Journal Homepage: -www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

Article DOI:10.21474/IJAR01/17126
DOI URL: http://dx.doi.org/10.21474/IJAR01/17126

RESEARCH ARTICLE

CLEAR ALIGNERS: AN INSIGHT TO BIOMECHANICS

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Manuscript Info

Manuscript History
Received: 20 April 2023
Final Accepted: 24 May 2023
Published: June 2023

Key words:-
Aligners, Biomechanics, Accuracy, Optimized Attachments

Abstract

Orthodontic techniques have revolutionized in the last decade and clear aligners play a major part in this. Earlier concept of using aligner treatment for mild cases has now been rejected due to development in auxiliaries, temporary anchorage devices, more refined computer programmed tooth movements, manufacturing techniques and materials. With the increasing accuracy of aligner treatment, need to understand the working biomechanics of clear aligners is of utmost important. This review articles gives a horse eye view of the biomechanics and the wide scope of malocclusion which can be treated with clear aligners.

Introduction:-

Orthodontic clear aligner treatment was used mainly for minor tooth movements or slight alignment relapses before 1998 but these are now being used as an alternative to braces since Kelsey Wirth and Zia Chisti, the founders of Align Technology in California, introduced Invisalign in 1997. Clear aligners use 3D technology to visualize and move the teeth in a virtual model , by combining this technology with 3D printing and manufacturing efficiencies, aligners can be produced in large quantities. Initial cases which were taken up were mild crowding or spacing which progressed to cases that need expansion and malocclusion correction. This clear aligner technique is constantly developing because of research and development in materials, manufacturing techniques, auxiliaries, and computer programming of tooth movement. (1)

Clear aligners involve a sequence of thermoformed appliances made from a transparent; thin (less than 1 mm) plastic material molded with the CAD-CAM technique.Excellent compliance is mandatory since the appliance has to be worn a minimum of 20 to 22 hours a day.(2)Each aligner is intended to move the teeth a maximum of about 0.25 to 0.3 mm over 2 weeks, and is worn in a specific sequence(3)The clear aligners can apply translation, torque, extrusion, and rotation forces to the teeth. In rocking motions, a single force is required, whereas in translational motions, there are at least two force systems.

Anchorage and root control are often the greatest challenges faced by any orthodontist. A plastic aligner encases the tooth and therefore provide both retention and activation in order to move the teeth. In general, the natural undercuts of the teeth provide the retention and the active component to move teeth by the elastic deformation of the aligner.(4)

Clear aligners are used to treat a wide scale of malocclusion inclusind crowding (4-6mm), narrow arches, distalisation , extraction cases with TADs , class II myofunctional cases etc. (5)

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Clear aligners material structure & properties

There are three different types of polymers based on their thermal behavior. Clear aligners belong to the thermoplastic group of polymers, the two most commonly used polymers for aligners are (6):

1. Polyethylene terephthalate glycol (PET-G)
2. Thermoplastic polyurethane (TPU)

Polymers being lightweight, inexpensive, easy to manufacture, and versatile are the choice of material for clear aligners. Two types of aging of clear aligners can be seen – physical and chemical.As polymer molecules age, they adopt a new conformation to a temperature lower than their glass transition temperature, this is called physical aging .(7) Physical Aging influences important product properties :

1. Reduces the volume of the polymer
2. Increases tensile strength
3. Increases stiffness
4. Increase in brittleness
5. Reduction in fatigue strength

By choosing an aligner with a glass transition temperature value much higher than the intraoral temperature, physical aging might be largely avoided.The physical aging of polymers can be influenced by exposure to water and many other kinds of molecules in the intraoral medium. From a clinical perspective, physical aging can affect an aligner in two ways:

1. Initially, the polymer will become softer due to the plasticizing effect. As a result, force magnitudes applied to the individual teeth are reduced.
2. In the long run due to the effect of physical aging, aligner polymers become harder, which will increase the applied forces and makes them more brittle thereby increasing the risk of breakage

Chemical aging of polymer occurs due to reaction with chemical such as saliva , food, beverages etc. A polymer suffering from chemical aging is more likely to develop cracks and induce notch effects.Amorphous polymers such as TPU and PET-G possess relatively low molecular density, which provides free volume for water intake. A study comparing these two materials showed that TPU shows higher water absorption characterized by a weight increase of 1.45% after 1-week water storage than PET-G showing only a 0.84% increase(8)

Biomechanics of clear aligners

A clear aligner's biomechanics can be summarized as root uprighting followed by crown tipping.Working principle of aligner therapy includes tooth position and aligner material ("mismatch").The pattern of mismatch-plastic deformation- orthodontic force is critical for attachment design during digital simulation to produce specific areas (active surfaces) that will contact aligner plastic at the predetermined force magnitudes, producing the desired force vectors and consequent tooth movements.While the magnitude of the force produced is determined by the amount of mismatch (along with the characteristics of the aligner material), the direction of the force will depend on the orientation of the active surface.

	Fixed appliances	Clear aligners
Force	Exerts a ‘pull’ force	Exerts a ‘push’ force
Engagement	Thicker the wire better the engagement	Longer the clinical crown better the engagement
Anchorage	Reciprocal anchorage	Anchorage systems are predetermined and are made immovable

Orthodontic tooth movement staging :

Staging is intended as the amount of programmed movement per tooth in each aligner. The staging amount is determined by each aligner company based on internal research, thus default staging settings may differ from one another

Amount of movement allowed per aligners (9):

Type of movement	
Rotation	<1.5
Intrusion/extrusion	0.2mm
Linear movement	0.2mm
Root torque	1

Accuracy of clear aligners (10)

	Highest	Lowest	Average
Intrusion	**Maxillary central incisors (45%) Mandibular central incisor (47%)**	**Maxillary lateral incisors (33%)**	**0.72mm**
Extrusion (least accurate)	**Maxillary canine (50%)**	**Maxillary central incisors (18% Mandibular central incisors (25%)**	**0.56mm**
Rotation	**Canines with IPR (43%)**	**Rotations > 15%**	**Mean accuracy 36%**
Mesiodistal tipping	**the maxillary (43%) and mandibular (49%) lateral incisors**	**The maxillary (35%) and mandibular (27%) canines and the maxillary central incisors (39%)**	**Mean accuracy 41%**
Buccolingual tipping	**lingual crown tip (53%)**	**labial crown tip (38%)**	
The mean accuracy of tooth movement was 41%. The most accurate tooth movement was lingual constriction (47.1%). The least accurate tooth movement was extrusion (29.6%) followed by rotation correction 30%			

Accuracy for premolar rotation correction is halved when a rotation greater than 1.5 degrees per aligner is planned(11).Upper molar distalization revealed the highest predictability (88%) when a bodily movement of at least 1.5 mm was prescribed.Significant increase in second interpremolar(0.45mm) width and in intermolar (0.5mm) widths was found with clear aligner therapy when compared with self-ligating appliance.(12)Predictability of clear aligner therapy shows that for every 1 mm of incisal edge movement planned, 0.7 mm is clinically achieved(13)

Working components of clear aligner treatment includes:

1. Interproximal reduction : anterior and posterior
2. Attachments: conventional and optimized; active (provides force vectors) or passive (for retention purpose only)
3. Pressure areas
4. Optimized deep bite attachments
5. Precision bite ramps
6. Precision cuts
7. Power ridges

Interproximal reduction

The IPR procedure has been used for mild-to-moderate crowning cases since 1944, when Ballard first described it(14). IPR may be prescribed in increments of 0.2, 0.3, 0.4, and 0.5 mm per contact area.The IPR amount is calculated during CAT digital planning based on digitally calculated dental index scores (Bolton index, Little index, space analysis, etc.), and the timing of IPR is programmed to ensure optimal interproximal surface access and prevent premature tooth surface collisionsThe maximum amount of IPR as reported by Sarig et al (15) in 2015 is 0.5mm / interproximal space in anteriors and 1mm/ interproximal space in posteriors. Different gauges available for IPR are shown in Figure 1.

Figure 1:- Various Gauges available for IPR.

Attachments

Attachments are useful to guide teeth in a determined direction and are also useful in providing anchorage control depending on the type of planned orthodontic movement. Attachments are divided into two categories:

1. Conventional attachments (rectangular, bevelled, or ellipsoid)
2. Optimized attachments

The "play" of aligners on teeth and attachments is another key factor in producing desired outcomes, which is strictly related to attachment application. Function of Attachments include-

1. Providing aligner retention
2. Avoiding aligner slipping
3. Delivering predetermined force vectors

Without the attachments aligners tend to move towards the gingiva therby concentrating all the forces on occlusal surface and no couple is generated. Conventional attachments are those which can be positioned by the clinician on every tooth (depending upon the compatibly with tooth dimension) and can be oriented in any direction.

Conventional attachments	
Rectangular 	Passive attachments Can be horizontal or vertical Increase anchorage in posterior teeth Reinforce the retention of appliance
Bevelled 	Have an active surface against which aligner generates 'push' force for the desired movement For intrusion :bevelled surface is on the occlusal side For extrusion :bevelled surface towards gingival side
Ellipsoid 	Passive attachments Primarily used for retention Used specially when tooth surface is limited Eg. Peg laterals
Optimized attachments	
	Used to generate couple force for rotation correction in canine and premolars specially. Positioned by software automatically when a certain thresholds of tooth movement is detected The orthodontist is not able to modify their position, dimension, and orientation. They control – • The point of application of force • The direction of the force • The amount of force applied

Pressure areas

Intrusive force from aligners is not directed along the long axis of the tooth resulting in incomplete correction of the deep bite. To address this problem pressure areas(Fig 2), or concavities are designed into the aligner surface on the lingual cingulum area of the incisors These pressure areas redirect the force along the long axis of the tooth making intrusion more predictable. The pressure areas are the most effective auxiliaries in lower incisors tipping, even more than rectangular attachments(16) and they are effective in controlling root movement with clear aligners(17)

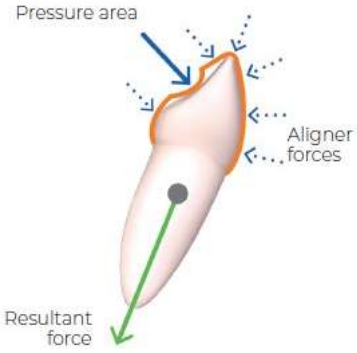


Figure 2:- Pressure area altering the direction of force along the long axis.

Optimized deep bite attachments

Optimized deep bite attachments are designed to be passive or active. Passive optimized deep bite attachments are usually placed on first or second premolars, or both, to provide anchorage for intrusion of anterior teeth. Active optimized deep bite attachments have an active surface built into their gingival surface.

Precision bite ramps

Precision bite ramps (Fig 3) may be placed on the palatal surfaces of either the maxillary central and lateral incisors or the maxillary canines to relieve the occlusal disturbances.These precision bite ramps are lingual prominences incorporated into the aligner at the cingulum area of these maxillary teeth.The depth of precision bite ramps may be up to 3 mm to accommodate the overjet.

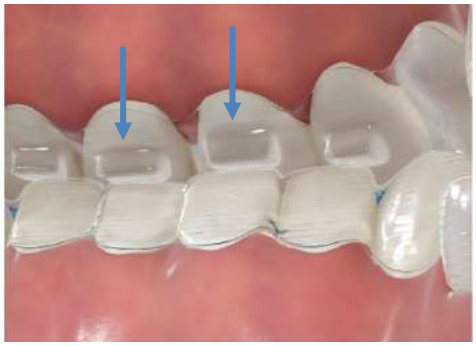


Figure 3:- Precision bite ramps to relieve occlusal disturbances.

Because precision bite ramps and pressure areas occupy the same palatal surface of the maxillary incisors, they cannot coexist on these teeth in the same aligner.Bite ramps should be removed once the incisor proclination has been achieved so that pressure areas can be incorporated for intrusion.

Precision cuts

Precision cuts(Fig 4)allow intra-oral elastics to be worn for correction of Class II malocclusion with differential movement of both dental arches.The intraoral elastic exerts a distal force on the entire arch because the elastic is hooked directly to the aligner.

Figure 4:- Precision cuts to engage intra-oral elastics.

Power ridges

In Class II, division 2 malocclusions, the maxillary incisors are retroclined. Before the advent of power ridges (Figure 5), it was very challenging to correct this incisor inclination and its associated deep bite.Power ridges may now be placed on the maxillary incisors for lingual root torque to correct the maxillary incisor inclination.

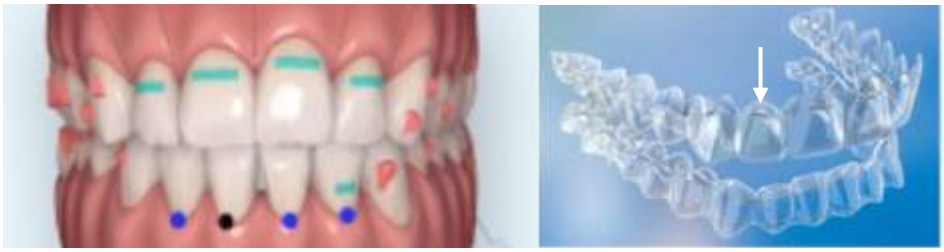


Fig 5:- Power ridges for lingual root torque.

Sequential distalization (18)
Sequential distalization of the maxillary molars is a predictable way of correcting a half-cusp class II malocclusion and may also be prescribed in combination with posterior IPR and/or class II elastic simulation.Sequentialdistalization is also commonly referred to as "V-pattern" staging(Fig 6). In this procedure the dental arch from first molar to first molar acts as an anchorage segment to push the second molars distally. When the second molar has moved halfway, the first molar starts to distalize and so on.This is a very conservative anchorage setup, and clear aligners allow us to distalize molars without concurrent labial movement of the maxillary incisors.

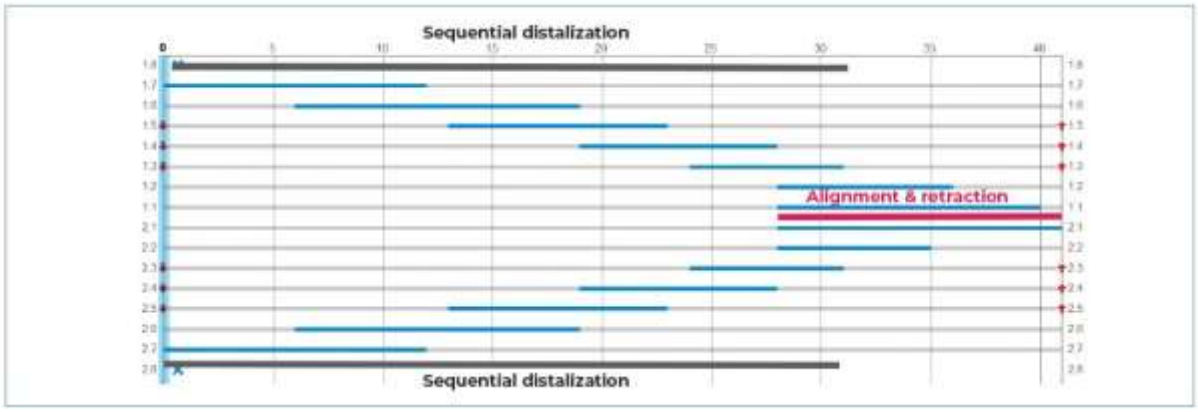


Fig 6:- Sequential distalization in class II div 1 case having a 'V' shape pattern.

There is a mild difference in the staging pattern for Class II, division 2 cases. The posterior teeth move in a similar V pattern, but the maxillary incisors also start moving from stage 1
In class II div 2 incisors are moved in following sequence – procline-intrude-retract

Pre-molar extraction treatment
3 patterns of staging in premolar extraction treatment exists :
1. Reciprocal retraction
2. The G6 maximum anchorage protocol.
3. Staggered staging protocol

Reciprocal retraction
In reciprocal retraction(Fig 7), only the two teeth on either side of the extraction site move in the beginning stages of treatment. Halfway through treatment, the extraction site is closed, and the two teeth on either side of the extraction site now act as the anchorage segment as the anterior teeth are retracted and the posterior teeth are mesialized to complete space closure.

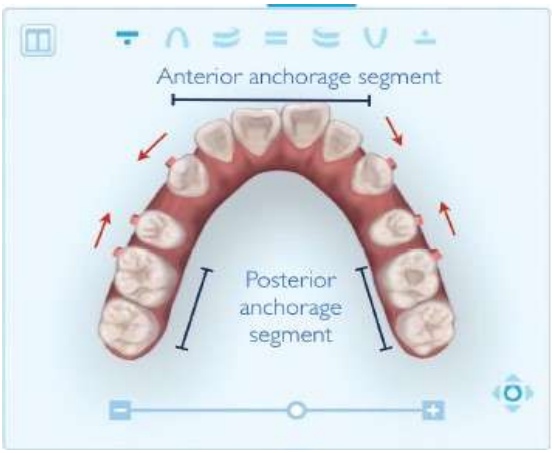


Figure 7:- Reciprocal retraction; teeth adjacent to extraction site are approximated first followed by retraction &mesialisation of anterior & posterior segment respectively.

G6 Maximum Anchorage Protocol

This protocol maximizes posterior anchorage while maintaining root parallelism during retraction and space closure.It also maintains incisor torque and prevents the overbite.The canine is first retracted one-third of the space into the extraction site. During this period, posterior segment mesialization is permitted up to 2 mm.As soon as the canine are retracted one-third into the extraction site, both the canine and the incisors are simultaneously retracted until the extraction site is closed.

The G6 protocol also incorporates Smart-Stage technology which includes an intrusive force and lingual root torque on the maxillary incisors to prevent torque lossduring incisor retraction. This maintains vertical control to prevent deepening of the overbite as the incisors are retracted during space closure.

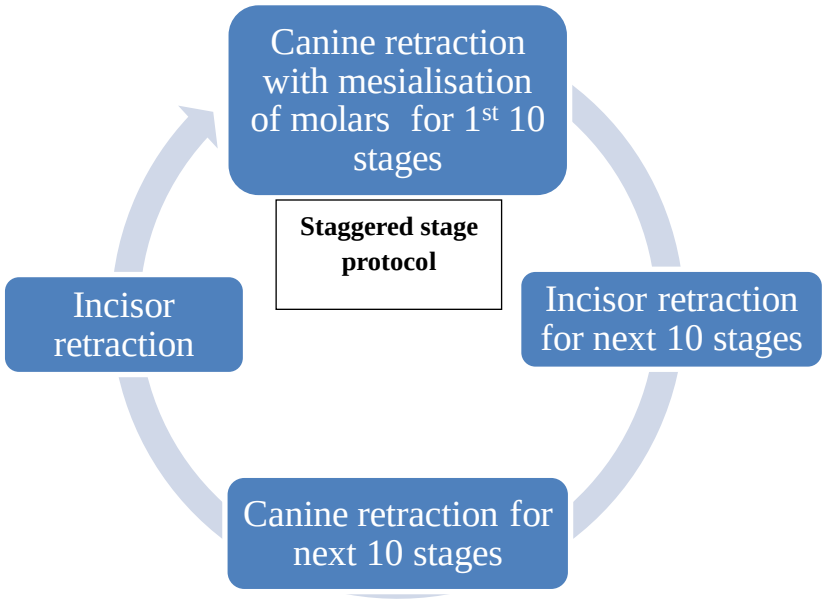
G6 protocol incorporates these critical elements:

1. Optimized retraction attachments on the canine to maintain root parallelism
2. Optimized anchorage attachments on the second premolars and first and second molars to maximize posterior anchorage

Aligner activations on the maxillary incisors to prevent undesirable tipping, thus maintaining incisor torque, and unwanted anterior extrusion, preventing a deepening of the overbite as the incisors are retracted

Staggered stage protocol

By controlling incisor torque with strict anchorage control, this treatment aims to minimize canine tipping and maximize incisor retraction. But the disadvantage being increased number of aligners makes it clinically not useful.



Growth modification by clear aligners

In 2017, Align Technology introduced Invisalign with the mandibular advancement feature.This appliance resembles a clear aligner with the addition of a feature called "precision wings"(Fig 8) placed on the buccal surface of both aligners. 3 stages are included in mandibular advancement procedure- Pre-Mandibular advancement stage,Mandibular advancement stage,Post-mandibular advancement stage.

Fig 8:- Mandibular advancement appliance showing precision wings.

Pre-mandibular phase includes correction of dental hindrance in mandibular advanmenti.e lingually placed/retroclined, correction of deep curve of Spee, correction of rotated molars, crossbite correction etc. This phase does not include precision wings. Mandibular advancement phase includes precision wings which interlock in occlusion to posture the mandible forward for Class II correction.This phase is a minimum of 26 stages, at a 7-day change intervals, that works out to 6 months of treatment time.Precision wings are placed on the maxillary and mandibular aligners during the MA phase.The default protocol is to sequentially advance the mandible 2 mm every 8 aligners (ie, 2 mm every 2 months).Post mandibular advancement phase is retention phase , precision wings are removed &any uncorrected rotations, residual deep bite, or mild class II buccal relationship may be corrected in the additional aligner phase.

Advantage of digitally designed clear aligners over traditional functional appliances is that simultaneous tooth movements i.e Alignment of anterior teeth, expansion of the maxillary arch, leveling of the curve of spee in the mandibular arch,maxillary and mandibular incisor intrusion for correction of a deep bitecan be done during the MA phase.

Over the past two decades, clear aligners have evolved to deliver an improved biomechanical force system for challenging tooth movements. There are a few indications where temporary anchorage devices (TADs) can aid in very challenging tooth movements with clear aligners[63] such as maximum anchorage cases (Fig 9),Deep bite ,molar distalisation& full arch distalisation (Fig 10),Molar intrusion (Fig 11) etc.

Fig 9: Showing the use of TADs with aligners in class I high anchorage case of simultaneous intrusion & retraction

Fig 11:- Showing the use of TADs with aligners for intrusion of maxillary molars.

Finishing (19)

A variety of finishing pliers are available to allow the clinician to make finishing bends in the aligner. These are used when there is lag in tooth movement resulting in a difference between the intraoral position of the tooth and the tooth position in the aligner. Detailing plier(Fig 12)that creates pressure points or dimples in the aligner that will nudge teeth into positions already built into the aligner.RaintreeEssix also has a series of pliers (Fig 13) that will make various indentations into the aligner for tooth movement. These pliers require preheating to 175°F to 200°F prior to use. Hu-Friedy (Fig 14) has a series of four pliers that enable the clinician to make precision-cut hooks, button cutouts, vertical indentations, and horizontal indentations in the aligner.

Figure 12:- Detailing pliers used to create pressure areas in aligners.

Figure 14:- Clear collection pliers from Hu-Friedy.

Figure 13:-Raintree Essixthermal pliers used for manipulating clear aligners.

Principles of finishing

Patients must be seen when they have approximately three aligners left in active treatment so that finishing bends may be made in these last few aligners, if necessary to complete treatment.Overcorrection of individual tooth position should be planned in additional aligner stage. If anterior contact points are open, virtual c chain aligners can be requested to close the contact and if contacts are closed these should be avoided as will lead to crowding.

Conclusion:-

Clear aligners being the most revolutionizing advances in orthodontic therapy havecompletely changed the perception of orthodontic therapy by patients. The fear of braces has now been replaced by the bliss of invisible braces. Using only computerized planning as an orthodontic specialistis not acceptable. Knowing the biomechanics behind the computerized planning opens up for new possibilities in treatment protocols and result in a biologically planned computerized treatment plan with a better accuracy.

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