



GRADUATION PROJECT

Degree in Dentistry

EFFECTIVENESS AND PREDICTABILITY OF ORTHODONTIC TREATMENT WITH INVISALIGN ALIGNERS

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RESUMEN

Introducción: La ortodoncia ha evolucionado significativamente con la Terapia de Alineadores Transparentes, ofreciendo una alternativa a los aparatos fijos tradicionales. Inicialmente utilizada para maloclusiones leves a moderadas, los alineadores han evolucionado para abordar casos más complejos, gracias a la planificación digital del tratamiento y al uso de accesorios y otros auxiliares, mejorando el control de las fuerzas aplicadas. A pesar de su creciente popularidad por su transparencia y comodidad, su eficacia comparada con los brackets convencionales sigue generando debate. Comprender sus capacidades y limitaciones es fundamental en la ortodoncia moderna; **Objetivos:** Evaluar la eficacia y predictibilidad de la Terapia con Alineadores Transparentes en pacientes adultos con tratamiento ortodóntico. También se analizó la efectividad de la rotación de incisivos y los desafíos asociados para obtener resultados óptimos; **Metodología:** Se realizó un análisis sistemático usando una pregunta de investigación en Medline, Dentistry and Oral Science Source y PubMed con texto completo. Se analizaron artículos publicados entre 2014 y 2024 según criterios de inclusión y exclusión; **Resultados:** Inicialmente, 324 artículos cumplían con los criterios establecidos. Tras varias rondas de selección, se evaluaron 8 artículos sobre las limitaciones de los tratamientos con alineadores transparentes, centrándose en la rotación de los incisivos; **Conclusiones:** Los alineadores transparentes son efectivos para muchas maloclusiones; pero rotaciones de los incisivos predecibles sigue siendo un reto. Las rotaciones severas requieren refinamientos, accesorios y auxiliares para mejorar precisión. Aunque la planificación digital ha mejorado los resultados, ciertos factores siguen afectando la efectividad, requiriendo una evaluación cuidadosa de los ortodoncistas.

PALABRAS CLAVE

Odontología, alineadores transparentes, rotaciones, incisivos, movimiento dental.

ABSTRACT

Introduction: Orthodontics has significantly evolved with Clear Aligner Therapy, offering an alternative to traditional fixed appliances. Initially used for mild to moderate malocclusions, aligners have evolved to address more complex cases through digital treatment planning and the use of attachment and auxiliaries, improving control of the applied forces. Despite their growing popularity due to transparency and comfort, their effectiveness compared to conventional braces remains a topic of debate. Understanding their capabilities and limitations is essential in modern orthodontics; **Objectives:** To assess the effectiveness and predictability of Clear Aligner Therapy in adult patients undergoing orthodontic treatment. Additionally, to analyze the effectiveness of incisor rotations and the challenges associated with achieving optimal results; **Methods:** A systematic review was conducted using a research question across Medline, Dentistry and Oral Science Source and PubMed in full text. Articles published between 2014 and 2024 were analyzed based on inclusion and exclusion criteria; **Results:** Initially, 324 articles met the established criteria. After multiple screening phases, 8 articles investigating the limitations of orthodontic treatments using Clear Aligner Therapy were evaluated, focusing on incisor rotation; **Conclusions:** Clear aligners are effective for many malocclusions. However, achieving predictable incisor rotation remains challenging. Severe rotations often require refinements, attachments and auxiliaries to enhance precision. While digital planning has improved outcomes, certain factors still impact effectiveness, requiring careful assessment by orthodontists.

KEYWORDS

Dentistry, clear aligner, rotations, incisors, tooth movement.

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1 INTRODUCTION

1.1 General introduction to orthodontic treatment

The field of Dentistry is a broad area covering various specialties, ranging from surgical, aesthetic, or functional (1). Orthodontics is one of them, and deals with the prevention, diagnosis, and treatment of malocclusion, which refers to dental misalignments and the improper relationships between the maxilla and the mandible (1). Untreated malocclusion can impair individuals from performing daily activities, such as chewing while consuming food, and on the other hand, can affect the physical appearance of a person, which may further lead to a lack of self-confidence (1,2).

1.2 History of aligners

In 1946, the orthodontist Dr. Harold D. Kesling pioneered the original concepts for Clear Aligner Therapy. Indeed, he created the "Tooth positioning appliance", a removable clear device used to make slight adjustments to teeth after braces were removed (3–6).

1.2.1 The emergence of clear aligners

Clear aligner appliances were first introduced in the 20th century by physician dentists (3). They began with a series of custom-made plastic aligners, each varying slightly from the previous one (7). They realized that when each aligner is worn by a patient for a period of more or less 2 weeks and is then replaced by the next one scheduled in the treatment sequence, it causes a series of tooth movements, and therefore the realignment of the teeth (7). The first system created was the Invisalign® system, introduced to the market by the company Align technology in 1999, in California (7). This system was approved in 2000 by the U.S. Food and Drug Administration (FDA), which made it gain a lot of popularity around the world (7).

1.2.2 Clear aligner brands

The notoriety of clear aligners has been growing since its creation, especially thanks to their transparency and comfort; which makes them attractive to a large part of the population who, above all, seek aesthetics (5,6,8). Since then, new companies have decided to market their own aligner system (7).

Nowadays, many different brands have launched their own aligners. In that regard, we can name Invisalign® that comes from an American company known as Align Technology (9). This brand

works with a specific software, the “ClinCheck”, and the aligners are made from a flexible material named “SmartTrack” (6,8,9). We may also find the Spark™ system which also comes from an American company named Ormco (9). Finally, we have the Angel Aligner® system which is as old as Invisalign®. This one comes from a Chinese company, the Angelalign Technology, and is gaining market share mostly in Asia due to its competitive costs (2,8,10).

Although they may appear very similar, the different types of Clear Aligner Therapy (CAT) may differ in terms of thickness of the aligners, application time, use of composite buttons or attachments, their treatment sequence, their mode of fabrication, and their prices (11).

1.3 Introduction to aligners

An aligner is a computer modeled, clear, removable tray made of thermoplastic materials through thermoforming process (1,2,8). They are nowadays designed with Computer-Aided Design – Computer-Aided Manufacturing (CAD-CAM) technology to move the teeth individually (1,2,8). It enables tooth movement by applying small and gradual forces (1,2,8). Clear Aligner Therapy was first introduced to treat small dental misalignment, but their use continues to grow due to the notoriety they are gaining over the years, and the technological advances that allow the treatment of more complex cases (12).

1.3.1 Advantages of Clear Aligner Therapy

What makes this system modern, apart from the fact that it is aesthetically pleasing due to its transparency, is that nowadays it may use computer technology to create the aligners (7). The orthodontist will start by using a digital scan of the patient's mouth to generate a digital model of the patient's upper and lower arches, as well as its occlusion. Using those models, the system itself will create the series of aligners needed to achieve the desired results (7).

Clear aligners present other advantages, such as the decrease of the number and duration of dental visits as opposed to traditional braces which require more adjustments, the oral hygiene facilitation since the patient removes his appliance to eat, brush his teeth and floss, and provoke less pain compared to fixed orthodontic appliances (8,13). Those appliances also show less cases of periodontal problems and white spot lesions development when compared to those that may be presented during an orthodontic treatment with braces (8,13).

1.3.2 The decision-making tool

Although Clear Aligner Therapy (CAT) obviously requires the treatment tool, the aligners, it also requires a decision-making tool. For example, the Invisalign® technology uses the ClinCheck, a software able to plan the treatment sequence in details (14). It is a tridimensional representation of the prescription provided by the clinician, enabling the clinician to visualize each stage of the treatment through 3D simulation of dental movements, until reaching the final outcome (14,15). In other words, this software can be considered as the communication tool between the clinician and the technician (15). The clinician can modify it as many times as desired, so that the treatment plan matches his treatment goals (14).

1.4 Materials and methods used in aligners fabrication

1.4.1 Manual fabrication

Two modes of fabrication of the clear aligners exist. The first one consists of taking a full arch impression of the patient teeth with polyvinyl siloxane in order to obtain the working cast (2,13). The next step will be to determine the teeth that need to be moved (13). Those teeth will be cut out of the working cast and will be fixed to the final position using a block-out wax (13). Interproximal reduction might be done if needed on the model at this stage in order to create space in between the teeth for them to move to the desired position (13). Then, by the mean of a thermoforming process over those working casts, the plastic aligner will be created and finally, trimmed (2,13). For this process, flexible thermoplastic materials are used, like polyvinyl chloride, polyurethane polyethylene terephthalate, polyethylene terephthalate glycol, or ethylene vinyl acetate (2,7).

A disadvantage that this process may present is the fact that one impression is only able to make a set of two to three aligners, and therefore, new impressions and working casts will have to be fabricated every one to two months (13).

1.4.2 CAD-CAM fabrication

CAD-CAM technology has transformed orthodontics by enabling the production of more precise and effective aligners (9). A digital representation of both arches of the patient are obtained by the mean of an intraoral scanner (9). Then, the CAD platforms will allow to treat the teeth one by one in order to obtain the desired final position of each one (9). At each step, the software creates a virtual model showing the position of the teeth (9). After that, the virtual models are transformed into physical models thanks to the CAM technology by a milling process or 3D printing (9). On each printed models, the aligners are thermoformed, trimmed and finally polished (9).

1.4.3 Disadvantages of the thermoforming process

The fabrication of clear aligners by a thermoforming process may present some disadvantages; that is why the manufacturing of aligners by direct 3D printing is gaining popularity (9). Some drawbacks that this process presents include the fact that the fabrication may be long and expensive (2). In addition, it may present waste of material, and therefore environmental pollution, which has become a significant challenge for orthodontists (2). Other problems that orthodontists may face are notable alterations in material properties caused by heat generated during processing over the models (2). In fact, thermoforming procedure may decrease the transparency of thick materials, can modify the hardness of some of them, and can decrease the thickness of the aligners (2).

1.4.4 Direct 3D printed aligners from digital models

Although this process is still developing, it is a concept that could revolutionize the market (9). Indeed, this technology presents various advantages (9). First of all, direct 3D printing of aligners will allow the reduction of cumulative errors as fewer steps are involved in the fabrication process (9). Secondly, the cost may be reduced because of the shortened supply chain (9). Another point would be the sustainability of the process because it allows to reduce the amount of waste material, when compared to the thermoforming process (2,9). The last point would be the customization of the thickness of the aligner at different areas across the dental arch (9). Indeed, thickness is important as it influences the force applied to the teeth and the mechanical properties of the aligners like flexibility and strength (9,13).

1.5 Biomechanics of aligners: How do aligners move teeth?

When it comes to tooth movement, there are some essential principles to consider (7). First, the aligner must apply controlled and constant forces to the teeth in order to be effective (7). The aligner is specifically designed to exert a precise force at the right place to move the tooth effectively and progressively towards its ideal position (7).

We can explain the mechanics of the tooth movements with clear aligners by defining two concepts: The displacement driven system and the force driven system (13).

1.5.1 The displacement driven system

Basic movements, including minor rotations and tipping, are controlled by the displacement driven system (13). It consists of moving the tooth gradually to fit the aligner (13). However, it will not be useful in case of bigger tooth movements and root movements within the bone (13).

1.5.2 The force driven system

The force driven system relies on biomechanical principles to guide the tooth movement in the intended direction (13). Specific forces are applied to the teeth in order to move it (13). In that purpose, the shape of the aligner may not exactly match the shape of the tooth in order to generate the right force (13).

1.6 Attachment devices

To enhance those tooth movements by the exertion of the desired forces on the teeth, and to retain the aligner, attachment devices may be used, which are composite attachments bonded to the buccal or lingual/ palatal surface of some specific teeth (6,7,10). Those devices allow to perform more complex tooth movement in order to treat more complex cases (13). It is the software that will first decide which type of attachment will be used and on which tooth, but the dentist can always change it if he finds it not appropriate (16). We distinguish two categories of attachment depending on their role, the first one is named Conventional Attachment, and the second one, Optimized attachment (16).

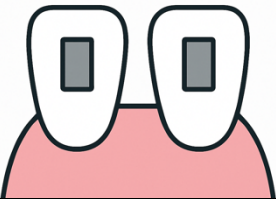
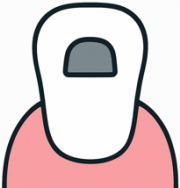
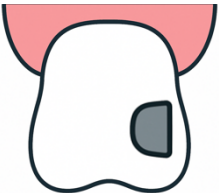
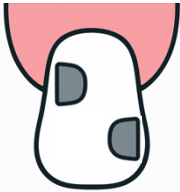
1.6.1 Conventional attachments

Conventional Attachments have retention of the aligner over the teeth as primary function (16). Those attachments are typically either rectangular gingivally beveled or rectangular occlusally beveled (16). The occlusally beveled attachments also play a role in the extrusion of upper molars, as more force is required to be directed in the occlusal direction (16).

1.6.2 Optimized attachment

Optimized attachments are specifically designed to move teeth more precisely by exerting specific and targeted forces as well as taking into account the tooth morphology (16). An important feature that this type of attachment presents is that the non-active surface (the side of the attachment not in contact neither with the aligner, nor with the tooth) is relieved to

avoid interference with the aligner's movement and allows it to function smoothly, without any friction (16).

Attachment	Type of movement	Teeth
Rectangular vertical conventional attachment with a thickness of 1 mm. 	To close the space after an extraction of a lower incisors.	Teeth localized next to the extracted tooth.
Deep bite attachment. 	Used for retention. Used for the extrusion of premolar when they are activated.	Upper and lower premolars.
Anchorage optimized attachment. 	For retention of posterior teeth.	Upper and lower second premolars. Upper and lower molars.
Extrusion optimized attachment. 	For movements of tooth extrusion.	Upper and lower incisors. Upper and lower canines. Less common on posterior teeth which usually erupt fully
Tipping or root control optimized attachment. 	For tipping movement.	Upper central incisors. Upper lateral incisors. Upper and lower canines. Upper and lower premolars.
Rotation optimized attachment. 	For movements of rotation.	Upper and lower canines. Upper and lower posterior teeth.

Retraction attachment. 	optimized	For the retraction of canines.	Upper and lower canines.
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*The illustrations represent the different attachments available for clear aligners, and were created by the author of this thesis

Table 1. Types of attachments and their movements (16).

1.7 Auxiliary elements

In some cases, additional elements, known as auxiliary elements, may be needed to improve the performance of the aligners, and consequently to optimize patient outcomes (17). These elements may have different objectives, such as apply targeted forces to the teeth, improve the aligner retention, facilitate tooth movements, and assist in more complex tooth movements (17).

1.7.1 Buttons

Buttons are small attachments bonded to teeth, used in combination with elastic bands, distinguishing them from the attachments (17). Their function is to help apply additional force to guide tooth movement more effectively (17). They are particularly effective in correcting bite discrepancies and assisting in complex tooth movements (17).

1.7.2 Elastics

Elastics are auxiliary elements used in combination with buttons (17). By applying a controlled force, elastics enhance the movement of teeth in the desired direction, helping to improve occlusal relationship (17).

1.7.3 Power ridges

Power ridges are small elevated section on aligners that exert additional force on specific teeth, facilitating more precise movement and making the treatment more efficient (17).

1.7.4 Interproximal reduction (IPR)

Interproximal reduction involves narrowing the width of certain teeth by removing small amount of enamel in order to create space for proper teeth alignment (17). This procedure is

performed using interproximal strips or other specific tools (17).

1.7.5 Bite ramps

Bite ramps are raised areas added to biting surfaces of the teeth, typically on the molars (17). They are used to adjust patients' bite and help correct deep bites (17). They gradually raise the lower front teeth, leading to improve occlusal relationships (17).

1.8 Aligners: Treatment effectiveness and limitations

A challenge that aligners might face is that they may not be suitable for all types of orthodontic treatment, depending on the complexity of the case (18). Indeed, their effectiveness might be doubtful in more severe situations such as significant bite problems, wide gaps, or severe crowding, which might necessitate orthodontic treatment with traditional braces (18).

However, clear aligners therapy is a good option in patients concerned about their physical appearance, presenting mild to moderate forms of malocclusion, including problems with crowding or spacing (ranging from 1 mm to 5 mm), overbite, crossbite, rotational malposition, tip molar distally, absolute intrusion of one or two teeth, and narrow dental arches that require expansion without the need of tipping too much the teeth (7,8,11).

Recent studies have shown that clear aligner therapy has a success rate of 80-90% for mild to moderate tooth movements, however this will depend on each case and the difficulties that they may present individually (7). Some studies show that the material used for fixed appliances assures better results in terms of precision and treatment predictability (7).

1.8.1 Importance of patient compliance in successful Aligner Therapy

A fundamental aspect that the patient must have when starting a treatment with aligners is cooperation (7). Indeed, treatment with this type of appliance requires a great deal of discipline, diligence, and oral hygiene (7). Actually, wearing an aligner for less than 22 hours a day will prevent the treatment from progressing as scheduled (7,8,11). This could extend the treatment duration beyond the initial estimate, which will subsequently increase the cost, and which may even affect the final result and lead to treatment failure (8,11). Moreover, the aligner will have to be changed every two weeks more or less, following the instructions of the dentist (7,8,11). In the event that an aligner breaks, the patient will have to wear the previous one used until the new one is delivered, which may take usually about two weeks (12).

Regarding hygiene, a lack of care can lead to an increase in tooth decays, gingivitis, or even bad breath problems (1,2).

1.9 Types of movements achievable with aligners

Clear Aligner Therapy may include a variety of movement in order to achieve our desired result (7).

Movements of tipping or minor rotations are known to be easier to control compared to those requiring root angulation changes, extrusion and bigger rotations, which will require auxiliary elements such as buttons or elastics (13).

For instance, corrections of crowding consist of movements to separate teeth too close together (7). On the contrary, spacing corrections intend to close the gaps between teeth (7).

Other types of movements exist, including rotational adjustments, where teeth are rotated along their long axis to properly align with the adjacent teeth (7). Extrusion are performed to adjust the height of teeth, enhancing both their appearance and bite (7). Transversal corrections involve shifting teeth from side to side to improve the bite and overall aesthetic (7). With the use of aligners, those movements are performed gradually by applying gentle pressure to the teeth (7).

Few studies exist regarding the predictability of orthodontic tooth movement using Clear Aligner therapy (CAT) as an evidence-based practice (12). There is relatively predictability in controlling the intrusion of anterior teeth and posterior buccolingual inclination (12). Nevertheless, the extrusion of the anterior teeth, the rotational adjustments of rounded teeth, and the changes in buccolingual inclination of the anterior teeth are movements, which when treated with aligners, are much more challenging (12).

1.10 Justification

Treatments with Clear Aligners are becoming very popular for orthodontic treatment nowadays (7). Indeed, those types of treatment, which provide a discreet and convenient option compared to traditional braces, are now widely available for both children and adults, allowing for the correction of a wide range of dental malocclusions (7). These aligners are able to provoke various tooth movements, including rotations, with a level of precision that has contributed to their expansion worldwide (7,13). However, the efficiency of aligners in performing those movements has been a topic of ongoing investigation, as it is crucial to assess their ability to

achieve desired results within a predictable time frame (6). Indeed, while aligners can be highly effective in performing certain tooth movements, their efficiency may vary depending on different factors such as the type and complexity of the movement (7). As the technology is constantly evolving, orthodontists using Clear Aligner Therapy must stay up-to-date with the technological developments to ensure the most effective and predictable outcomes for their patients (7).

2 OBJECTIVE

1. To assess the effectiveness and predictability of Clear Aligner Therapy in adult patients requiring orthodontic treatment.
2. To assess the effectiveness of incisor rotations generated by Clear Aligners, as well as the challenges that they may present in achieving optimal results.

3 MATERIAL AND METHODS

In this literature review, articles available in the CRAI library dated between 2014 and 2024 have been reviewed and evaluated if they have been considered as pertinent for the subject.

The databases used were Dentistry & Oral Science Source, MEDLINE and PubMed, considering only fully accessible articles.

To complete the research, search terms and keywords were used, such as: aligners, clear aligner therapy, orthodontic treatment, orthodontic technology, tooth movements, rotations, incisors rotation.

The results were chosen according to the criteria for inclusion and exclusion outlined in Table 2.

The research formulas applied in the databases were “aligner” OR “clear aligner therapy” AND “rotation”; “incisors” AND “tooth movements”.

The PICO research question (Participants, Intervention, Comparison, and Outcomes) developed to meet the objective is as follows: What is the effectiveness and predictability for obtaining the desired final result (O) in adult patients (P) undergoing orthodontic treatments with clear aligners (I) for rotational movements of incisors? (C)

By defining these components, a focused selection and analysis of relevant literature and articles can be carried out, promoting a greater comprehension of the topic.

Inclusion criteria	Exclusion criteria
Scientific articles dated from 2014 to 2024	Scientific articles dated before 2014
Fully available articles	Restricted Access articles
Data extracted from reliable databases	Data extracted from any other unreliable databases
Long longitudinal studies that have evaluated a large sample of patients	Studies that only focus on one single case
Patients aged over 19 years old	Patients aged under 19 years old
Orthodontic treatment with clear aligners including rotational movements of incisors	Orthodontic treatment with clear aligners including movements other than rotation, for teeth other than incisors

Table 2. Inclusion and exclusion criteria

4 RESULTS

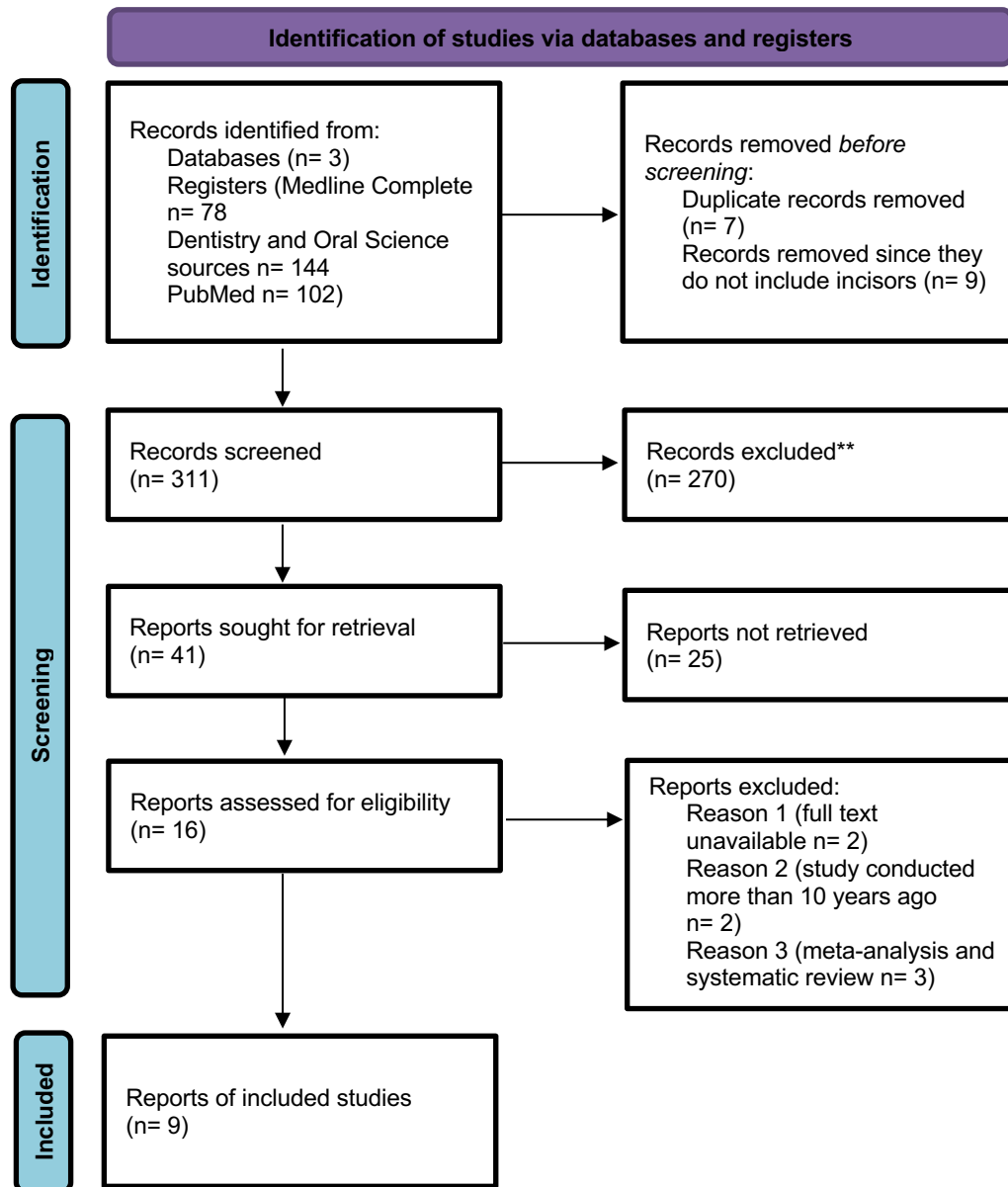


Figure 1. PRISMA Flowchart of the included reports in the study (19)

A thorough analysis of scientific papers was conducted using three different databases with specific keywords, yielding 324 records. A PRISMA diagram (Figure 1) illustrates the selection process. After eliminating seven duplicates and nine other records since they do not include incisors, 308 records remained, of which 283 were eliminated, resulting in 41 reports sought for retrieval. Among them, 9 were unavailable in full text, and three were excluded as they were conducted more than 10 years ago. Ultimately, four studies met the inclusion criteria (Table 2), and therefore were considered in this review.

Title	Author and year	Type of study	Outcomes	Summary
Accuracy of clear aligners in the orthodontic rotational movement using different attachment configurations (19).	Fiorillo, <i>et al.</i> 2024	Retrospective study	Rotated teeth are more present in female (n=156, 73.58%) and in the lower arch (60.85%). It affects predominantly lower canines (18.87%), followed by lateral incisors (17.45%). Optimized attachments have the highest median accuracy for rotational movements (70 [49, 81]), followed by rectangular attachments (65 [41, 82]). The lowest accuracy for those movements was observed without attachments (63 [39, 81]), but these differences were not statistically significant (p=0.5).	Examination of the accuracy of rotational movements with Invisalign, focusing on gender, tooth type, and attachment types. Accuracy of rotational movements varied slightly by attachment type but was not statistically significant. Age was the only significant predictor, with a small decrease in accuracy as age increased.

Comparison of labio-palatal incisor movement between two wear protocols: a retrospective cohort study (20).	Wei, <i>et al.</i> 2024	Retrospective cohort study	Palatal movements did not reveal significant variations ($p=0.001$), however labial movements showed statistically significant discrepancies ($p<0.001$). Root movement varied, with higher conformity in uncontrolled tipping cases (67-77%) compared to torque cases (33-67%). No significant differences were found between 1 weakly wear and 2 weakly wear protocols for overall accuracy.	Evaluation of the accuracy of predicted versus achieved tooth movements based on wear protocols (1 or 2 weakly wear), and movement direction. No significant differences were found for palatal movements, but labial movements showed statistically significant discrepancies and therefore are less accurate.
Accuracy evaluation of orthodontic movements with aligners: a prospective observational study (21).	Bilello, <i>et al.</i> 2022	Prospective observational study	Rotation accuracy averaged 86%, with the highest accuracy for maxillary central incisors (96%) and the lowest for mandibular first premolars (70.4%). Almost half of the examined teeth showed over 90% accuracy, while the rest ranged between 80-90%. Intrusion predictability was analyzed only for anterior teeth, with an overall accuracy	The study assessed the accuracy of orthodontic movements using clear aligners, focusing on rotation, intrusion and vestibulolingual tipping. It found out that vestibulolingual tipping was the most predictable movement (93.1%), while rotations of canines, premolars, and lateral incisors were the least

				of 92%. Vestibulolingual tipping was the most accurate movement (93.1%), with maxillary central incisors showing the lowest accuracy (80.7%) and mandibular central incisors the highest (97.5%).	predictable (70.4%). Intrusion was highly predictable up to 2 mm (92% accuracy). The authors included that, with careful treatment planning and the use of auxiliary features, clear aligners can achieve clinically successful results, but larger samples are needed to assess predictability in more complex cases.
Movement of anterior teeth using clear aligners: a three-dimensional, retrospective evaluation (22).	Tepedino, <i>et al.</i> 2018	Retrospective study	The standard error for predicted torque movements for incisors and canines ranged from 1.2° to 1.3°, confirming measurement reliability. Mean predicted torque movement varied between 1.7° and 3.2°, depending on the tooth and the arch. No statistically significant differences were found between predicted and achieved torque values, meaning that the planned movements were generally achieved	The study assessed the accuracy of predicted torque movements for incisors and canines. Results showed no statistically significant difference between predicted and achieved torque movements, confirming the system's reliability. The findings suggest that small torque movements can be predictably achieved especially when treatment progresses in 12-aligners steps with periodic reassessment.	

Predictability of orthodontic movement with orthodontic aligners: A retrospective study (5).	Lombardo, <i>et al.</i> 2017	Retrospective study	F22 aligners achieved an average movement predictability of 73.6%, with mesiodistal tipping being the most accurate (82.5%) and rotation the least (66.8%). Rotational movement of lower canines was the least (54.2%), while the highest accuracy was shown for mesiodistal tipping of upper molars (93.4%) and lower premolars (96.7%). To conclude, orthodontic aligners alones cannot achieve 100% accuracy, especially for rotations, without the use of auxiliaries.	The study has evaluated the tooth movements predictability using F22 aligners, without the use of any auxiliaries. Each type of tooth was analyzed separately, and three types of movements were taken into consideration (mesiodistal tip, vestibulolingual tip and rotation).
Predictability of orthodontic tooth movement with aligners: effect of treatment design (23).	Castroflorio, <i>et al.</i> 2023	Prospective study	The lack of correlation was significant for all movements and tooth groups ($P<0.01$), except for rotation of maxillary first molars ($P=0.3613$). results showed that angular movements and rotations, especially for round-shaped teeth like upper	The study assessed the accuracy of Invisalign aligners in achieving planned orthodontic tooth movements, with angular movements and rotations being the least predictable, especially for upper canines

			canines and lower premolars, had the highest discrepancies, with an average loss of 0.4° per 1° prescribed. Second molars showed minimal movement expression, and extending the aligner change interval from 7 to 14 days improved correction accuracy by 12%.	and lower premolars. The findings highlight the need for better attachment designs and overcorrection strategies in treatment planning.
Integrated three-dimensional digital assessment of accuracy of anterior tooth movement using clear aligners (24).	Zhang, <i>et al.</i> 2015	Retrospective study	The findings revealed that while the mean discrepancies for crown positions were relatively small, around 0.376 mm in the maxilla and 0.398 mm in the mandible, root positions exhibited larger differences, averaging 2.062 mm in the upper jaw and 1.941 mm in the lower jaw. These findings indicate that clear aligners mainly facilitate tooth movement through titling, effectively repositioning crowns but not roots as intended.	In this study, CBCT scans were conducted before and after treatment with clear aligners in 32 patients. The study sought to evaluate the precision of anterior tooth movement by comparing predicted and achieved positions of tooth crowns and roots using integrated three-dimensional digital models.
Effectiveness of Clear Aligner Therapy in Rotational	Alaçam, <i>et al.</i> 2024	Retrospective study	Results showed that lower central incisors had the highest	This study assessed the effectiveness of clear aligners in

Tooth Movement (25).			accuracy (80%), followed by lower laterals incisors (74.29%), upper central incisors and lower second premolars (71.43%), while lower canines were the least accurate (28%), indicating difficulty in rotating round-shaped teeth.	correcting rotational tooth movements by comparing planned and actual outcomes. Researchers examined 3D models to measure discrepancies between predicted and achieved rotations. The study highlights the need for careful planning and potential overcorrections to improve accuracy with aligners.
Invisalign® vs. Spark Template: Which Is the Most Effective Attachment Bonding Procedure? A Randomized Controlled Trial (26).	Bruno, <i>et al.</i> 2021	Randomized Controlled Trial	87.5% of Spark™ patients experienced no bonding failure, compared to patients treated with Invisalign® who showed 27.5%. Thus, the difference in bonding success was statistically significant ($p < 0.001$), suggesting Spark™ templates are more effective in transferring attachments to the tooth surface.	The study showed that Spark™ templates were significantly more effective than Invisalign® for attachment bonding. A much higher percentage of attachments remained in place with Spark™, indicating greater accuracy and reliability in the bonding procedure.

Table 3. Summary of the 9 included studies assessing the effectiveness and predictability of rotational movements of incisors with clear aligners

5 DISCUSSION

Clear aligner therapy has become a widely used and advanced approach in orthodontics, particularly for the treatment of malocclusions and aesthetic concerns (7,13). However, the predictability and accuracy of rotational movements, especially for incisors, remain a critical challenge (5,21,25). The studies reviewed provide valuable insights into the success, limitations, and factors influencing rotational movements of incisors with clear aligners.

5.1 Rotational movements of incisors

Fiorillo *et al.* focused on the precision of rotational movements with clear aligners using various attachment configurations, finding a mean accuracy of 68.62% (19).

The investigations by Lombardo *et al.*, Alaçam *et al.* and Bilello *et al.* all emphasize the difficulty in achieving accurate rotational movements of incisors with clear aligner therapy (5,21,25). Aligners are more effective for basic movements like tipping or translation, but struggle with the precise force application required to rotate teeth around their long axis (5,21,25).

Alaçam *et al.* further observed better outcomes for mild to moderate rotations or when the space available for the tooth to move is sufficient (25). However, for severe rotations, the predictability decreased, and additional refinements or auxiliaries were often needed (25). Similarly, Bilello *et al.* found that accuracy dropped as rotational complexity increased, particularly with larger misalignments (21).

5.2 Factors affecting predictability

Several factors have been identified across the studies as critical in determining the effectiveness of rotational movements of incisors with aligners.

5.2.1 Initial tooth position and angulation

The initial alignment of incisors strongly influences the success of rotational movements with clear aligners (5,24,27). Moderately aligned teeth respond better, while severely rotated teeth show less predictable outcomes and often require more refinements (5,27). Tepedino *et al.* confirmed that minor rotations are more predictable than those requiring substantial movements (22).

Proper planning must integrate this factor (27). Zhang *et al.* used 3D digital models to accurately assess force distribution, improving the quality of treatment planning (24).

5.2.2 Treatment design and force application

Castroflorio *et al.* and Bilello *et al.*, reported movement accuracy tooth by tooth, stressing the importance of individualized planning (21,27). Zhang *et al.* showed that 3D digital simulations help optimize force direction and amount, especially for rotations (24).

Aligners work in sequences, incrementally moving teeth (5). However, rotational control is more complex and often less effective than with braces (5,27). Lombardo *et al.* linked the variability in rotational success to insufficient force generation (5). The applied forces must be directed accurately around the tooth's long axis to achieve rotation (27). Castroflorio *et al.* confirmed that rotational movements of incisors are often less predictable compared to other types of movements (27).

5.2.3 Attachments and auxiliaries

The use of attachments and auxiliaries improves predictability and efficiency for complex rotations by providing additional points of contact and thus more control over specific areas of the tooth (19,25,27). Attachments must be chosen with their appropriate position and shape, according to the case (22).

In the study by Fiorillo *et al.*, no significant differences were observed among the various attachment types and no attachment (19). However, although rectangular attachment tend to perform better for people over 30, the optimized ones were found to be more effective under 30 years old (19).

5.2.4 Tooth size and shape

Tooth size and shape are parameters that also influence rotational movements outcomes (5,27). Larger or anatomically complex teeth complicate aligner fitting and movement (5). Rounded teeth, such as canines and premolars, also present greater challenges in achieving rotational movements with clear aligners, reducing the predictability for these movements (18,20).

In the prospective observational study by Bilello *et al.*, the upper central incisors showed the highest mean accuracy percentage for rotational movements, at 96.1%, followed closely by lower central incisors at 94.4% (21). This accuracy may be attributed to their straightforward root morphology and position, which are amenable to the controlled forces exerted by clear

aligners (21).

These findings confirm that anterior teeth rotate more easily with aligners, however further research and technological advancements are necessary to improve the predictability and efficiency of treatments with clear aligner across all tooth types (21).

5.2.5 Alveolar and root considerations

Zhang *et al.* highlighted that root position and alveolar bone structure also impacts rotations (24). Clear aligners primarily act on the crown of the tooth, but for accurate rotational movements, forces need to be applied to both the crown and the root (24). When root or bone anatomy is not favorable, predictability decreases (24).

5.2.6 Treatment time and refinement

Longer treatment duration and additional aligners may be necessary for refining rotational movements (5). Lombardo *et al.* and Castroflorio *et al.* showed that additional refinements were often required after initial alignment (5). This finding aligns with the general orthodontic principle that clear aligners may require more time and multiple adjustments compared to traditional methods like braces (5).

Castroflorio *et al.* also reported that treatment design, particularly the number of aligners, and the specific movements programmed in each stage, has a significant impact on the predictability of rotational movements (27). Poor staging leads to unpredictable or inefficient results, particularly for incisors with more challenging rotations (27).

5.2.7 Personal characteristics

Gender and age do not significantly influence rotational accuracy, though women may present more rotated teeth than men (19).

Bilello *et al.*, emphasized analyzing each tooth individually, given its distinct root and crown morphologies, as well as the specific histology of the supporting alveolar bone (21). This was also reported in the study by Tepedino *et al.*, who insisted that patient characteristics and clinician performance are important indicators in the success of an orthodontic treatment (22). In their study, Wei *et al.* noted that the buccal bone offers less resistance than the palatal bone, leading to greater accuracy in labial root movement (palatal crown movement) (20).

They also found lower accuracy (55 - 58%) for labial angulation of upper incisors, while palatal were more accurate (20).

5.3 Challenges in severe rotations

Both Lombardo *et al.* and Alaçam *et al.* showed that severe rotations are harder to manage, often requiring more aligners or adjustments (5,25). Wei *et al.* confirmed that greater rotations need extended protocols (20).

In these challenging cases, the use of refinements, where new aligners are fabricated to adjust for the progress of treatment, is often required (5,25). However, the outcome can still be unpredictable for large rotations, and the treatment duration may need to be extended (5,25).

5.4 Digital planning and 3D assessment

Advances in digital orthodontics have significantly improved the predictability of aligner therapy (22,24). The studies by Zhang *et al.* and Tepedino *et al.* demonstrated that 3D digital models provide better planning tools for simulations and predictions of tooth movements (22,24). Despite these advances, some inaccuracies remain, especially for rotations (22,24).

5.5 Brands

Tepedino *et al.* pointed out in their retrospective study that most of the studies only focus on one brand of aligner, limiting generalization (22). Different systems or brands yield different characteristics, and therefore, different results can be achieved (22). In short, the predictability of tooth movement will depend also on the clear aligner system used, which is why the relevance of studies only analyzing one specific system or brand of aligners should be questioned (22).

Bruno *et al.* suggested that the Spark™ template had fewer debonding issues than Invisalign® template, due to more flexible material (26). This highlights the importance of template design and flexibility for clinical success (26).

Tepedino *et al.* studied the Nuvola® aligner system, finding no difference between predicted and actual torque movements of the anterior teeth, while Invisalign® showed lower torque accuracy in previous studies (22).

Lombardo *et al.* investigated the predictability of orthodontic tooth movements using F22® aligners (5). The results indicated that F22® aligners were particularly effective for translations,

but less predictable for rotations, requiring additional refinements and adjustments were (5).

6 CONCLUSIONS

1. Clear aligners are an effective treatment option for many malocclusions, but their predictability for rotational movements, especially for incisors, remains challenging. Factors such as initial tooth position, space available, treatment design, force application, use of attachments and auxiliaries, tooth size and shape, as well as the alveolar bone and the root length, may impact the effectiveness of rotational movements.
2. Different aligner brands report distinct treatment outcomes, with various systems showing varying levels of effectiveness for rotational movements. Orthodontists must carefully assess the feasibility of achieving rotational movements with clear aligners and may need to use adjunctive methods or multiple aligner refinements for precise outcomes.

7 SUSTAINABILITY

Sustainability in healthcare, including orthodontics, involves economic, environmental and social considerations. Clear aligners offer advantages in terms of digital workflows and material efficiency but also present challenges related to plastic waste and energy consumption. From an economic perspective, treatment with clear aligners reduces the need for frequent in-office visits through remote monitoring, lowering costs for both patients and clinics. Digital impressions eliminate the need for disposable materials, optimizing resource allocation. However, the high production costs of aligners can limit accessibility compared to traditional braces.

In terms of the environment, clear aligners are made from a medical-grade thermoplastic material that is not biodegradable, contributing to plastic waste. Unlike traditional braces, which use metal components that can be recycled, discarded aligners add to environmental concerns. Additionally, digital treatment planning minimizes material waste, while remote consultations help reduce the carbon footprint associated with travel.

The social impact of Clear Aligner Therapy is significant, offering a discreet and comfortable option that improves patients' confidence and oral health. The ability to remove aligners enhances hygiene compared to fixed braces, contributing to better long-term dental outcomes. Moreover, the integration of digital tools in orthodontics promotes accessibility to treatment in remote areas through tele-dentistry solution.

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