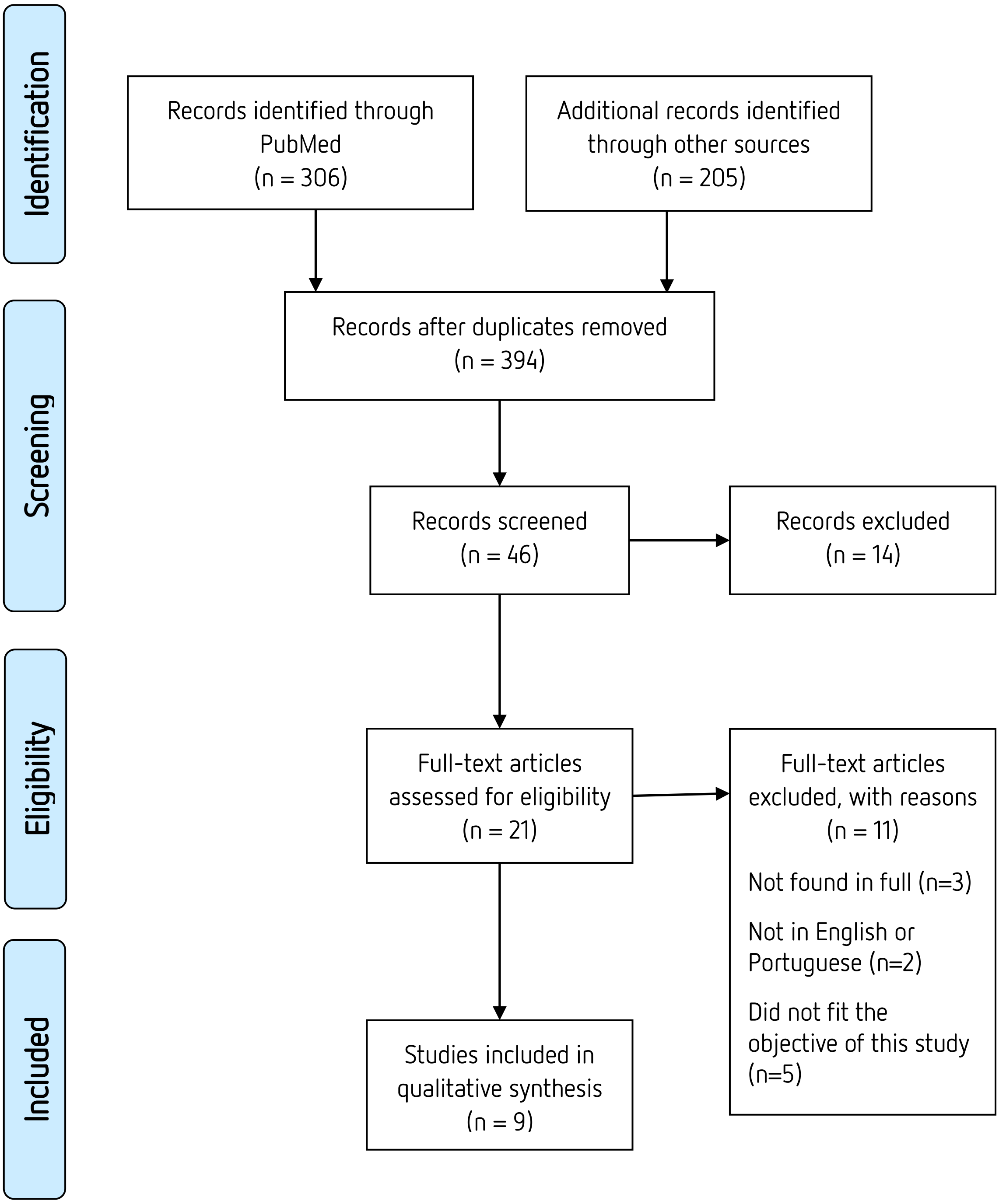

Figure 1- PRISMA Flow Diagram

3.2- Study Characteristics

3.2.1- Year of publication

Regarding the publication period, the year 2020 recorded the highest number of articles on the topic in question, presenting five articles (50%), the year 2019 with two articles (9.1%) and, finally the year 2013, 2016 and 2017 with one article each (10%). Articles from the years 2010, 2011, 2012, 2014, 2015, 2018 and 2020 were not selected. Figure 2 shows the distribution regarding the years of publication.

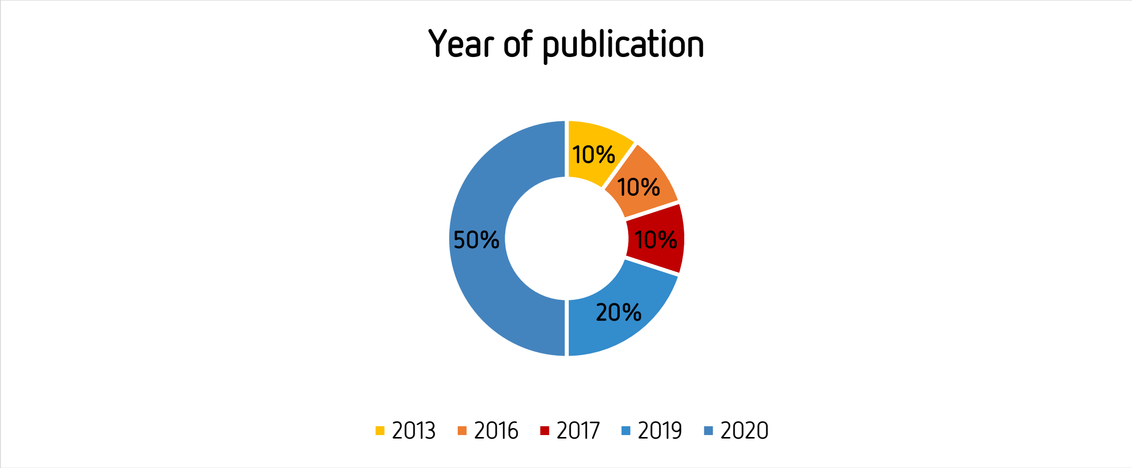

Figure 2- Year of publication

3.2.2-Study Design

As for the type of studies of the articles evaluated all of them are in vitro studies also referred as "test-tube" lab research. Figure 3 shows the distribution regarding the study design they have.

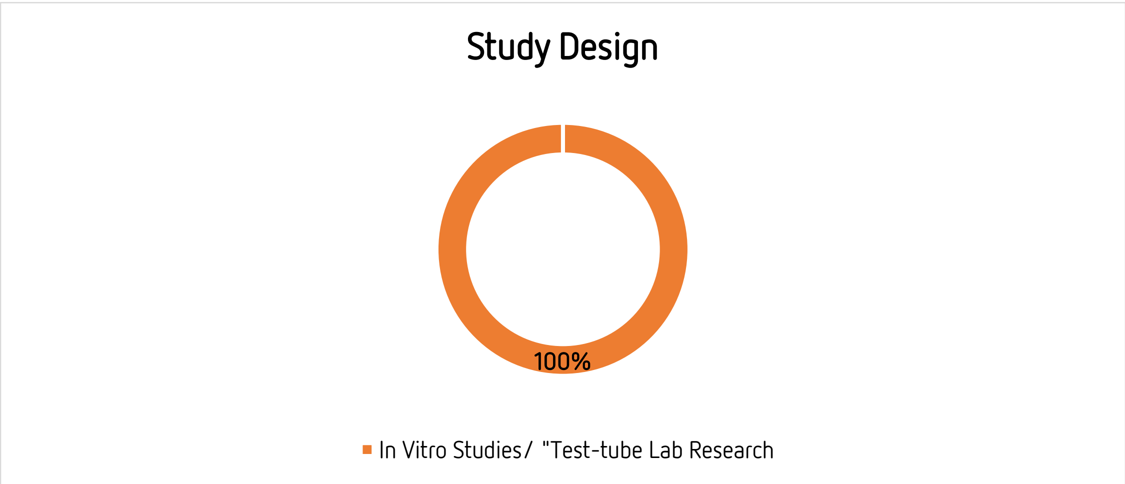

Figure 3-Study Design

3.2.3-Study characteristics

Author (Year)	Study Design	Title	Material characteristics	Intervention characteristics	Main results
Fang Det al. (2020)	In vitro study	**Changes in mechanical properties, surface morphology, structure, and composition of Invisalign material in the oral environment**	Thickness: 0.75mm Brand: Invisaling Selected area: Facial one-third of maxillary central incisors Size: 2.5 mm x 9 mm Type: Multilayer aromatic thermoplastic polyurethane / copolyester	Pressure: NR Temperature: 37° Indentation depth: NR Deflection: NR Force: 0,6 MPa (preload of 0,5 N) Time: 2h	**Mechanical characteristics:** Tensile/Yield test: NR Indentation modulus: NR Martens Hardness (HM): NR Relaxation/stress test: - Control group: 5,30 MPa (initial)/ 19,89 MPa (2h) / 0,83 MPa (residual) - Group 2 weeks: 5,17 MPa (initial)/ 15,91 MPa (2h) / 0,83 MPa (residual) Elastic modulus (EM): - Control group: 842 MPa - Group 2 weeks: 806 MPa Stress: - Control group: 15.91 6% - Group 2 weeks: 19.89%
Papadopoulou AK et al. (2019)	In vitro study	**Changes in Roughness and Mechanical Properties of Invisalign ® Appliances after One- and Two-Weeks Use**	Thickness: 0.75mm Brand: Invisaling Selected area: 1st molars Size: NR Type: Multilayer aromatic thermoplastic polyurethane / copolyester	Pressure: 4,9N Temperature: NR Indentation depth: of 30 μm Deflection: NR Force: -Control group: 3,6 N -Group 1 week: 2,6 N -Group 2 week: 2,6N Time: 60s	**Mechanical characteristics:** Tensile/Yield test: NR Indentation modulus: -Control group: 2600 MPa -Group 1 week: 1600 MPa -Group 2 week: 1500 MPa Martens Hardness (MH): -Control group: 120 N/mm^2 -Group 1 week: 78 N/mm^2 -Group 2 week: 89 N/mm^2 Relaxation/stress test: Relaxation index (RI):

					-Control group: 4,0% -Group 1 week: 8,3% -Group 2 week: 6,5% Elastic modulus (EM): NR Stress: NR
Gerard Bradley T et al. (2016)	In vitro study	**Do the mechanical and chemical properties of InvisalignTM appliances change after use? A retrieval analysis.**	Thickness: 0.75mm Brand: Invisaling Selected area: buccal surface of the central incisors Size: 5 × 5 mm Type: Multilayer aromatic thermoplastic polyurethane / copolyester	Pressure: Temperature: Indentation depth: 5 μm Deflection: NR Force: 4.9 N Time: 120 s Stress: NR	**Mechanical characteristics:** Tensile/Yield test: NR Indentation modulus: -Control group: 2466 MPa -Group 44 days: 2216 MPa Martens Hardness (MH): -Control group: 119 N/mm^2 -Group 44 days: 110 N/mm^2 Relaxation/stress test: NR Relaxation index (RI): NR Elastic modulus (EM): NR Stress: NR
Fang D et al. (2013)	In vitro study	**Dynamic stress relaxation of orthodontic thermoplastic materials in a simulated oral environment**	Thickness: 1.0 mm Brand: Erkodur, Biolon, Masel, Keystone, Duran Selected area: NR Size: 115 mm long, 2,.0 mm wide at both ends, 6,0 mm wide in the narrow middle part Type: - Erkodur: Polyethylene terephthalate glycol-modified (PET-G) - Biolon: Polyethylene terephthalate (PET) - Masel: Copolyester - Keystone: Copolyester - Duran: Polyethylene terephthalate glycol-modified	Pressure: NR Temperature: Water Bath: 37°C Environment: 20°C Indentation depth: NR Deflection: NR Force: NR Time: 3h Stress: - Erkodur: 37,26 MPa - Biolon: 37,70 MPa - Masel: 41,46 MPa - Keystone: 42,24 MPa - Duran: 37,32 MPa	**Mechanical characteristics:** Tensile/Yield test: NR Indentation modulus: NR Martens Hardness (MH): NR Relaxation/stress test: NR Relaxation index (RI): NR Elastic modulus (EM): NR Stress: (residual) - Erkodur: 66.49% - Biolon: 53.24% - Masel: 65,27% - Keystone: 50,22% - Duran: 55,48%

			(PET-G)		
Inoue S et al. (2020)	In vitro study	**Influence of constant strain on the elasticity of thermoplastic orthodontic materia ls**	Thickness: 1,0 mm Brand: Essix A+ Plastic, Duran, Erkodur, Essix C+ Plastic Selected area: Maxillary central incisors and right lateral incisor Size: NR Type: - Essix A+: Polyester (PES) - Duran: Polyethylene terephthalate glycol- modified (PET-G) - Erkodur: Polyethylene terephthalate glycol- modified (PET-G) - Essix C+: Polypropylene (PP)	Pressure: Temperature: 37° C Indentation depth: NR Deflection: NR Force: 500 N Time: 24h/ 2 weeks Stress: NR	**Mechanical characteristics:** Tensile/Yield test: NR Indentation modulus: NR Martens Hardness (MH): NR Relaxation/stress test: NR Elastic modulus (EM): Immersion 24h without strain: - Essix A+: 705,8 MPa - Duran: 684,8 MPa - Erkodur: 726,3 MPa - Essix C+: 366,6 Mpa Immersion 2 weeks without strain: - Essix A+: 783,6 MPa - Duran: 724,1 MPa - Erkodur: 782,8 MPa - Essix C+: 351,5 MPa Immersion 2 weeks with 1% strain: - Essix A+: 598,7 MPa - Duran: 641,4 MPa - Erkodur: 619,5 MPa - Essix C+: 403,6 MPa Stress: NR
Elkholy F et al. (2019)	In vitro study	**Mechanical Characterization of Thermoplastic Aligner Materials: Recommendations for Test Parameter Standardization.**	Thickness: 0,4mm; 0,5mm; 0,625 mm; 0,7 mm Brand: Duran Selected area: Size: 40mm in length and 10mm in width Type: Polyethylene terephthalate glycol (PET-G)	Pressure: NR Temperature: 37°C Indentation depth: NR Deflection: Thermoformed: - 0,4 mm: 0,2 mm - 0,5 mm: 0,15 mm - 0,625 mm: 0,15 mm	**Mechanical characteristics:** Tensile/Yield test: NR Indentation modulus: NR Martens Hardness (MH): NR Relaxation/stress test: NR Elastic modulus (EM): NR Stress: TF with flat metal plate:

				- 0,7 mm: 0,10 mm Force: NR Time: 24 hours Stress: NR	- 0,4 mm: 14,61 MPa - 0,5 mm: 14,70 MPa - 0,625 mm: 17,30 MPa - 0,7 mm: 14,03 MPa TF with stone model base: - 04 mm: 13,45 MPa - 0,5 mm: 12,97 MPa - 0,625 mm: 15,57 MPa - 0,7 mm: 13,45 MPa TF with round stone disc: - 0,4 mm: 14,61 MPa - 0,5 mm: 14,41 MPa - 0,625 mm: 16,72 MPa - 0,7 mm: 14,41 MPa TF with stone roof form: - 0,4 mm: 13,45 MPa - 0,5 mm: 12,97 MPa - 0,625 mm: 14,99 MPa - 0,7 mm: 12,49 MPa
Tamburrino F et al. (2020)	In vitro study	Mechanical Properties of Thermoplastic Polymers for Aligner Manufacturing: In Vitro Study	Thickness: 0.75, 1 mm Brand: Duran, Biolon and Zendura, Selected area: NR Size: diameter of 125 mm Type: - Duran: Polyethylene terephthalate glycol (PET-G) - Biolon: Polyethylene terephthalate glycol (PET-G) - Zendura: Thermoplastic polyurethane (TPU)	Pressure: Temperature: - 37°C initial (storage in artificial saliva) - 23°C tests Indentation depth: NR Deflection: NR Force: NR Time: - Speed test of 0.25 mm/min (tolerance ±20) Stress: NR	**Mechanical characteristics:** Tensile/Yield test: - Duran: -As supplied (A.S.): 49,29 MPa -Thermoformed (T.): 53,53 MPa -Stored in artificial saliva (S.A.S.): 49,49 MPa - Biolon: -As supplied (A.S.): 52,10 MPa -Thermoformed (T.): 48,75 MPa -Stored in artificial saliva (S.A.S.): 50,62 Mpa - Zendura: -As supplied (A.S.): 62,37 MPa -Thermoformed (T.): 41,92 MPa

					-Stored in artificial saliva (S.A.S.): 44,61 MPa Indentation modulus: NR Martens Hardness (MH): NR Relaxation/stress test: NR Elastic modulus (EM): - Duran: -As supplied (A.S.): 1531 MPa -Thermoformed (T.): 1693 MPa -Stored in artificial saliva (S.A.S.): 1368 MPa - Biolon: -As supplied (A.S.): 1556 MPa -Thermoformed (T.): 1447 MPa -Stored in artificial saliva (S.A.S.): 1519 MPa - Zendura: -As supplied (A.S.): 1478 MPa -Thermoformed (T.): 1730 MPa -Stored in artificial saliva (S.A.S.): 1466 MPa Stress: NR
Lombardo L et al. (2017)	**In vitro study**	**Stress relaxation properties of four orthodontic aligner materials: A 24-hour in vitro study**	Thickness: - One layer: 0,75mm - Multilayered: 1 mm and 1,2 mm Brand: F22 Aligner, Duran, Erkoloc-Pro, Durasoft Selected area: Size: 25 x 50 mm cut from 125mm diameter disks Type: - F22 Aligner: Thermoplastic polyurethane (TPU) - Duran: Polyethylene	Pressure: Temperature: 37°C Indentation depth: Deflection: - Maximum: 7mm - At ¼ yield strength: - F22 Aligner: 1.26 mm - Duran: 1,04 mm - Erkoloc-Pro: 1,45 mm	**Mechanical characteristics:** Tensile/Yield test: Yield strength: - F22 Aligner: 81,36 MPa - Duran: 77,04 MPa - Erkoloc-Pro: 31,53 MPa - Durasoft: 27,57 MPa Indentation modulus: NR Martens Hardness (MH): NR Relaxation/stress test: NR Elastic modulus (EM): NR Stress:

			terephthalate glycol-modified (PET-G - Erkoloc-Pro: Polyethylene terephthalate glycol-modified (PET-G)/ Thermoplastic polyurethane (TPU) - Durasoft: Polycarbonate (PC)/ Thermoplastic polyurethane (TPU)	- Durasoft: 1,1 mm Force: Preload: 1N Time: 24h Stress:	- F22 Aligner: Initial Stress: 23.7 MPa Final Stress: 10.7 MPa Relaxation: 13 MPa - Duran: Initial Stress: 20.1 MPa Final Stress: 7.6 MPPa Relaxation: 12.5 MPa - Erkoloc-Pro: Initial Stress: 5.5 MPa Final Stress: 4.1 MPa Relaxation: 1.4 MPa - Durasoft: Initial Stress: 20.1 MPa Final Stress: 7.6 MPa Relaxation: 12.5 MPa
Daniele V et al. (2020)	**In vitro study**	**Thermoplastic Disks Used for Commercial Orthodontic Aligners: Complete Physicochemical and Mechanical Characterization**	Thickness: 0,75mm, 1mm Brand: Erkodur, Essix Plastic, Ghost Aligner, Zendura Selected area: NR Size: 5 mm × 40 mm Type: - Erkodur: Polyethylene terephthalate glycol- modified (PET-G) - Essix Plastic: Polyethylene terephthalate (PET) -Ghost Aligner: Polyethylene terephthalate (PET) - Zendura: Thermoplastic Polyurethane (TPU)	Pressure: NR Temperature: 20 °C Indentation depth: NR Force: measured with a load cell of 5 kN Time: 24h Stress: NR	**Mechanical characteristics:** Tensile/Yield test: Indentation modulus: NR Martens Hardness (MH): NR Relaxation/stress test: NR Elastic modulus (EM): - Erkodur: 1933.03 MPa - Essix Plastic: 1742.03 MPa - Ghost Aligner: 2102.83 MPa - Zendura: 2489.43 MPa Stress: NR

4- Discussion

In order to analyze the mechanical properties of OAs, we first need to understand what they consist of, in this case being the thermoplastics disks. So, the optimal composition of the physical properties of the thermoplastic materials must be determined.

The current technological advancements allow us to use various materials in manufacturing thermoplastic disks. Each of these materials has different properties and constituents and is named accordingly.

All of the thermoplastic disks, included in the studies, fall into two major groups: the "Commodity plastics/ polymers" and "Engineering plastics/polymers". The former being plastics produced in high volumes for applications where exceptional material properties are not required. The latter plastics that have better mechanical and/or thermal properties than the more widely used commodity plastics.(5)

Commodity plastics/polymers	Engineering plastics/polymers
Polycarbonate (PC)	Copolyester (CP)
Polypropylene (PP)	Polyethylene terephthalate (PET)
	Polyethylene terephthalate glycol-modified (PET-G)
	Thermoplastic polyurethane resin (TPU)

Table 3- Polymers

4.1- Different types of Thermoplastic Disks Materials

The studies used in this review mention several possible materials:

- Copolyester (CP)(2,6–8)
- Polyethylene terephthalate (PET)(3,6)
- Polyethylene terephthalate glycol-modified (PET-G)(1,3,4,6,9–11)
- Polycarbonate (PC)(4)
- Polypropylene (PP)(9)
- Thermoplastic polyurethane resin (TPU)(1–4,7,8)

Out of these materials: copolyester (CP), polyethylene terephthalate (PET), polyethylene terephthalate glycol-modified (PET-G) and thermoplastic polyurethane (TPU) are indicated to have the best properties according to most studies and that surpass the other materials' shortcomings.

4.1.1- Copolyester (CP), Polyethylene terephthalate (PET) and Polyethylene terephthalate glycol-modified (PET-G)

Polyester , a category of commodity plastic. PET is an aromatic polyester.

Purified terephthalic acid or a combination of dimethyl ester dimethyl terephthalate and monoethylene glycol constitute PET. When modifications are made to polyesters, it turns into a copolyester. (5,12,13)

Copolyesters retain their strength, clarity, and other mechanical properties even when exposed to a spread of chemicals that typically affect other materials. This, plus their versatility and elasticity, allows manufacturers to use them effectively within the design of both high-volume, low-cost parts also as critical, costlier component parts.

PETG exchanges the glycol in the molecular chain, which blocks the molecules from banding together thereby lowering the melting point and inhibiting crystallization. This improves on its predecessor PET, which is vulnerable to crystallisation at high temperatures and becomes opaque and weakens the structure.(3,12)

4.1.2- Thermoplastic polyurethane resin (TPU)

Polyurethane (PU) is a molecule that consists of many urethane segments. A urethane is a molecular structure.(14)

By combining hard and soft materials, PU achieves both high elasticity and high toughness.

This natural strength of the urethane linkage, in conjunction with that branching flexibility, offers polyurethane the benefit over different generally used materials including PETG, PP and CP that are much less successful in attaining the simultaneous toughness and strength.(15)

For aligner applications, stress retention guarantees that the aligner constantly moves the teeth to its ideal position, under applied force without losing its exact shape.(5)

Even though it seems like the best out of all it has a limitation. It is very sensitive to moisture throughout processing, has a higher melting point and is tougher to reshape than other plastics, and calls for a high-priced base resin.(14,15) Thermoplastic polyurethane (TPU) is a class of polyurethane plastics, so it shares the same properties.

4.2- Mechanical Properties

When speaking of OAs' thermoplastic materials there are key properties to be had: relatively low hardness, good elasticity, resilience and resistance.

According to Fang D et al. (8), Elkholy F et al. (10) and Tamburrino F et al. (1) the properties that can influence the materials clinical performance are: elastic modulus (EM), tensile yield strength (TYS), stress relaxation (SR).

Elasticity is the ability that a material has of resisting to a deforming force, by returning to its original shape, when the force is removed. So, the elastic modulus quantifies that ability.(16)

Inoue S et al. (9), Tamburrino F et al. (1) say the aligners' ability to maintain their shape while accompanying tooth movement is the reflection of this property.

The tensile yield stress for a material is the value of stress at which the material begins to deform plastically, which means it can't return to its original form.(1) This means it can be associated with elasticity.

The loss of stress within thermoplastic materials evoked by initial deformation tends to cause the deterioration of mechanical properties with time as a result of them being viscoelastic. Such a phenomenon, referred to as "stress relaxation" (SR), leads to extra loss of the capability of a thermoplastic appliance to maneuver a tooth over time, that makes predicting orthodontic forces and tooth movement more difficult. (4,9)

In the oral cavity, treatment efficacy of OAs can be influenced by the aggressive environment that can lead to a high degradation of their properties.(1,3,10) Therefore, by determining the mechanical properties of commercially available thermoplastic materials, we can evaluate and qualify this influence.

Previous studies have shown that these properties: elastic modulus (EM), tensile yield stress (TYS), stress relaxation (SR), depend on factors (1,6,8,10), such as:

- The type of thermoplastic material
- The measuring technique
- The testing environment

Although since the mechanical properties of OAs the testing environment has to simulate the oral cavity.

The elastic modulus calculated from the tensile test found in Tamburrino F. et al.' (1) study is compatible with typical values of PET-G, 1.69 for one and 1.45 GPa for another. As for the TPU polymer in this study it showed a value of 1.73 GPa.

Daniele V. et al. (3) observe that PET-G and two different PETs and a PET-G have comparable values, curiously one PET has the lowest elastic modulus (1.74 GPa), the other has the highest of the three (2.10 GPa) .

As for TPU samples, the elastic modulus exhibits the highest average values (2.49 GPa).

Contrarily, Fang D. et al. (6) found very low EM for a TPU/CP mix (0,84 GPa), which may be because of the mixing of these two polymers, which doesn't necessarily mean better results.

Indentation modulus, quantifies the elastic response of a material subjected to the action of a concentrated load in a single point, thus providing information on its elasticity.

If it has a higher IM, it has better elastic response, so it would be logical to assume it would have a higher elastic modulus as well. Unfortunately, only studies about PET-G evaluated IM, achieving the values of 2600 MPa in Papadopoulou A. et al.' (7) study and 2466 MPa in Gerard Bradley T. et al study'. (2). Although it is surmisable that TPU would have similar results.

A decreased elastic modulus implies that the material tends towards a more brittle/plastic behaviour quicker. (2,7)

So, in terms of elasticity, among the most common materials, TPU generally has a better overall performance. Although a deterioration in its mechanical properties is documented in the intraorally aged appliances in the study by Gerard Bradley et al. (2) , is typical of the polyurethane softening mechanism.(14) The degradation of the mechanical properties can be also related to relaxation of residual stresses developed during the manufacturing procedure or leaching of plasticizers during intraoral exposure. (2,6)

With regard to tensile yield stress, in Tamburrino F. et al.' study PET-G was found to have a higher value than TPU, which means TPU deforms plasticly easier, (1) which means that it's less resistant to stress and deforms permanently, contradicting other studies. This is likely due to the testing method and sample size. (6,10)

Lombardo L. et al. found that with the greatest absolute initial stress value (23.7 MPa) was TPU, meaning it in order to suffer permanent deformation it has to be subjected to higher forces.

One of the PET-G/TPU mixes studied has initial stress of 20.1 MPa, which indicates that mixing the two best materials doesn't result in better performance, which is in accordance with Inoue S. et al and Fang D. et al. (8,9)

At the other end of the spectrum, another of these mixes exhibited the lowest stress values (5.5 MPa), and a PC/TPU mix had a value of 6.3 MPa. (4)

5- Limitations

This integrative systematic review has some limitations, such as:

- The number of selected articles may be small, resulting from the article selection process, since the articles were selected in the 2011 to 2021 timeframe. A longer reference period would include more studies, but our objective focused on relevant, updated information about the mechanical properties of currently used OAs.

- Language limitation, English and Portuguese, may have contributed to the loss of some potentially relevant articles. However, English is irrefutably the universal language and most of the articles found throughout the search were in this language. Thus, we considered this parameter to be the least problematic and conditioning.

- The search methodology and strategy itself, although comprehensive, may have excluded relevant articles, although we resorted to different databases, PubMed and Web of Science. This problem was minimized when searching the bibliographic references of the selected studies.

- In the included studies, although many properties were tested, few articles focused on the same properties and tests, so the results needed to be interpreted with caution. The materials that are evaluated should be submitted to a standardized series of tests, based on which properties are actually important. There also should exist more comparison between the same properties of each material in order to achieve more reliable results.

- The type of studies included are all in vitro studies, which may be a limitation as far as content goes, but the variables studied are very difficult to evaluate in vivo, since the test ends up destroying the samples.

Although the results of this systematic review do not address all the properties that can influence OAs clinical performance, this systematic integrative review brings together an important and comprehensive body of theoretical knowledge that help to better understand the explored topic.

To date, no systematic review has been published on this theme and although with some limitations, this represents an important step in attempting to synthesise useful information to assist clinical practice, contributing as a fundamental basis for clinical success.

6- Conclusion

The outcome the integrative systematic review Orthodontic aligners' mechanical properties and their influence on clinical applicability, led to the conclusion that:

- PET, PET-G and are cheaper in terms of production, which allows more cost-accessible treatment prices, TPU ends up having better mechanical properties because while both materials have high elasticity, TPU adds its inherent strength.

- The properties that can influence OAs clinical performance include elasticity, tensile yield stress and stress relaxation. When speaking of elasticity, between the more used: PET-G, PET, CP and TPU ,the latter has a better performance overall. TPU exhibits better stress relaxation properties as well and a higher yield point.

- Mixing different polymers doesn't always result in a union and subsequent upgrade in mechanical properties.

Having knowledge of the properties of the materials that constitute OAs and their reflection in terms of clinical effectiveness allows the orthodontist to select the best aligners to provide the best possible treatment

Therefore, it becomes essential that a greater number of studies be carried out about this topic, which would contribute to evolution and perfecting of these materials, ensuring more efficient orthodontic aligners and treatments.

7- References

1. Tamburrino F, D'Antò V, Bucci R, Alessandri-Bonetti G, Barone S, Razionale AV. Mechanical properties of thermoplastic polymers for aligner manufacturing: In vitro study. Dentistry Journal. 2020 Jun 1;8(2).

2. Gerard Bradley T, Teske L, Eliades G, Zinelis S, Eliades T. Do the mechanical and chemical properties of InvisalignTM appliances change after use? A retrieval analysis. European Journal of Orthodontics. 2016 Feb 1;38(1):27–31.

3. Daniele V, Macera L, Taglieri G, di Giambattista A, Spagnoli G, Massaria A, et al. Thermoplastic disks used for commercial orthodontic aligners: Complete physicochemical and mechanical characterization. Materials. 2020 May 1;13(10).

4. Lombardo L, Martines E, Mazzanti V, Arreghini A, Mollica F, Siciliani G. Stress relaxation properties of four orthodontic aligner materials: A 24-hour in vitro study. Angle Orthodontist. 2017 Jan 1;87(1):11–8.

5. Andrady AL, Neal MA. Applications and societal benefits of plastics. Philosophical Transactions of the Royal Society B: Biological Sciences. 2009 Jul 27;364(1526):1977–84.

6. Fang D, Zhang N, Chen H, Bai Y. Dynamic stress relaxation of orthodontic thermoplastic materials in a simulated oral environment. Dental Materials Journal. 2013;32(6):946–51.

7. Papadopoulou AK, Cantele A, Polychronis G, Zinelis S, Eliades T. Changes in roughness and mechanical properties of Invisalign® appliances after one- and two-weeks use. Materials. 2019 Aug 1;12(15).

8. Fang D, Li F, Zhang Y, Bai Y, Wu BM. Changes in mechanical properties, surface morphology, structure, and composition of Invisalign material in the oral environment. American Journal of Orthodontics and Dentofacial Orthopedics. 2020 Jun 1;157(6):745–53.

9. Inoue S, Yamaguchi S, Uyama H, Yamashiro T, Imazato S. Influence of constant strain on the elasticity of thermoplastic orthodontic materials. Dental Materials Journal. 2020;39(3):415–21.

10. Elkholy F, Schmidt S, Amirkhani M, Schmidt F, Lapatki BG. Mechanical Characterization of Thermoplastic Aligner Materials: Recommendations for Test Parameter Standardization. Journal of Healthcare Engineering. 2019;2019.

11. Cianci C, Pappalettera G, Renna G, Casavola C, Laurenziello M, Battista G, et al. Mechanical Behavior of PET-G Tooth Aligners Under Cyclic Loading. Frontiers in Materials. 2020 May 8;7.

12. Geyer R, Jambeck JR, Law KL. Production, use, and fate of all plastics ever made [Internet]. 2017. Available from: http://advances.sciencemag.org/

13. Bhattacharjee R, Biswas P. A Review of Plastics Processing From Raw Materials to Finished Products. Reference Module in Materials Science and Materials Engineering. 2020 Jan 1;

14. Samarth N, Kamble V, Rane A v., Abitha VK, Gohatre O, Kanny K. Mechanical and Dynamic Mechanical Properties of Polyurethane Blends and Interpenetrating Polymer Networks. Polyurethane Polymers: Blends and Interpenetrating Polymer Networks. 2017 Jan 1;377–97.

15. Giles HF, Wagner JR, Mount EM. Processing Recommendations for Various Resin Systems. Extrusion. 2005 Jan 1;207–19.

16. Campo EA. Mechanical Properties of Polymeric Materials. Selection of Polymeric Materials. 2008 Jan 1;41–101.