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RESEARCH ARTICLE

EVOLUTION OF THE EFFICIENCY AND PREDICTABILITY OF CLEAR ALIGNER THERAPY: A NARRATIVE REVIEW

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ABSTRACT

Background:- Clear aligners have provided patients willing to undergo orthodontic treatment with a highly aesthetic and comfortable alternative to conventional braces and hence are gaining popularity especially among adults who wish to have their smile corrected. Clear aligner technology has evolved over the last 20 years and is continually being modified to achieve most predictable tooth movements possible. However, there is not enough clinical research available to describe the complete predictability of the appliance and hence the overall efficiency of outcome is controversial. Although clear aligner therapy is an aesthetic and comfortable treatment option, it has its limitations. This review highlights on the evolution of clear aligner technology and the changes it underwent till date to provide efficient tooth movements comparable to conventional fixed appliance. It discusses in detail on the ability of clear aligners to predictably achieve tooth movements like rotations, mesio-distal tipping, bodily movement, alignment, intrusion, extrusion and anterior bucco-lingual tip (root torque) posterior bucco-lingual tip (expansion). Simple tooth movement like tipping is fairly predictably achieved by clear aligner therapy, but complex movements require adequate treatment planning and use of additional auxiliaries like attachments, intra-oral elastics, inter-proximal reduction, power ridges, auxiliary anchorage devices and over correction in some tooth movements to improve their outcome. The inclusion of such additional aids can help provide a more stable, predictable and efficient outcome for patients and the scope for improvement in treatment outcomes is immense considering the constantly evolving appliance and innovative treatment strategies on the part of clinicians.

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INTRODUCTION

In this new era, where computer aided design/ computer-aided manufacturing has allowed individualized orthodontic treatments, clear aligner therapy is facing upsurge due to the increased demand for aesthetics by adults as well as by teens. Clear aligners that satisfy this demand are also prone to rapid technological improvements in aligner materials and production techniques (Tamer, 2019). The idea of using an aligner to straighten or position teeth was first introduced somewhere around 1940s when Kesling used a rubber based tooth positioning appliance to refine the final stages of tooth positions towards the end of treatment (Kesling, 1946). In 1971, Ponitz used a similar "Invisible Retainer" using Kesling's idea of creating a positioner on a study model and found that minor movements could be affected with them (Ponitz, 1971). Sheridan, in 1993, came up with the concept of combining his technique of inter-proximal reduction with aligners to bring about more tooth movement (Sheridan, 1993). However, as a 'Kesling setup' was required for every tooth movement, it required a new impression each visit, hence increasing clinical and laboratory time manifold. Nearing the end of the 20th century, Align technology brought into the market their Invisalign® system in 1999; this was the first orthodontic appliance to use computer-aided design (CAD) and computer-aided manufacturing (CAM). The requirement for a new impression for each tooth movement was no longer necessary; this technology allowed for multiple tooth set-ups to be created from a single impression (Hajeer, 2004). The entire digital process negated the impracticality of previous aligner systems and made Kesling's concept a reality. In today's time, there are multiple other aligner systems that use similar principles to achieve their results, each showing its own evolution over time (Jones, 2009).

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GENERATIONS OF ALIGNERS

First generation aligners: The earliest aligners relied solely on themselves to achieve results, and no auxiliary elements were used. Limited literature is available on these aligners to assess the tooth movements brought about by them. Djeu *et al*, 2005 compared 48 Invisalign® cases with fixed appliance cases and found them to be at par with each other for marginal ridge alignment and root angulation; however for occlusal contacts, occlusal relationship, bucco-lingual inclination and overjet they were found lacking as compared to fixed appliance treated cases (Djeu, 2005).

Second generation aligners: The use of attachments began to be encouraged by manufacturers and clinicians began using composite buttons on teeth as well as the use of inter-maxillary elastics. In two separate studies, Kravitz *et al* assessed the accuracy of tooth movements produced by these newer aligners; both clinical trials suggest that there is a large difference between the proposed virtual results and the actual clinical tooth movements (Kravitz, 2008; Kravitz, 2009). In conclusion, the attachments introduced in the second generation aligners did not seem to improve overall accuracy.

Third generation aligners: For improved movement control, manufacturers provided the option of placing attachments on the teeth that were software driven, that aided in crucial tooth movements like extrusion, de-rotation and root movements. Indentations in the aligners are fabricated where torque is to be expressed and non-precision attachments can be requested by the clinician to aid in tooth movement of certain teeth. There are three types of attachments; ellipsoid, beveled and rectangular. Ellipsoid attachments are used singly for de-rotations, or in pairs where root movements are attempted. They may also allow the appliance to achieve bodily movement, similar to the labial fixed appliance, through the use of Moment of Couple (MoC) and Moment of Force (MoF). Bevelled attachments are used most often when trying to extrude a tooth. They have an active border, like fixed appliances, that should limit the slipping (or loss of tracking) that can occur between the aligner and the tooth. Rectangular attachments are used when large mesio-distal movements are requested. It is proposed that these attachments will allow teeth to be moved bodily by allowing for a longer span for force application (Hennessy, 2016).

Biomechanics of aligner treatment: The clear aligner biomechanics may be explained with two perspectives: the displacement driven system and the force driven system (Tamer, 2019). The displacement driven system is known to be less efficient in producing root movements and overall tooth movements. The force driven system attempts to utilize the principles of biomechanics. Hence, the shape of the aligner is altered by incorporating pressure points and /or power ridges so as to apply the desired forces to the teeth. Pressure points lead to more difficult movements such as intrusion and uprighting, whereas power ridges control the axial root movements and torque (Chan, 2017). Inspite of these alterations in the shape, root paralleling, extrusion and rotation corrections were still difficult to obtain until Align Tech. (Align Technology, Santa Clara, CA, USA) presented with smart force attachments for the Invisalign® system. These are small composite attachments tailored to apply force in the anticipated direction and are designed via the Clincheck® software (Tamer, 2019). The flat surface of these composite attachments determines the direction of tooth movement it is going to cause. Thus, the clinician can customize the set of aligners for a particular tooth movement by placing these smart force attachments via the Clincheck® software. Extrusion attachment, rotation attachment and root control attachments are currently used (Chan, 2017). Nonetheless, movements like extrusion, severe rotation corrections and molar uprighting are still some of the challenging movements to achieve and have less documented literature on its predictability. There still remains confusion regarding the efficacy and efficiency of clear aligners thus making it difficult to objectively characterize the accuracy of various tooth movements (Hennessy, 2016; Kunchio, 2007).

Force delivery systems and accuracy of aligners

CAT has undergone significant changes and upgrades by introducing many features so as to maximize the predictability of various tooth movements. For example, the Invisalign® system introduced the Smart Force features (2008), such as optimized attachments, pressure zones and customized staging and the Smart Track aligner material (2011) that gives better force delivery and thus results. With improvements in design of the appliance, predictability improved of some tooth movements. In a most recent study by Haouili *et al*. (2020), it was concluded that the overall mean accuracy of the Invisalign® system had improved to 50% as compared to 41% as predicted by Kravitz *et al* in 2009. Lombardo *et al*. (2017) have observed a mean predictability of movements achieved using F22 aligners was 73.6% (Lombardo, 2017).

Evolution of accuracy for different tooth movement

Alignment: In 2003, in a RCT conducted by Clements *et al* found improvements in PAR score for alignment of 78% of the analysed sample, while 12% showed no significant change and remaining 10% had worsening of results (Clements, 2003). In 2012, Krieger at al showed an improvement of Little's irregularity index between pre and post-treatment casts in maxillary (-3.8mm) and mandibular (-5mm) arches (Krieger, 2012). Grunheid *et al* in found that clear aligners tended to increase mandibular inter-canine width during alignment in contrast to fixed appliance (Grunheid *et al*., 2016). Hennessy *et al*. (2016) found that fixed appliance produced more mandibular incisor proclination during alignment than aligners did, but the difference between the two groups was statistically insignificant (Hennessy, 2016).

Gu *et al*. (2017) conducted a retrospective study and compared the PAR score between fixed appliance and Invisalign® system. They described the treatment being quicker by Invisalign than fixed appliance system by 30% along with final occlusal scores that were comparable between the two systems (Gu, 2017). In an updated systematic review by Rossini *et al* in 2017, the authors concluded that clear aligners are effective in aligning arches even in severe crowding cases (>6mm of crowding) without extractions (Rossini, 2017).

Mesio-distal tipping/ bodily movement: Baldwin *et al*(2008) had observed a mean change in radiographic and dental cast inter-dental angle of about 17° after CAT ($P < .0001$) (Baldwin, 2008). Djeu *et al* reported that no significant difference in OGS scores between CAT and fixed appliance treatment for root angulation achieved (Djeu, 2005). In 2009, Kravitz *et al*. in a study on the treatment of anterior teeth with aligners observed a mean accuracy of 41% for mesio-distal tipping, in which the highest accuracy was achieved by the maxillary (43%) and mandibular (49%) lateral incisors; the maxillary (35%) and mandibular (27%) canines and the maxillary central incisors (39%) had the lowest accuracy.

Drake *et al*.(2012) reported through their study that 4.4 times more OTM occurred during the first week than during the second week of aligner wear, considering all of the 2-week periods, also reporting that despite programming bodily protraction of the target tooth, it resulted in uncontrolled tipping (Drake, 2012). Simon *et al*. (2014) revealed a high predictability (88%) of the distallization of upper molars (bodily movement) when supported by attachments (Simon, 2014). Ravera *et al*. (2016) analyzed effective amount of distallization with CAT in non-growing patients on lateral cephalograms and found the average amount was 2.25mm for 1st molar and 2.52mm for 2nd molar when vertical attachments were planned (Ravera, 2016). Similar results were found by Garino *et al*. (2016) reporting a mean distallization of 2mm and an additional intrusion of 1mm (Garino, 2016).

Lombardo *et al* reported that mesio-distal tipping showed the most predictability, at 82.5% with respect to the ideal; mesio-distal tip on the upper molars and lower premolars were achieved with the most predictability (93.4 and 96.7%, respectively) (Lombardo,2017). Charalampakis *et a. l*(2018) stated that horizontal movements of all incisors seemed to be accurate, with small (0.20-0.25 mm) or insignificant differences between predicted and achieved amounts (Charalampakis, 2018). Haouili *et al* reported that with regards to accuracy between arches, the distal crown tip of the maxillary second molar (63%) was significantly more accurate than the mandibular second molar (50%) (Haouili, 2020).

Rotation: A prospective study by Kravitz *et al* conducted on 53 canines of 31 subjects assessed a mean accuracy for canine rotation of 36%. The highest mean rotational accuracy and lowest standard deviation (43%; SD = 22.6%) was observed in canines that underwent inter-proximal reduction (IPR). Kravitz *et al* has stated that the maxillary canine accuracy of rotation was 32%, lower than that of the maxillary central incisors (55%) and mandibular lateral incisors (52%); the least accuracy was detected for the mandibular canine (29%). The accuracy of maxillary canine movement was significantly reduced for rotations greater than 15° (19%; SD = 14.1%; P < .05) (Kravitz, 2009). Simon *et al* achieved similar results, demonstrating that staging (amount of rotation/aligner) had a considerable impact on the treatment efficacy; for premolar rotations with a staging of <1.5°/ aligner, the total efficacy was 41.8% (SD = 0.3%), whereas with a staging of >1.5°/aligner, the accuracy decreased to 23% (SD = 0.2%) (Simon *et al*., 2014).

Lombardo *et al* in their study found the accuracy of rotations to be 66.8%; rotation on the lower canines was the least efficaciously achieved (54.2%) in comparison to mesio-distal and bucco-lingual tipping movements (Lombardo *et al*., 2017). Charalampakis *et al* found in a retrospective study on the accuracy of clear aligners and need for further refinement in the end stages that All achieved rotations were significantly smaller than those predicted, the greatest difference of 3.05°(P<0.001) being exhibited by the maxillary canines (Charalampakis, 2018). Haouili *et al* have reported the lowest overall accuracy occurred with rotation (46%), and specifically, the least accurate movements were the mesial rotation of the mandibular first molar (28%); with regards to directionality, mesial rotation of the maxillary canine (52%) was significantly more accurate than distal rotation (37%) (Haouili, 2020).

Intrusion: In 2006, Nguyen and Cheng reported that the mean accuracy of anterior intrusion was 79% (Nguyen, Chen, 2006). In 2009 Kravitz *et al* conducted a prospective clinical study in which superimposition of the virtual model of the predicted tooth position over the virtual model of the achieved tooth position was performed for 189 intruded teeth; the intrusion was achieved with highest accuracy by maxillary (45%) and mandibular (47%) central incisors, while the least accurate movement of intrusion was achieved by the maxillary lateral incisors (33%). An average of 0.72mm of true intrusion was attempted (Kravitz, 2009). A systematic review by Rossini *et al* conducted in 2015 that assessed the scientific evidence related to the efficacy of clear aligner treatment in controlling orthodontic tooth movement concluded that anterior intrusion movement achieved by CAT is comparable to that reported for the straight wire appliance (Rossini *et al*., 2015).

In 2017, predicted and achieved digital models were superimposed with a best-fit registration by Grunheid *et al* for efficacy of tooth movement by Invisalign®. Percent accuracy was calculated but movements that had greatest difference between predicted and achieved were mandibular incisor intrusion and mandibular lateral, canine and premolar rotations (Grünheid, 2017). Similar to Grunheid *et al*, in 2018 Charalampakis *et al* designed a study to determine the accuracy of specific tooth movements with Invisalign® where they compared the predicted and achieved models from Clincheck® (Align Technology) and the amount of predicted tooth movement was compared with the amount of movement achieved. It was concluded that intrusion was the most inaccurate of all linear movements. Maxillary central incisors had the greatest difference of 1.5mm (P<0.001). Mandibular incisor intrusion was the least predictable tooth movement. The authors suggested over-correction so as to decrease the need for refinement (Grünheid, 2017; Charalampakis, 2018).

Extrusion: Boyd in 2005 reported that absolute extrusion is still challenging even with attachments and advocated that the extrusive movement could be combined with more accurate movements such as retraction (lingual constriction) or retroclination to improve it'spredictability (Boyd, 2005). In 2009 Kravitz *et al* in their prospective study found that least accurate tooth movement was extrusion (29.6%). The maxillary (18.3%) and mandibular (24.5%) central incisors had the lowest accuracy for extrusion (30% predictability). The maxillary lateral incisors were the most commonly extruded teeth. The average amount of extrusion attempted was 0.56mm (Kravitz *et al*., 2009). In a systematic review by Rossini *et al* where eleven relevant articles were selected (two Randomized Clinical Trials (RCT), five prospective non-randomized and four retrospective non-randomized), it was concluded that extrusion was the most difficult movement to control and that lack of efficiency could be due to the difficulty of the appliance in developing enough force to extrude teeth in a significant way (Rossini *et al*., 2015). A retrospective study conducted by Charalampakis *et al* to determine the accuracy of specific tooth movements concluded that extrusion and horizontal movements of all incisors were near accurate with insignificant differences (0.20-0.25 mm) between predicted and achieved amounts (Charalampakis, 2018). Papadimitriou *et al* in a systematic review in 2018 concluded that use of additional-novel attachments might be more effective for various types of movement, such as bodily expansion of the maxillary posterior teeth, canine and premolar rotational movements, extrusion of maxillary incisors, and in overbite control (Papadimitriou, 2018). A recent systematic review by Robertson *et al*(2020) established that extrusion of maxillary anterior teeth was more predictable than intrusion (Robertson, 2020). Two other studies, also support this finding that anterior teeth were more occlusally placed than predicted and mesio-buccal cusp of maxillary molar was significantly intruded where no intrusion was planned (Chan, 2017; Kunchio, 2007). Thus, the application of clear aligners could be found in anterior open bite cases where aetiology is intruded anterior teeth. This is an improvement over the results of a previously published systematic review that suggested limitations of clear aligners for extrusion of incisors. Agreeing with previous findings, Haouili *et al* in their recent prospective clinical study measured mesio-distal crown tip, bucco-lingual crown tip, intrusion, extrusion and rotation to assess the efficacy of these movements with Invisalign® and concluded that extrusion of maxillary central incisors (56%) was significantly more accurate than intrusion (33%) and intrusion of the mandibular second molar (51%)was significantly more accurate than extrusion(37%) (Haouili *et al*., 2020).

Anterior buccolingual tipping/ root torque:

Djeu *et al* observed better scores for fixed appliances than for CAT in relation to bucco-lingual tipping (braces:-2.8; SD=2.6; CAT:-4.2; SD=2.73; P<.05) (Djeu, 2005). Kravitz*et al* showed significantly higher accuracy of lingual crown tip (53%) than labial crown tip (38%), particularly for maxillary incisors. Kassas *et al*. (2013), retrospectively, showed a significant improvement for bucco-lingual inclination, using the Model Grading System (MGS) score, especially in the posterior region (-0.74; P < .05) (Kassas, 2012). Simon *et al* showed no substantial differences if the upper central incisor torque was supported by a horizontal ellipsoid attachment (mean accuracy: 51.5%; SD = 0.2%) or by an altered aligner geometry (mean accuracy: 49%; SD = 0.2%). Grunheid *et al*. conducted a CBCT study which demonstrated a significantly high value for bucco-lingual inclination for mandibular canines with CAT compared with fixed appliances (2.6° difference) (Grunheid, 2016). Duncan *et al*. (2016) analysed cepahlometric position of mandibular incisors. In mild to moderate anterior crowding cases there wasn't any significant change in the inclination and angulation of mandibular incisors. However, in case of severe anterior crowding, mandibular incisors showed higher bucco-lingual inclination (Mandibular incisor inclination relative to mandibular position or L1-NB= -4.7°, Mandibular incisor position relative to mandible or L1-NB= -1.5mm, Angle between lower incisor and APog line or L1-APog=-4.82°, distance between lower incisor and APog line or L1-APog= -1.74mm) (Duncan, 2016). Henessey *et al* reported no significant change in the bucco-lingual inclination of mandibular incisors treated with CAT or fixed labial appliances in mild crowding cases (Hennessy, 2016). Lombardo *et al* reported that the accuracy of bucco-lingual tipping was 72.9% in their study (Lombardo, 2017). Haouili *et al* stated that specifically the most accurate movement was the labial crown tip of the maxillary lateral incisor (70%) (Haouili, 2020).

Posterior bucco-lingual tipping/ expansion:

Pavoni *et al*. (2011) conducted a study comparing the post treatment casts of CAT treated patients and fixed selfligating appliance treated patients. CAT group showed a significant increase at three points- the fossa point, the second inter-premolar width(0.45mm) and inter-molar width(0.5mm) , and the fixed self ligating appliances showing a significant decrease at these points (Pavoni, 2011). Kassas *et al*. (2013) and Li *et al*. (2015) concur on the finding that the planned anterior and buccolingual expansion and actual results showed an inverse proportion; this further emphasizes that for bodily expansion and crown uprighting of more than 2 mm on molars and 0.7 mm on canines, the use of auxiliaries and intra arch elastics would better serve an increased predictability of results and limit corrections during treatment (Kassas, 2013; Li, 2015). Grunheid *et al* showed at statistically significant increase in the mandibular inter-canine width in patients treated with expansion with CAT(0.7mm). Houle *et al*(2017) reported that in expansion cases with CAT, the accuracy decreased from anterior to posterior. Mean accuracy of expansion in the upper arch was 72.8%(82.9% at cusp tips and 62.7% at gingival margins) and for the lower arch 87.7%(98.9% at cusp tips and 76.4% at the gingival margins) (Houle, 2017). Solano – Mendoza *et al*(2017) reported similar results with good accuracy(p=0.031)of molar expansion prediction, in cases of planned lower arch expansion of less than 2mm (Solano-Mendoza, 2017). Zhou and Guo(2020) found while assessing the efficiency of upper arch expansion with the Invisalign® system that there were significant differences between the expected and actual expansion amounts (P< .05) (Zhou, 2020). The average expansion efficiencies of the upper canine crown, first premolar crown, second premolar crown, and first molar crown were 79.75 +/- 15.23%, 76.1 +/- 18.32%, 73.27 +/- 19.91%, and 68.31 +/- 24.41%, respectively. The average efficiency of bodily expansion movement for the maxillary first molar was 36.35 +/- 29.32%.The preset amount of expansion movement and initial torque are negatively correlated with bodily expansion efficiency, making it necessary to preset sufficient buccal root torque of posterior teeth according to the preset amount of expansion and initial torque. Haouili *et al* have reported the highest overall accuracy was achieved with a bucco-lingual crown tip (56%); specifically, the lingual crown tip of the maxillary second molar (61%) was significantly more accurate than the buccal crown tip (35%), while the buccal crown tip of the mandibular second premolar (70%) was significantly more accurate than the maxillary second premolar (61%) (Haouili, 2020). Overall, there was little difference in accuracy between maxillary and mandibular teeth, similar to results found by Kravitz *et al*. (2009)

Conclusion

The overall literature available till present suggests that the predictability of orthodontic tooth movement and its control during clear aligner therapy has significantly improved over time.

- Invisalign® has reported an accuracy of 50% for all tooth movements; this overlooks the fact that despite such a high accuracy, the Invisalign® appliance struggles with certain types of tooth movements such as intrusion, bodily movement and torquing teeth. It was observed a mean predictability of movements achieved using F22 aligners was 73.6%. This percentage changes with every aligner system depending upon the clinical data available.

- Molar distallization of 2.5mm and premolar extraction space closure have become more predictable tooth movements.

- Rotation remained the most difficult movement to predict for all aligner systems with canine rotation being the most difficult to correct, especially that of the lower canine.
- Arch expansion of up to 2mm in the molar region and 0.7mm in the canine region can be easily achieved.
- In severe crowding cases of up to 6mm or more, effective alignment can be achieved without extraction.
- Maxillary incisor extrusion becomes more predictable when performed with attachments and combined with retraction (lingual constriction) of incisors; maxillary incisor intrusion, however, still remains a challenge
- Tipping is one of the most easily achieved and predictable movement with CAT.
- Incisor extrusion still seems to be a challenging movement to achieve with CAT and more data is required to study its predictability.
- Tooth inclination and occlusal contacts seem to be among the limitations of CAT.
- Additional novel attachments might be useful in improving results in tooth movements such as bodily expansion of maxillary posterior teeth, canine and premolar rotational movements, extrusion of maxillary incisors and in overbite control.
- Auxiliaries such as different types of attachments, intra-oral elastics, IPR, power ridges, auxiliary anchorage devices and over correction in some tooth movements should be considered to obtain the maximum predictability.

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GLOSSARY OF ABBREVIATIONS

1) ABO – American Board of Orthodontics
2) CAD – Computer Aided Design
3) CAM – Computer Aided Manufacturing
4) CAT – Clear aligner technique
8) IPR – Inter-proximal Reduction
7) L1-APog – Distance between lower incisor and APog line
9) L1-APog – Angle between lower incisor and APog line
10) L1-NB – Mandibular incisor inclination relative to mandibular position
11) L1-NB – Mandibular incisor position relative to mandible
12) MGS – Model Grading System
13) MoC – Moment of Couple
14) MoF – Moment of Force
15)mm - Millimeter
16)OGS – Objective Grading System
17)OTM – Orthodontic Tooth Movement
18)P – Value of significance
19)PAR – Peer Assessment Rating Index
20)RCT – Randomized Control Trial
21)SD – Standard Deviation

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