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Original Article

Evaluation of Postural Balance, Cervical Lordosis and Neck Disability after Orthognathic Surgery

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Main Points

- Bimaxillary orthognathic surgical correction for skeletal Class III malocclusion did not result in a significant change in cervical lordosis.
- Neck pain and disability did not significantly change due to their multifactorial nature.
- Skeletal correction primarily based on maxillary advancement did not significantly impact the postural balance or mandibular proprioception.

ABSTRACT

Objective: The present study aimed to investigate changes in cervical lordosis, neck disability, and postural balance through static and dynamic tests in patients with skeletal Class III malocclusion who were treated with bimaxillary orthognathic surgery.

Methods: In this prospective observational study, 18 patients (mean age 23.3±5.4 years) with maxillary retrusion and mandibular prognathia were treated by bimaxillary orthognathic surgery. Static and dynamic balance tests were recorded with the Kinesthetic Ability Trainer preoperatively (T1) and at least 2 months postoperatively (T2). Cervical lordosis angle (C2-C7) was evaluated with the posterior tangent method on the lateral cephalometric films taken at T1 and T2. Neck disability and pain were assessed through questionnaires at both time points.

Results: The median follow-up time was 5.8 months. The mean maxillary advancement was 4.0 mm at point A (p=0.001). The mean mandibular setback was 2.4 mm at point B (p=0.166). An 8.4 mm maxillomandibular correction was observed according to the Wits appraisal (p=0.001). Static and dynamic balance tests, cervical lordosis angle, neck disability, and pain revealed no significant change between T1 and T2. No statistically significant correlation was observed between surgical movements and changes in the cervical lordosis angle.

Conclusion: Orthognathic surgical correction of skeletal Class III malocclusion, —primarily through maxillary advancement with less mandibular setback— did not lead to significant changes in cervical lordosis, neck disability, or postural balance as assessed through static and dynamic tests.

Keywords: Cervical lordosis, neck pain, maxillofacial orthognathic surgery, postural balance

INTRODUCTION

Maxillomandibular deformity is defined as an incorrect relationship of the maxilla and mandible leading to malocclusions.[1] Skeletal deformities within the maxillo-mandibular complex have been associated with altered head and neck posture. Patients diagnosed with skeletal Class III malocclusion, have been observed to exhibit

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a posteriorly positioned and flexed head, accompanied by a diminished cervical lordosis when compared to patients exhibiting skeletal Class I or Class II malocclusion.[2] In addition to sagittal malocclusions, vertical discrepancies in the maxillo-mandibular complex have been reported to be associated with neck posture. The conclusion that the reduction of facial height, as observed following orthognathic surgery, results in a change in neck posture has been determined by measuring a significant change in craniocervical angulation.[3] Orthognathic surgery is performed to improve the malocclusion, and facial aesthetics by repositioning the structures of the maxilla and mandible.

The loss of cervical lordosis has been identified as a contributing factor to chronic neck pain. Patients exhibiting loss of cervical lordosis may present with symptoms analogous to those observed in individuals experiencing nonspecific neck pain. Since skeletal Class III patients have been found to have straighter cervical columns compared to Class I patients, the relationship between Class III malocclusion and neck disability requires further investigation.[4] The Neck Disability Index (NDI) is a self-rated and reliable scale that has been developed for assessing disability in patients presenting neck pain.[5]

Postural control is defined as the capacity to sustain, achieve, and reestablish a given state of balance during any posture or activity. This is achieved by integrating signals from the visual, vestibular, and proprioceptive systems.[6] The stomatognathic system has ligamentous and muscular connections in the cervical region forming a craniocervical-mandibular complex, which may affect body balance. Research examining the relationship between posture and malocclusion highlights the potential role of jaw positions in maintaining postural control.[7-10] Paya-Argoud et al.[11] showed that head orientation and postural stabilization in a static situation were improved by providing orofacial muscular harmonization in the 10th week after orthognathic surgery. They suggested that mandibular proprioception was improved by establishing a novel reference frame and will lead to the head orienting in space by enhancing postural stabilization. However, there is no study analyzing the consequences of orthognathic surgery on postural stabilization under dynamic tests. Therefore, this study was aimed at investigating changes in cervical lordosis, neck disability, and postural balance through static and dynamic tests in patients with skeletal Class III deformity and being treated with orthognathic surgery.

METHODS

This prospective study was approved by Başkent University Medical and Health Sciences Research Board (approval no.: D-KA19/26-19/85 date: 11.09.2019). The study was conducted in accordance with the provisions of the Declaration of Helsinki. All participants were informed about the study protocol and the consent form. A total of 18 patients with skeletal Class III malocclusion, ranging in age from 18 to 40 years and with an indication for orthognathic surgery, participated in the study. Patients with symptoms of temporomandibular joint disorder, a history of dentofacial surgery, neurologic disorders, musculoskeletal diseases, and immune deficiency as well as those presenting a shift or discrepancy between centric relation and centric occlusion, were excluded from the study.

The patients received presurgical orthodontic treatment to establish a proper occlusion following orthognathic surgery and to eliminate anteroposterior or lateral shifts due to occlusal interferences. They lacked anterior guidance due to negative overjet during the preoperative period. Maxillary advancement was achieved with the Le Fort 1 osteotomy, and mandibular setback was performed by bilateral sagittal split ramus osteotomy in the surgical procedure. The occlusion following the surgical correction of the skeletal problem was achieved through canine guidance in some patients, while group function was established for others. Since it has been reported that both canine-guided and group function occlusions are acceptable functional occlusion schemes, no specific occlusal scheme was chosen.[12] Additionally, all patients had anterior guidance after surgery, which led to obtaining proper overjet and overbite values.

G* Power (Heinrich Heine Universität, Dusseldorf, Germany) 3.1.9.2 software was employed to estimate the sample size. The static balance of patients with skeletal Class III deformity was used as a parameter for calculation of the sample size, using a study in the literature as a reference.[11] The power analysis revealed that 18 patients were required to detect 85% power at a significance level of 0.05.

Cephalometric Measurements

All lateral cephalometric radiographs were captured using the same X-ray machine (Morita Veraviewepocs, Kyoto, Japan). A slight modification was incorporated into the lateral cephalometric radiographs to encompass all structures from the Nasion-Sella line to the seventh cervical vertebra, as outlined in the study by de Oliveira Andriola et al.[8] Cephalometric analysis of all patients was performed using *Dolphin 11.9 Software* by an orthodontist. Sagittal and vertical movements following orthognathic surgery in both the maxilla and mandible were measured.

The cervical lordosis angle formed between the second and seventh cervical vertebrae of the patients was calculated using the posterior tangent technique preoperatively (T1), and at least 8 weeks after the operation (T2) by the same researcher (Figure 1). One researcher identified the landmarks and conducted all measurements twice. The mean values of the two measurements were calculated and evaluated in the statistical analysis.

A subsample of 30% of the radiographs was re-measured 4 weeks after the initial measurements. The intraclass correlation coefficients for these measurements were found to be greater than 0.912, indicating excellent intra-rater reliability.

Neck Disability and Pain Perception

Patients were examined at T1 and T2. The modified NDI-Turkish questionnaire was administered to patients during the T1 and T2 periods to assess how neck pain affected their ability to perform daily living activities, since it has been determined to be a valid and reliable tool.[5] In addition, a 10-mm visual analogue scale (VAS) was employed to evaluate the patients' pain perception of neck pain preoperatively and postoperatively.

Balance Index

The balance index is a quantitative metric of an individual's capacity to maintain balance, with a low index suggesting a favorable aptitude for balance-related tasks. The balance index was determined using the Kinesthetic Ability Trainer (KAT) 3000 (KAT 3000, Breg, Vista, CA) device. The KAT 3000 is a device consisting of a movable platform supported by a small pivot at its central point.

The device is composed of a platform and a base engineered as a circular pneumatic cushion. The stability of the platform is modulated by the varying pressure of the cushion. At the forefront of the platform is a tilt sensor, which is connected to the computer. The computer records the deviation of the platform from the reference situation 18.2 times per second. In each record, the distance from the center of the platform to the reference position is measured. The calculation of the Balance Index score is the sum of these distances. The objective of the static test involves overlaying the cross, which corresponds to the center of the platform, onto the cursor. In dynamic tests, the cursor moves at a constant speed, completing a full circle on the computer screen every 10 seconds. Participants are asked to superimpose the cross on the moving cursor. The device under consideration is composed of two components: a movable platform and a tilt sensor connected to a computer.

Evaluation of Static Balance

The patients were requested to stand on the platform and maintain body balance for 30 seconds to measure double-leg static balance. During the test, the patients were also requested to keep their gaze on the red X symbol, which was situated in the middle of the computer screen.

Evaluation of Dynamic Balance

The patients were requested to follow the moving target point that appeared on the monitor for 30 seconds. During the test, the patients constantly followed the mark on the monitor showing the displacement of their center of gravity, relative to the target point. The lowest value, indicating the most achieved balanced position, was considered the final score, as it helps limit inherent variability in the assessment.

Statistical Analysis

Statistical analyses were conducted using SPSS version 25.0 (Statistical Package for the Social Sciences, USA). The Shapiro-Wilk test was employed for the assessment of the normality of the variables. Descriptive statistics included the mean, standard deviation, median, minimum, and maximum values. The paired t-test and Wilcoxon signed-rank test were performed to evaluate the mean differences between the periods (T2-T1). Spearman's rho analysis was employed to correlate surgical movements with changes in the cervical lordosis angle. A p-value of less than 0.05 was deemed statistically significant.

RESULTS

Sample Characteristics

Initially, the study comprised 30 patients; however, 12 patients were excluded from the analysis due to nonattendance at the follow-up appointments. Consequently, the present study encompassed 18 patients (7 female, 11 male) who were treated with bimaxillary orthognathic surgery and attended subsequent follow-up controls. The mean age of patients was 23.3±5.44 years and the mean body mass index was 24.50±4 kg/m^2. The median follow-up time was 5.7 months (2-22 months) (Table 1).

Maxillary and Mandibular Movement

The mean maxillary advancement was 4.0±3.2 mm at point A (p=0.001). The mean mandibular setback was 2.4±7.0 mm at point B (p=0.166). The Wits appraisal revealed an 8.4±4.0 mm maxillomandibular correction based on the occlusal plane (p=0.001). Additionally, a mean upward displacement of 3.1±6.3 mm in the mandible was observed (p=0.049). The study did not reveal a statistically significant mandibular rotation, as determined by the sum of posterior angles (p=0.616) (Table 2).

Changes in the Lordosis Angle (C2-C7)

The mean C2-C7 angles were 19.7±8.4 degrees preoperatively and 18.2±9.3 postoperatively (p=0.312) (Table 1). No

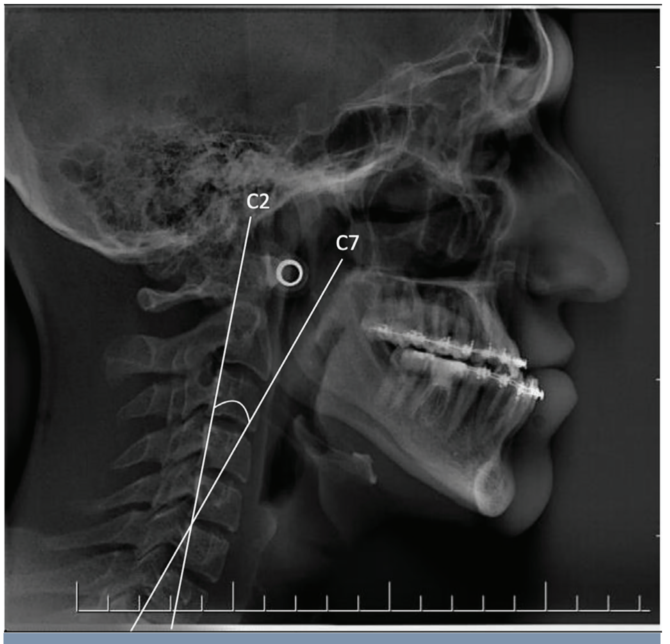

Figure 1. The cervical lordosis angle measured by the posterior tangent technique between C2 and C7

statistically significant correlation was observed between surgical movements and changes in the cervical lordosis angle.

Static Balance

The discrepancy between the preoperative and postoperative values (336.2 and 356.3, respectively) did not demonstrate statistical significance (p=0.913) (Table 1).

Dynamic Balance

The difference between preoperative and postoperative values (1673.3 and 1799.9, respectively) was not statistically significant (p=0.386) (Table 1).

NDI

The mean preoperative NDI score for the patients was 1.8, and the mean postoperative NDI score was 2.9, indicating that no significant change occurred after orthognathic surgery (p=0.341) (Table 1).

Table 1. Descriptive characteristics of the patients at preoperative (T1) and postoperative (T2) periods

				95% Confidence interval of the difference		
	Parameters	Mean±SD	Median (Min.-Max.)	Lower	Upper	p-value
Demographic characteristics	Age (years)	23.3±5.4	21.5 (17-36)	20.3	25.7	
	Follow-up (months)	6.8±5.1	5.8 (2-22)	4.3	9.4	
	Body mass index	24.5±4.0	24 (18-32)	22.5	26.5	
Pain	VAS (T1)	1.2±2.2	0 (0-6)	0.1	2.2	0.288‡
	VAS (T2)	1.7±2.7	0 (0-8)	0.3	3.0	
Balance measurements	Static balance (T1)	336.2±298.0	172.5 (112.0-1228.0)	188.0	484.4	0.913‡
	Static balance (T2)	356.3±457.2	238.0 (76.0-2119.0)	129.0	583.7	
	Dynamic balance (T1)	1673.4±732.4	1448.5 (207.0-3434.0)	1309.2	2037.6	0.386
	Dynamic balance (T2)	1799.9±625.9	1630.0 (775.0-3115.0)	1488.7	2111.2	
Neck disability	Neck disability index (T1)	1.8±1.9	1 (0-6)	0.9	2.8	0.341‡
	Neck disability index (T2)	2.9±3.5	2 (0-11)	1.2	4.6	
Cervical lordosis	Cervical lordosis angle (T1)	19.7±8.4	20.1 (4.3-32.3)	15.6	23.9	0.246
	Cervical lordosis angle (T2)	18.2±9.3	18.5 (1-38.5)	13.6	22.9	
Cephalometric measurements	SNA (°) (T1)	77.1±5.3	78.0 (60.8-85.4)	74.4	79.7	**<0.001‡**
	SNA (°) (T2)	82.7±5.0	83.2 (70.4-94.0)	80.2	85.2	
	SNB (°) (T1)	81.3±4.8	81.0 (68.3-88.6)	79.0	83.7	0.312
	SNB (°) (T2)	80.8±4.4	80.6 (68.7-90.4)	78.6	83.0	
	ANB (°) (T1)	-4.3±2.5	-4.1 (-8--0.7)	-5.5	-3.0	**<0.001***
	ANB (°) (T2)	1.9±1.3	2.6 (-0.5-3.6)	1.3	2.5	
	Wits (mm) (T1)	-11.2±5.00	-10.5 (-21-1.6)	-13.6	-8.7	**<0.001‡**
	Wits (mm) (T2)	-2.8±3.7	-3.1 (-7.3-8.8)	-4.7	-0.9	
	A-FH (mm) (T1)	30.6±3.3	30.3 (25.6-36.5)	29.0	32.3	0.421
	A-FH (mm) (T2)	29.9±3.0	29.9 (24.8-35.9)	28.4	31.4	
	A-N perp (mm) (T1)	-4.6±5.3	-4.2 (-19.1-5.5)	-7.2	-2.0	**0.001‡**
	A-N perp (mm) (T2)	-0.6±4.6	0.5 (-10.8-8.1)	-2.9	1.6	
	B-FH (mm) (T1)	72.8±5.9	71.4 (65.0-84.7)	69.9	75.7	**0.049***
	B-FH (mm) (T2)	69.7±5.9	68.1 (61.7-81.4)	66.7	72.6	
	B-N perp (mm) (T1)	-1.6±9.1	-1.7 (-18.2-13)	-6.2	2.9	0.166
	B-N perp (mm) (T2)	-4.0±6.6	-2.7 (-20.6-6.6)	-7.3	-0.8	
	Sum of posterior angles (°) (T1)	394.7±5.8	392.9 (387.0-408.0)	391.9	397.6	0.616‡
	Sum of posterior angles (°) (T2)	394.1±5.2	393.8 (385.0-403.0)	391.6	396.7	

*p<0.05, Paired t-test was used; ‡p<0.05, Wilcoxon signed-ranks test was used.
SD, standard deviation; VAS, visual analogue scale; FH, Frankfort horizontal plane; Min.-Max., minimum-maximum.

Table 2. Descriptive statistics regarding orthognathic surgical movements measured by the cephalometric analysis

Orthognathic surgical movements	Parameters	Mean±SD	Median (Min.-Max.)	95% Confidence interval of the difference		p-value
				Lower	Upper	
Maxillary sagittal movements	SNA (°)	5.6±2.5	5.4 (0.8-9.6)	4.4	6.9	**<0.001‡**
	A-N perp (mm)	4.0±3.3	3.5 (-2.9-13.7)	2.3	5.6	**0.001‡**
Mandibular sagittal movements	SNB (°)	-0.6±2.2	0.0 (-4.2-3.1)	-1.7	0.6	0.312
	B-N perp (mm)	-2.4±7.0	-1.7 (- 14.0-9.0)	-5.9	1.1	0.166
Maxillomandibular sagittal movements	ANB (°)	6.2±2.3	5.8 (2.7-10.5)	5.0	7.3	**<0.001***
	Wits (mm)	8.4±4.0	7.6 (1.7-16.8)	6.4	10.3	**<0.001‡**
Maxillary vertical movement	A-FH (mm)	-0.7±3.7	-1.0 (-6.6-7.0)	-2.6	1.1	0.332
Mandibular vertical movement	B-FH (mm)	-3.1±6.3	-3.3 (-15.1-6.7)	-6.3	0	**0.049***
Mandibular rotation	Björk sum (°)	-0.6±3.7	0.4 (-10.7-4.5)	-2.4	1.2	0.616‡

*p<0.05, Paired t-test was used; ‡p<0.05, Wilcoxon signed-ranks test was used.
SD, standard deviation; VAS, visual analogue scale; FH, Frankfort horizontal plane; Min.-Max., minimum-maximum.

DISCUSSION

Cervical lordosis has been suggested to be associated with the overjet, and the mandibular position, length, and divergence.[7] Individuals with Class III malocclusion are supposed to exhibit a flexed head posture, reduced cervical lordosis, and a tendency towards posteriorization.[13,14] Since body posture and balance are closely related, the postural balance of individuals who undergo orthognathic surgery may be affected.[10] As far as we know, this is the first study to prospectively evaluate cervical lordosis, neck pain, and postural balance through static and dynamic tests using an objective measurement device such as the KAT in patients who have all undergone orthognathic surgery for the correction of skeletal Class III.

The KAT is a valid and reliable computerized balance test and training device used to assess static and dynamic balance abilities and to provide information about postural stability. It has been reported to be user-friendly and relatively affordable.[15]

The 'normal' or 'ideal' position of the cervical spine is generally considered to be a lordotic curve. Still, the exact values are uncertain depending on the measurement methods.[16] Cervical lordosis angle has been described as being within the normal range between 16-40° with the posterior tangent measurement method.[17-19] The impact of orthognathic surgery on cervical vertebrae posture was investigated in several studies.[8-10,20] In the present study, the preoperative cervical lordosis angle was 19.7°, which fell within the normal limits described in the literature and did not demonstrate a significant change following orthognathic surgery. In this case, the study population had a different lordotic structure preoperatively than that described in the broader literature for Class III patients, which may help explain the lack of significant change after surgery. Similarly, Sinko et al.[20] found no significant differences in spinal posture of Class III patients before and after orthognathic surgery. They also reported that the mouth-breathing patterns could play a more important role in head and body posture than the occlusal relationships alone. Indeed, mouth-breathing was observed to be strongly associated with the forward head posture and cervical extension.[21,22] On the other hand, de Oliveira Andriola et al.[8] found an increase in cervical lordosis angle indicating the extension of the cervical column, which might be related to compensate the deficiency in airway size following mandibular setback surgery. A compensatory increase in the craniocervical angle has also been reported in the long-term follow-up after mandibular setback surgery.[23] The differences of the findings in the present study may be attributed to the severity of the skeletal malocclusion and number of the surgical movements in the study sample.

Several factors have been identified for neck pain in adults. These include female sex, older age, a history of smoking low back pain, or previous neck pain, and the presence of other musculoskeletal disorders or psychosocial factors.[24] Since skeletal Class III patients have a flattened cervical curvature, the effect of double jaw orthognathic surgery on neck disability and pain was also examined in this study; however, no significant change was found. Even in the preoperative period, the patients' NDI scores and VAS pain scores were observed to be less than expected. The multifactorial nature of neck disability and neck pain may provide a possible explanation for these findings. Moreover, a strong relationship between temporomandibular dysfunction and neck disability has been reported in the literature.[25,26] It points to the relationship between the temporomandibular joint and neck muscles rather than the classification of skeletal malocclusion.

Balance has been defined as the ability to maintain the body's center of gravity over the base of support, which is closely related to the functioning of postural control.[6] The center of gravity in Class III patients prior to orthognathic surgery has been found to displace anteriorly. Additionally, some postural misalignments throughout the whole body have been identified in these patients, which affect the agonist and antagonist muscles and cause muscle imbalances and pain.[27] However, Paya-Argoud et al.[11] have found no significant change in the position of the center of foot pressure following orthognathic surgery. Additionally, they explained the effect of surgical correction of skeletal malocclusion on postural control using a neurophysiological theory. According to this theory, surgical improvement harmonizes the orofacial muscles and improves postural stabilization by changing mandibular proprioception and head orientation. On the other hand, Kulczynski et al.[9] identified an increased tension on the suprahyoid muscles in Class III patients generated by the reverse overjet. They have reported that orthognathic surgery can change the neck and head position by moving the chin back and decreasing the tension in the suprahyoid muscles. Correcting the occlusion from Class III to Class I can also significantly affect the adjustment of spinal posture.[9] However, the findings in this study did not show any statistically significant change in static or dynamic balance. A possible explanation for this is that the mean mandibular setback in this study was 2.4 mm, and the vertical reduction was 3.1 mm. The observed skeletal correction was primarily due to the 4 mm maxillary advancement. From a clinical perspective, the authors stated that the amount of mandibular setback was limited during surgical planning to avoid airway obstruction and to reduce the risk of soft tissue sagging under the chin. However, this approach is associated with the failure to observe significant reorganization of head and neck muscles or changes in mandibular proprioception.

Study Limitations

Limitations of this study may include the lack of assessment of the entire vertebral column and lack of assessment of the center of gravity. Additionally, the small sample size and 40% patient dropout rate from initial recruitment may have limited the generalizability of the findings, and may have failed to eliminate the high individual variability of the investigated parameters. Lastly, the lack of a nonsurgical Class III or Class I control group makes it difficult to definitively attribute the observed findings solely to surgery or to other time-dependent factors. Moreover, long-term studies are required to evaluate balance and cervical spine changes following orthognathic surgery.

CONCLUSION

Within the limitations of this study, orthognathic surgery for skeletal Class III malocclusion did not lead to significant changes in cervical lordosis, neck disability, or postural balance, as assessed through static and dynamic tests. Despite the known association between malocclusion and postural changes, the moderate surgical interventions, particularly maxillary advancement, may not have been sufficient to produce observable effects on postural alignment. These findings highlight the need for further research with larger sample sizes and more extensive surgical approaches to better understand the impact of orthognathic surgery on cervical posture and balance. Additionally, evaluating the full spinal alignment and center of gravity shifts may provide a more comprehensive insight into postural changes following such procedures.

Ethics

Ethics Committee Approval: This prospective study was approved by Başkent University Medical and Health Sciences Research Board (approval no.: D-KA19/26-19/85 date: 11.09.2019).

Informed Consent: All participants were informed about the study protocol and the consent form.

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Footnotes

Author Contributions: Surgical and Medical Practices - B.B., S.Ç.; Concept - S.İ.-B., S.Ç., O.Ü.Y.; Design - S.Ç.; Data Collection and/or Processing - E.B.; Analysis and/or Interpretation - S.İ.-B., E.B.; Literature Search - S.Ç., S.İ.-B.; Writing - S.İ.-B., S.Ç., O.Ü.Y.

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Original Article

Face Mask versus Carrière Motion® Class III Appliance: Comparison of Skeletal, Soft Tissue, and Dental Effects in Growing Individuals

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Main Points

- Both the face mask and Carrière Motion® III improve sagittal relationships in growing Class III malocclusion patients.
- The face mask produces greater maxillary advancement compared to the Carrière Motion® III.
- The Carrière Motion® III provides more controlled dentoalveolar changes.
- Both appliances have a positive impact on the soft tissue profile.
- Appliance selection should be based on whether skeletal or dental changes are prioritized.

ABSTRACT

Objective: To compare the effects of the face mask and Carrière Motion® III appliance in growing patients with Class III malocclusion associated with maxillary retrognathia. The null hypothesis was that both appliances, applied after rapid maxillary expansion, would have similar effects.

Methods: Skeletal, dental, and soft tissue changes were evaluated using lateral cephalometric radiographs of 26 patients aged 6-9 years, taken before (T0) and after treatment (T1). Cephalometric analyses were performed using Nemoceph® software (NEMOTEC, Madrid, Spain). Statistical analyses were carried out with MedCalc version 12.7.7 (MedCalc Software bvba, Ostend, Belgium) with significance set at $p<0.05$.

Results: SNA°, A-NasionPerp, and Co-A increased significantly in both groups, with no significant intergroup difference. Co-Gn, Wits, ANB°, S-N, and the articular angle also increased significantly in both groups. SNB° decreased significantly only in the Carrière Motion® III group. Greater anterior maxillary rotation occurred with the face mask, while reduced rotation was observed with the Carrière Motion® III. Lower facial height decreased slightly but significantly in the Carrière Motion® III group, and increased in the face mask group. Overjet and molar relationship improved significantly in both groups. The UL-E line distance decreased in the face mask group, while the Carrière Motion® III showed no significant soft tissue changes.

Conclusion: The null hypothesis was rejected. The two appliances had different effects; however, the Carrière Motion® III proved effective for early Class III treatment and may be considered an alternative, particularly for patients with social concerns about extraoral traction.

Keywords: Carrière Motion® appliance, class III malocclusion, face mask, rapid maxillary expansion

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INTRODUCTION

Class III malocclusion might be related to maxillary growth deficiency, mandibular overgrowth, or a combination of these two conditions. The majority of Class III malocclusion patients include maxillary retrognathia as a contributing etiologic factor; it has been previously reported that 60% of the Class III malocclusions are characterized by maxillary deficiency.[1] Meanwhile, vertical and transverse discrepancies may also be present.

Non-surgical treatment of Class III malocclusion remains challenging for orthodontists because of unpredictable growth potential and dependence on patient cooperation. However, early diagnosis and intervention for Class III malocclusion may help reduce the severity of the malocclusion in late adolescence.[2]

The Carrière Motion® appliance was designed by Doctor Luis Carrière to distalize posterior teeth as a segment and to correct the inclination of the occlusal plane.[3] It has been reported that the Carrière Motion® III appliance, when used with Class III intraoral elastics, provides distalization of the mandibular posterior teeth and causes mesialization of the maxillary dentoalveolar complex, thus moving the dentition to a Class I relationship.[4] According to our literature review, there is currently no study available in the literature comparing the effects of the Carrière Motion® III appliance with conventional maxillary protraction achieved with a face mask (FM). Within the scope of this study, we expected that the Carrière Motion® Class III appliance following rapid maxillary expansion, would contribute to correcting Class III malocclusion in growing patients. The aim of the present research was to compare the skeletal, dental and soft tissue effects of the FM and the Carrière Motion® Class III device applied following rapid maxillary expansion in growing individuals aged 6-9 years with skeletal and dental Class III malocclusion. The null hypothesis was that the effects of these two devices applied following rapid maxillary expansion would be the same.

METHODS

The study was performed at the Department of Orthodontics, Bezmialem Vakıf University Faculty of Dentistry between July 1, 2021, and September 1, 2022. The research project was approved and monitored by the Non-Interventional Research Ethics Committee at Bezmialem Vakıf University (date: November 9, 2020, approval no.: 13079). Written informed consent for participation and publication of clinical images was obtained from the patients' legal guardians in accordance with the institutional ethical standards and the Declaration of Helsinki.

Based on a power analysis conducted using data from the study by Keles et al.,[5] which reported a significant 3.11° change in the SNA angle following maxillary expansion and protraction, a minimum of 11 individuals in each group was required to reach a 95% confidence level with a Type I error of 0.05 and a power of 80%. Considering potential participant losses, determined that at least 14 individuals should be included in each group.

The inclusion criteria for the study were as follows: being aged between 6 and 9 years old, having a negative (up to -4mm) or edge-to-edge incisor relationship, having no severe crowding, having no previous orthodontic treatment history, and having no systemic disease, syndrome etc. that may interfere with orthodontic treatment. Patients who were conveniently allocated to the Carrière Motion® group were required to have at least two-thirds of their lower deciduous canines present. This criterion was assessed using periapical radiographs.

Some data from the individuals included in the FM group (n=6) were collected from the archive of the Bezmialem Vakıf University Department of Orthodontics using the same inclusion criteria.

Rapid maxillary expansion was performed for at least seven days with a McNamara type acrylic cap expander, and the patients were instructed to turn the screw one-quarter-turn twice a day till the desired expansion was achieved. After the expansion, patient treatment was continued with either a FM or a Carrière Motion® III appliance.

The distance from the midpoint of the buccal surface of the mandibular first molar to the mesial one-third of the mandibular primary canine crown was measured with a special ruler to determine the appropriate Carrière Motion® III size. The appliance was bonded according to the recommended bonding procedure. Ormco™ (Glendora, CA, USA) intermaxillary elastics producing 1/4″ 6.0 oz force (Ram) were used between the Carrière Motion® appliance and the hook at the posterior of the expansion device. Patients were instructed to use the elastics for 24 hours except while eating (Figures 1 and 2).

The elastics of the FM were positioned at an angle of 30° to the occlusal plane. The force magnitude was adjusted with an extraoral force gauge to provide 450 grams. The patients were instructed to use their appliances for 12-14 hours a day (Figures 3 and 4).

In both groups, the sagittal correction was completed when a Class II canine relationship was achieved, and the appliances were removed. For the retention phase, patients were instructed to wear the Class III Bionator for at least 12 hours per day over a period of 12 months. Follow-up visits were scheduled at 3-month intervals to monitor compliance and ensure treatment stability.

Lateral cephalometric radiographs were taken before treatment (T0) and after the removal of the expansion appliances (T1). Cephalometric analyses were carried out with the Nemoceph® (Nemotec Software, Madrid, Spain) software.

Figure 1. Intraoral records of a patient from Carrière group; a) Pretreatment, b) Before removal of the appliances, c) Posttreatment.

Figure 2. Extraoral records of a patient from Carrière group; a) Pretreatment, b) Posttreatment.

Figure 3. Intraoral records of a patient from FM group; a) Pretreatment, b) Before removal of the appliance, c) Posttreatment.
FM, face mask.

Figure 4. Extraoral records of a patient from FM group; a) Pretreatment, b) Posttreatment.
FM, face mask.

During the study, the lower deciduous canines of two children wearing the Carrière Motion® appliance could not withstand the forces and began to show mobility. These two children were excluded from the study and their treatment continued with a FM.

Statistical Analysis

Descriptive analyses were used to describe continuous variables. Mean and standard deviation values are given for normally distributed data, and median values for non-normally distributed data. The relationship between two dependent, non-normally distributed continuous variables was examined using the Wilcoxon Signed Rank test. The relationship between two independent, non-normally distributed continuous variables was examined using the Mann-Whitney U test. The statistical significance level was set at 0.05. Analyses were performed using MedCalc Statistical Software version 12.7.7 (MedCalc Software bvba, Ostend, Belgium; http://www.medcalc.org; 2013).

RESULTS

There was no statistically significant difference between the groups in which the Carrière Motion® appliance (Carrière) and the FM were used, in terms of gender and age (p>0.05) (Table 1). The total treatment duration was 225±72 days in the facemask group and 256±83 days in the CMIII group.

The comparison between groups according to the cervical vertebral maturation (CVM) stage is presented in Table 2. No statistically significant difference was found in the comparison between groups according to the CVM stage (Table 2).

The comparison of the skeletal parameters within and between groups (Carrière and FM) revealed statistically significant changes (Table 3). Co-A, SNA°, NperpA, Co-Gn, Wits, ANB°, and S-N showed a statistically significant increase between T0 and T1 in both groups. The SNB° decreased significantly from T0 to T1 only in the Carrière Motion® group (Table 3).

Besides those sagittal parameters, some vertical skeletal parameters such as ANS-Me, N-Me, S-Go, and the articular angle also showed a statistically significant increase. N-ANS and FH-MP° showed a statistically significant increase from T0 to T1 only in the Carrière Motion® group, while a significant increase was observed in the FH-PP° only in the FM group. There was no statistically significant difference between the two groups in the FH-PP° value comparison at T0, but there was a statistically significant difference between the two groups at T1.

Table 4 compares dental parameters within and between the Carrière and FM groups. Overjet and molar relationship showed statistically significant differences between T0 and T1 in both groups. There was a significant decrease in L1-A/Pg in both groups. The U1-A/Vert showed a statistically significant increase from T0 to T1 only in the Carrière Motion® group. While there was no statistically significant difference between the groups at T0 in overjet, L1-A/Pg, or the Holdaway ratio, there was a significant difference between the groups at T1. While the amount of overjet increased more in the FM group, the L1-A/Pg distance decreased more in the FM group. In the Carrière Motion® group, the Holdaway ratio increased, whereas in the FM group, it decreased (Table 4).

The U1-A/Vert increased in both groups, but only the Carrière Motion® group showed a significant difference within group comparisons. For several parameters, there were statistically significant differences between the two groups at T1. Table 5 compares the soft tissue parameters within and between the Carrière and FM groups. The UL-E line value significantly increased only in the FM group. None of the soft tissue parameters seemed to be affected by the Carrière Motion appliance (Table 5).

Twenty lateral cephalograms were randomly retraced after a 2-week interval by the same examiner to assess measurement reliability. Intra-examiner error, calculated using Dahlberg's formula, was within clinically acceptable limits (<0.5 mm for linear and <0.5° for angular measurements). The intraclass correlation coefficient values were ≥0.90, indicating excellent reliability.

Table 1. Demographic comparisons between groups using Carrière and FM

	Carrière n=12	FM n=14	Total n=26	p-value
Gender				1.000[1]
Male	5 (41.6%)	7 (50%)	12 (46.1%)	
Female	7 (58.3%)	7 (50%)	14 (53.8%)	
Treatment age/year				0.818[2]
Mean±SD	7.9±0.8	7.6±1.3	7.7±1.1	
Med (Min.-Max.)	8 (6-8.8)	8 (4.7-9.1)	8 (4.7-9.1)	

[1]Continuity correction; [2]Mann-Whitney U test (p<0.05*) (p<0.01**)
FM, face mask; SD, standard deviation; Min.-Max., minimum-maximum.

Table 2. Comparison between groups according to the CVM stage

	CS1 n=16	CS2 n=10	Total	p-value
Gender n (%)				0.212[1]
Male	9 (56.2)	3 (30)	12 (46.1)	
Female	7 (43.7)	7 (70)	14 (53.8)	
Treatment age/year				0.347[2]
Mean±SD	7.6±1.2	8.0±0.9	7.7±1.1	
Med (Min.-Max.)	8 (4.7-9.1)	8 (6-8.9)	8 (4.7-9.1)	
Carrière/FM n (%)				1.00[1]
Carrière	7 (43.7)	5 (50)		
FM	9 (56.2)	5 (40)		

[1]Continuity correction; [2]Mann-Whitney U test (p<0.05*).
SD, standard deviation; Min.-Max., minimum-maximum.

Table 3. Intra- and inter-groups comparisons of the skeletal parameters

	T0	T1	p-value
Saddle angle (°)			
Carrière	124.9±5.1	124.2±4.9	0.302
	126 (116-133)	124.5 (116-132)	
FM	124±5.3	123.2±4.5	0.263
	124.5 (112-135)	123 (111-130)	
P	0.504	0.678	
Co-A (mm)			
Carrière	70.6±3.5	72.6±4	**0.001*****
	70.9 (61.2-75.3)	72.9 (62.7-78)	
FM	70.4±3.8	75±4.2	**<0.001*****
	71 (63.9-75.5)	74.8 (64.4-82)	
P	0.872	0.148	
SNA (°)			
Carrière	78.3±3.5	79.5±3.5	**0.026***
	78 (69-84)	80 (71-85)	
FM	78.9±4.4	81.1±3.7	**0.009****
	79 (70-87)	81.5 (75-88)	
P	0.517	0.310	
A-Nperp (mm)			
Carrière	-3.6±2.8	-2.3±3	**0.021***
	-3.6 (-10.2-1.2)	-2.3 (-9.1-2)	
FM	-2.7±3.8	-1.0±3.3	**0.013***
	-2.6 (-10.2-4.1)	-0.5 (-6-5.2)	
P	0.382	0.408	
Co-Gn (mm)			
Carrière	94±4	96.7±5.1	**0.005****
	94.3 (84.7-101.5)	96 (84.7-105.5)	
FM	96.6±3.8	99.6±4.6	**0.002****
	97.1 (88.9-101.9)	100.3 (88.6-106.7)	
P	0.054	0.108	
SNB (°)			
Carrière	78.2±2.5	77.2±3.1	**0.017***
	79 (72-82)	77.5 (71-82)	
FM	79.2±3.2	78.3±2.6	0.127
	80 (74-84)	78 (73-82)	
P	0.286	0.392	
Pg-Nperp (mm)			
Carrière	-6.5±5.6	-7.4±4.4	0.221
	-6.2 (-17.8-3.1)	-7.8 (-17.7-1.2)	
FM	-5.7±5.7	-5.9±5.7	0.650
	-4.2 (-16.8-3.6)	-6.2 (-16.8-6.1)	
P	0.646	0.535	

Table 3. Continued

	T0	T1	p-value
Gonial angle (°)			
Carrière	125.8±9.0	125.9±8.1	0.964
	126 (111-142)	126.5 (111-140)	
FM	126.1±8.1	125.9±8.9	0.719
	125 (114-143)	125 (113-146)	
P	0.908	0.963	
Wits (mm)			
Carrière	-4.0±3.1	-2.2±2.2	**0.021***
	-5.2 (-8.5-0.9)	-2.0 (-5.1-1.5)	
FM	-5.9±2.3	-2.6±2.1	**0.001*****
	-5.6 [-11-(-2.1)]	-2.8 (-6.3-1.2)	
P	0.215	0.662	
ANB (°)			
Carrière	-0.1±2.2	2.3±2.4	**0.001*****
	-0.5 (-4-4)	3 (-4-5)	
FM	-0.4±2.3	2.8±1.8	**<0.001*****
	-0.5 (-5-3)	3 (0-6)	
P	0.870	0.798	
FH-occlusal plane (°)			
Carrière	10.9±4.1	10.5±3.1	0.782
	10.5 (5-18)	11.0 (3-15)	
FM	12.3±3.8	10.9±4	0.128
	12.5 (5-18)	11 (2-18)	
P	0.433	0.625	
FH-palatal plane (°)			
Carrière	1.6±2.6	0.8±2.5	0.225
	2 (-3-6)	0.5 (-3-5)	
FM	0±2.9	-1.7±3.2	**0.020***
	-0.5 (-5-5)	-2 (-7-4)	
P	0.165	**0.023***	
Mandibular plane angle (MPA) (°)			
Carrière	25.7±6.2	26.6±5.3	0.098
	26 (15-38)	28 (17-33)	
FM	25.5±6.5	26.4±6.7	0.237
	24.5 (13-39)	24.5 (16-39)	
P	0.982	0.963	
N-ANS (mm)			
Carrière	44.2±2.6	45.6±2.6	**0.005****
	43.7 (40.4-48.9)	45.1 (41.9-50.4)	
FM	43.1±2.6	44.1±3	0.084
	43.3 (37.1-47)	44.4 (38.8-48)	
P	0.395	0.358	

Table 3. Continued

	T0	T1	p-value
ANS-Me (mm)			
Carrière	58.9±21.2	58.6±11.4	**0.019***
	53(40.4-130)	55(40-90)	
FM	64±30.6	67.9±32.4	**<0.001*** **
	55.9 (51-170)	59 (54.1-180)	
P	0.241	0.118	
SN-occlusal plane (°)			
Carrière	19.4±4.2	17.8±5	0.167
	21 (12-26)	19 (8-23)	
FM	19.8 ±3.7	18.4±4.3	0.106
	20.5 (13-25)	18.5 (8-26)	
P	0.853	0.871	
FH-MP (°)			
Carrière	26.6±5.4	27.9±4.4	**0.049***
	25.5 (18-38)	29 (19-33)	
FM	26.8±6.2	27.7±6	0.242
	26.5 (15-39)	27 (18-39)	
P	0.836	0.872	
Maxillary height (°)			
Carrière	56.9±3.5	57.9±3.6	0.146
	57.5 (51-63)	57.5 (52-67)	
FM	55.5±2.4	55.3±3.4	1.000
	56 (51-59)	57 (50-60)	
P	0.340	0.131	
Maxillary depth angle (°)			
Carrière	86±3.8	87.6±3.4	0.052
	86 (77-93)	88 (80-92)	
FM	86.3±4.6	89.1±3.8	**0.005****
	86.5 (78-95)	90 (83-96)	
P	0.799	0.267	
N-Me (mm)			
Carrière	94.1±9.5	98.4±10.3	**<0.001*****
	94.9 (65.2-106.5)	99.3 (67.1-110.8)	
FM	97.5±5.2	101.7±5.9	**0.002****
	98.9 (88.6-108)	101.3 (93.1-115)	
P	0.270	0.476	
S-Go (mm)			
Carrière	66.8±10.8	69.5±12	**0.002****
	65.4 (57.7-101.7)	67.2 (58.7-108.3)	
FM	65.2±5.1	67.5±5	**0.010****
	64.4 (57.7-73.9)	66.9 (59.1-77.2)	
P	0.927	0.909	

Table 3. Continued

	T0	T1	p-value
SN-FH (°)			
Carrière	7.9±1.6	8±1.9	0.951
	7.5 (7-13)	7.5 (6-14)	
FM	7.4±0.5	7.6±0.5	0.317
	7 (7-8)	8 (7-8)	
P	0.600	0.920	
S-N (mm)			
Carrière	60.3±2.7	61.5±2.6	**0.018***
	59.7 (55.9-65.5)	60.9 (57-67.2)	
FM	60.3±2.3	61.8±2	**0.005****
	60.3 (55.9-65.3)	62.3 (57-64.5)	
P	0.696	0.490	
Articular angle (°)			
Carrière	141.6±6.6	144.2±6.4	**0.013***
	141.5 (130-154)	145 (132-153)	
FM	143.2±8.8	145.6±8.3	**0.018***
	143 (130-161)	146 (129-160)	
P	0.645	0.730	

[1]Wilcoxon signed-rank test; [2]Mann-Whitney U test (p<0.05*) (p<0.01**) (p<0.001***)

DISCUSSION

When selecting patients to be included in the present study, care was taken to ensure that both groups' participants had Class III malocclusions with maxillary retrognathia but no significant mandibular prognathia. The sagittal position of the maxilla and mandible was verified by evaluating the related parameters on the lateral cephalometric radiographs (SNA°, SNB°, A-NasionPerp).

In the Carrière group, careful consideration was given to the root resorption status of the lower deciduous canines to ensure adequate resistance to Class III elastic forces. Nevertheless, our findings indicated that the absence of teeth between the canines and molars compromised direct force transmission, increasing the risk of appliance debonding. This problem may also be explained by the short crown length of the anchoring teeth and the challenges of maintaining adequate isolation in pediatric patients.

Although the appliance was initially assumed to function as a space maintainer in cases with missing posterior teeth, these patients demonstrated increased mobility and extrusion of the deciduous canines, most likely due to uneven force distribution. As a result, two patients had to be excluded from the study and were subsequently managed with facemask therapy.

In Class III cases, the Carrière system recommends Force 1 elastics (1/4" 6.0 oz-340 grams), avoiding the use of higher-force Force 2 elastics.[6] This is due to the shorter and smaller

Table 4. Intra- and inter-groups comparisons of the dental parameters

Overbite (mm)	T0	T1	p-value
Carrière	1.1±2.5	0.7±1.9	0.553
	1.2 (-3.2-3.7)	0.9 (-3.2-3.9)	
FM	1.5±1.9	2±1.3	0.183
	1.7 (-1.8-4)	1.9 (-0.3-4.3)	
P	0.908	0.068	
Overjet (mm)			
Carrière	-1.9±1.1	2.3±1.3	**0.018***
	-1.9 [-4-(-0.7)]	2.5 (-0.3-5.2)	
FM	-0.7±1.8	3.5±1.2	**0.012***
	-1 (-2.6-2.9)	3.6 (1.1-5.7)	
P	0.353	**0.022***	
Interincisal angle (°)			
Carrière	134±13.3	134.6±7.2	0.610
	135 (108-153)	135 (121-147)	
FM	138±9.1	138.6±6.2	0.933
	136.5 (124-154)	137.5 (129-148)	
P	0.601	0.200	
Molar relationship (mm)			
Carrière	-1.7±1.6	-0.3±1.8	**0.020***
	-1.5 (-4.8-0.6)	-0.7 (-2.6-3.3)	
FM	-2.6±2.9	0.1±2.1	**0.001****
	-1.9 (-8.3-0.8)	0.3 (-3.9-3)	
P	0.679	0.890	
U1-A/Vert (mm)			
Carrière	17.2±3.3	19.5±1.8	**0.018***
	17.4 (10.6-20.7)	18.8 (17-22.9)	
FM	20.2±2.1	21.1±1.5	0.161
	20.3 (17.4-23.4)	21.3 (17.8-23.7)	
P	**0.037***	**0.047***	
U1-FH (°)			
Carrière	108.9±9.9	109.8±6.5	0.351
	108 (97-127)	109 (97-120)	
FM	108.3±9.9	109.6±5.5	0.140
	105.5 (96-122)	109 (103-122)	
P	0.908	0.848	
L1-A/Pg (mm)			
Carrière	3.2±1.5	2±1.3	**0.009****
	3 (0.8-5.8)	2.4 (-0.1-3.6)	
FM	3.2±1.8	0.9±1.6	**0.001*****
	3.3 (0.3-6.6)	0.9 (-1.5-4.2)	
P	0.927	**0.036***	
L1-MPA (°)			
Carrière	87.6±8.8	87.3±7.8	0.833
	87 (73-104)	86 (74-100)	
FM	86.5±6.8	84.2±7.7	0.058
	84 (79-101)	85 (74-100)	
P	0.712	0.333	

Table 4. Continued

Overbite (mm)	T0	T1	p-value
Holdaway ratio (/)			
Carrière	2.4±12.1	6.1±14.6	0.650
	0.2 (-15.6-28)	4.1 (-20-44)	
FM	4.7±19.7	-3.5±12.7	0.245
	-0.5 (-24-63)	0.6 (-43-10)	
P	0.963	**0.022***	
U1/SN (°)			
Carrière	100.9±10.2	101.8±7.5	0.310
	100 (89-121)	101 (89-113)	
FM	100.5±9.7	101.9±5.9	0.141
	98 (89-114)	101 (96-116)	
P	0.954	0.827	
U1/Palatal plane (°)			
Carrière	110.1±10.2	110.8±7.6	0.173
	110 (96-129)	108 (97-123)	
FM	108.1±8.7	107.7±4.9	0.610
	107 (97-120)	108 (97-115)	
P	0.908	0.478	
U1/Occlusal plane (°)			
Carrière	60.4±7.1	59±4.8	0.248
	61 (47-70)	58 (50-67)	
FM	59.5±6.7	60.5±3.3	0.888
	61.5 (49-67)	61 (55-65)	
P	0.954	0.367	
L1/Occlusal plane (°)			
Carrière	75.9±7.5	76.5±5.9	0.549
	74.5 (61-90)	75.5 (67-88)	
FM	78.9±6.2	79.1±4.5	0.861
	77.5 (69-89)	78.5 (73-88)	
P	0.268	0.181	

[1]Wilcoxon signed-rank test; [2]Mann-Whitney U test; (p<0.05*) (p<0.01**) (p<0.001***)

roots of the lower canines and the more cortical structure of the mandible. In a small subset of our patients, increased mobility and extrusion of deciduous canines were observed with Force 1 elastics, necessitating the use of Ram elastics (6 Oz, 1/4" diameter) 24 hours a day, except during meals. These findings underscore the importance of adapting elastic protocols to individual dental anatomy and patient characteristics.

Co-A, SNA° and A-Nasionperp, which determine the sagittal position of point A, showed a significant increase in both groups. This might be explained by the forward movement of point A with the combined effects of treatment and growth. These results are consistent with previous studies evaluating protraction using a FM.[7-13]

An et al.[14] applied the Carrière Motion® and Tandem appliances to two 8-year-old patients and reported that SNA° and

Table 5. Intra- and inter-groups comparisons of the soft tissue parameters

UL-E line (mm)	T0	T1	p-value
Carrière	-1.5±1.8	-1±1.5	0.099
	-1.4 (-5.1-3.1)	-1.1 (-4.6-2.1)	
FM	-1.8±1.7	-0.5±1.3	**0.005****
	-1.8 (-5-1.2)	-0.4 (-2.6-1.6)	
P	0.836	0.357	
LL-E line (mm)			
Carrière	1.6±1.4	1.2±1.9	0.593
	1.4 (-1.3-4.1)	1.3 (-2.3-4.4)	
FM	0.9±1.6	0.3±1.7	0.402
	0.8 (-1.4-3.7)	-0.1 (-2.3-4.3)	
P	0.198	0.154	
Nasolabial angle (°)			
Carrière	111.1±14.3	111.7±12	0.753
	108 (79-133)	110.5 (87-136)	
FM	110.3±12.7	110.4±13.9	0.420
	113 (87-131)	109.5 (94-135)	
P	0.747	0.679	

[1]Wilcoxon signed-rank test; [2]Mann-Whitney U test (p<0.05*) (p<0.01**)

A-Nasionperp values increased more with the Carrière Motion® appliance. On the other hand, in a study that used the Carrière Motion® appliance to treat patients with Class III malocclusion in the permanent dentition, there was no statistically significant difference observed in the parameters describing the sagittal change of the point A during the 6.3 month of the sagittal correction phase of the treatment.[15] However, there was a significant increase in Wits and ANB° and these changes were thought to be caused by the change in point B.

In the present study, Co-Gn increased statistically significantly in both groups. This result is consistent with those of Cozza et al.[8] and Chong et al.[16] An increase in Co-Gn was also observed in McNamara et al.'s[18] study, which examined the effects of the Carrière Motion® appliance in patients with Class III malocclusions in individuals with at least the 4th CVM stage. Similar findings were found in our investigation, and we may speculate that growth was the cause of the increase in Co-Gn.

SNB° decreased significantly in the Carrière group, but the decrease in the FM group was not statistically significant. The decrease in SNB° recorded in the Carrière group coincides with studies reporting that point B was moved backward with the use of a FM and the mandible was rotated posteriorly, reducing the mandibular projection.[8,9,17] While no significant difference was found in the MPA° value in the comparison between and within the groups, a significant difference was found within the group in the Carrière group in the FH-MP° value. This can be explained by the fact that the cGo point referenced when creating the mandibular plane is different from the Go point in MPA value, but the significant difference recorded in this value is quite small (1.3°). Contrary to our findings, in An et al.'s[17] report comparing the effects of Carrière Motion® and Tandem appliances, a higher SNB° value was reported with the Carrière Motion® appliance. McNamara et al[15] determined that the SNB° decreased as in our study, and reported that the mandibular plane inclination (FH-MP°) did not show a statistically significant difference. In this context, the change in the SNB angle in our study is consistent with the significant increase in the FH-Mandibular plane angle.

In studies evaluating the effects of the Carrière Motion® II appliance, which works with biomechanics opposite to Class III correction, significant reductions in ANB° and Wits were observed.[3,18-20] On the other hand, ANB° and Wits showed a significant increase in studies on the Class III appliance.[14,15] In the present study, the increase in ANB° and Wits in both groups can be explained by the increase in SNA°; additionally, in the Carrière group, the decrease in SNB° also contributed to this increase.

The FH-PP° of the FM group decreased from T0 to T1 statistically significantly, this decrease was not significant for the Carrière group. The application of higher forces and the shorter duration of daily usage in the FM group. In other words, the orthopedic effects, can explain why the anterior rotation of the maxilla with the use of a FM might be related to this difference between groups. The elastics used in the Carrière group may have caused less anterior rotation of the palatal plane due to the weaker forces, and the 24-hour usage might have led to more dental effects.[21]

The lower anterior facial height showed a statistically significant decrease in the Carrière group. On the other hand, a significant increase was found in the FM group. The reason for the decrease in the Carrière group might be the counterclockwise rotation of the occlusal plane. Studies evaluating the Carrière Motion® Class II appliance have shown a significant increase in lower anterior facial height.[3,18-20] With reverse biomechanics, counterclockwise rotation in the occlusal plane could be expected with a Class III appliance. In contrast, McNamara et al,.[15] observed an increase in lower anterior facial height when using the Carrière Motion® appliance for Class III malocclusion, which is not in harmony with our findings. However, these authors also reported significant counterclockwise rotation in the occlusal plane. Based on these findings, it might be reasonable to assume that counterclockwise rotation of the occlusal plane was not statistically significant, and counterclockwise rotation in the mandibular plane was not detectable due to early contacts present in the majority of the x-rays in our study, since T1 radiographs were taken just after the removal of the expansion devices, following the completion of the sagittal correction. Furthermore, the decrease in ANS-Me in both groups may help explain this finding, which was possibly induced by the posterior intrusion caused by the acrylic cap splint expansion device followed by mandibular anterior rotation.

The N-ANS value in our study increased in both groups, but the increase was statistically significant only in the Carrière group.

This change can be explained by the fact that the individuals in both groups showed anterior and downward growth of the maxilla during the treatment process. In addition, a significant counterclockwise rotation was observed in the FH-PP° in the FM group. This rotation was not significant in the Carrière group. Consistent with the rotation observed in the palatal plane, in the FM group, the increase in the N-ANS distance was not significant, possibly related to the anterior rotation of the maxilla. Similar to the N-ANS parameter, the FH-MP° increased in both groups, but the change was statistically significant only in the Carrière group. This can be explained by the posterior vertical control that occurs with the use of an acrylic cap-splint device. This result is similar to the results of McNamara et al.[15]

The maxillary depth angle, which is an important parameter to evaluate the sagittal position of the maxilla, increased in both groups, but the amount of increase was statistically significant only in the FM group. In our study, an increase in SNA° was also observed in both groups. Although there was no statistically significant difference in the increase in SNA° between the two groups, the increase in the FM group (2.2°) was greater than that in the Carrière group (1.2°), which may have affected the maxillary depth parameter.

In our study, anterior and posterior facial heights (N-Me and S-Go) showed a statistically significant increase in both groups. The distance between Sella and Nasion (S-N) increased significantly in both groups, as did the articular angle. All these changes might be related to the growth of the individuals included in the study sample. It can be assumed that there may be deviations in vertical values due to early contacts in the patients' occlusion, and parameters related to the position and rotation of the lower jaw may be affected since T1 lateral cephalometric radiographs were taken immediately after removal of the acrylic cap type expansion appliances. This issue may be considered a limitation of the study. After the occlusion has settled, lateral cephalometric X-rays may be repeated to assess changes at this stage.

The overjet showed a significant increase in both groups. This finding is supported by the findings of many authors who reported anterior movement of point A, an increase in overjet, and amelioration of the sagittal relationship of the upper and lower jaws.[8,17,22,23] There are also studies reporting retroclination of the lower incisors as well as the anterior movement of the upper incisors contributing to the overjet correction in Class III individuals.[24,25] In the paper by An et al.,[14] an increase in the overjet was found in both Tandem and Carrière appliances. A significant increase in overjet was observed by McNamara et al.[15] in an older group of Class III individuals. All these findings are in harmony with our results. The significant increase in the overjet in both groups in our study indicates that the increase in the parameters determining the sagittal position of the maxilla causes the upper incisors to move forward. In addition, a decrease was observed in L1-A/Pg in both groups, while the decrease in this distance was statistically greater in the FM group. In addition, while the L1-MPA° value was almost unchanged in the Carrière group, it showed a greater change, close to the significance level, in the FM group. This indicates that the lower incisors inclination was preserved in the Carrière group since there is no pressure-causing-chin pad in the design of the Carrière appliance.

Another dental parameter, the molar relationship, increased statistically significantly in both groups in our study. In studies by Yin et al.[3] and Kim-Berman et al.,[18] in which Class II malocclusion corrections were achieved with the Carrière Motion® appliance, significant improvements were observed in the molar relationship, similar to the findings of our study.

The change in the U1-A/Vert parameter increased significantly in the Carrière group, but the increase in the FM group was not statistically significant. Although the inclination of the upper incisors did not change significantly in both groups, the movement of the true vertical line, which moves forward with growth, was accompanied by proclined upper incisors in the FM group. The less proclination observed in the Carrière group may help to explain this difference. Another explanation might be that the change in SNA° was greater in the FM group, and the incisors in the FM group were able to move more forward to maintain the U1-A/Vert distance.

In our study, the L1-A/Pg parameter showed a significant decrease in both groups. We can assume that the distalization of the posterior segment caused traction of the transseptal fibers that also distalized the lower incisors in the Carrière group. A greater amount of decrease in the L1-A/Pg distance was recorded in comparison between groups. This finding might be related to the fact that the lower incisors retroclined more in the FM group, causing a greater decrease in the L1-A/Pg distance, because of the pressure applied by the chin pad of the FM.[21]

In our study, some individuals had deciduous incisor teeth at the beginning of the treatment. In some patients, deciduous incisor teeth were lost during the treatment. These patients' data were excluded from the comparison since the parameters determined for permanent and deciduous teeth are different. Hence, the number of samples (Carrière: n=7; FM: n=8) should be taken into consideration when evaluating the overbite, overjet, interincisal angle, U1-A/Vert, U1-FH°, U1/SN°, and U1/Palatal Plane° parameters.

The UL-E-line distance decreased in both groups, but the decrease was statistically significant only in the FM group. The larger forces applied by the orthopedic appliance and the fact that these larger forces were more effective on the basal portion of the alveolar process suggest that the change in the perioral tissues was more pronounced in the FM group.

The 6-9 year age group was chosen because this stage corresponds to the early mixed dentition period, during which orthopedic modification of maxillary growth is considered most effective. Previous studies have shown that facemask therapy produces the most favorable skeletal effects when initiated at an early age.[9,10,22] Likewise, the Carrière Motion® III appliance has been reported to be more effective in growing patients due to the responsiveness of craniofacial structures during active growth.[15,21]

Study Limitations

This study has some limitations that should be considered. The relatively small sample size, which was further reduced due to the early loss of deciduous teeth, limits the generalizability of the results. Furthermore, the combined use of prospective and retrospective data may be a source of methodological bias, and the relatively short follow-up period prevents definitive conclusions about long-term treatment stability. Although FM has long been used in the early treatment of Class III malocclusions due to its strong skeletal effects and predictable clinical outcomes, and CMIII produced similar results, the limited sample size in the present study prevented the true differences between the two appliances from being fully revealed. Moreover, the absence of patient-specific and distance-based elastic selection in the CM group can be considered a limitation, as it prevents standardization of force application.

In the present study, the mean treatment duration was approximately 225±72 days in the FM group and 256±83 days in the CMIII group. These findings are consistent with previously reported treatment durations for orthopedic correction of skeletal Class III malocclusion. The relatively comparable values suggest that both approaches require a similar clinical timeframe, which should be taken into account when considering their efficiency and applicability in daily practice. Another clinically important factor is patient compliance, particularly with regard to elastic wear and appliance maintenance. Although compliance was monitored during routine follow-up visits, no objective compliance measurement tool was implemented in this study. This limitation should be acknowledged, as compliance directly affects treatment outcomes. Future studies incorporating standardized compliance assessment methods (e.g., wear-time sensors or patient-reported diaries) could provide more accurate insights into the impact of compliance on treatment effectiveness.

Future studies with larger sample groups, randomized designs, and long-term follow-ups are needed to validate and expand these findings. In addition, incorporating factors such as patient compliance, appliance wear time, treatment stability, and retention protocols into future investigations is strongly recommended.

CONCLUSION

The dental, skeletal, and soft tissue effects of the FM and the Carrière Motion® Class III appliance used following rapid maxillary expansion were compared in children aged 6 to 9 years with Class III malocclusion.

Within the limitations of this study, both appliances were effective in improving skeletal and dental relationships in growing Class III patients. While the FM produced more pronounced maxillary rotation and dentoalveolar effects, the Carrière Motion® Class III appliance corrected sagittal discrepancies with better preservation of lower incisor inclination and reduced dependence on an extraoral device. These findings suggest that the Carrière Motion® Class III may serve as a practical treatment alternative, particularly in patients who refuse extraoral appliances or when maintaining lower incisor position is a clinical priority. Future long-term studies are required to evaluate the stability of these outcomes and to further clarify the comparative skeletal and soft tissue effects of the two approaches.

Ethics

Ethics Committee Approval: The research project was approved and monitored by the Non-Interventional Research Ethics Committee at Bezmialem Vakıf University (date: November 9, 2020, approval no.: 13079).

Informed Consent: Written informed consent for participation and publication of clinical images was obtained from the patients' legal guardians.

Footnotes

Author Contributions: Surgical and Medical Practices - M.P., B.Y.; Concept - M.P., B.Y.; Design - M.P., B.Y.; Data Collection and/or Processing - M.P., B.Y.; Analysis and/or Interpretation - M.P., B.Y.; Literature Search - M.P.; Writing - M.P.

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Original Article

Orbital Compartment Stress Responses Related to Rapid Maxillary Expansion: A Finite Element Analysis

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Main Points

- Stress, particularly around the orbital compartment, increases with bone ossification; however, this can be reduced by using a hybrid device.
- Significant stresses occur at the superior orbital fissure and optic foramen, through which the oculomotor nerve and the optic nerve pass.
- Increased ossification reduces displacement but elevates Von Mises stresses, thereby increasing the risk of neurovascular compression.

ABSTRACT

Objective: This study aimed to use finite element analysis to evaluate the effects of acrylic HYRAX and hybrid HYRAX devices in the treatment of rapid maxillary expansion (RME), particularly on the orbital compartments.

Methods: In the present study, a craniofacial model was developed utilizing computed tomography data obtained from the visible human project. A total of four distinct models were generated by designating the sutures in the adult variation as closed and those in the non-adult variation as open while incorporating both expansion devices into the model. Both acrylic and hybrid device models were subjected to expansion forces of 0.25 mm and 5 mm, yielding eight distinct scenarios for comprehensive analysis.

Results: Significant stress and displacement were observed, particularly around the orbital compartments in all scenarios. Displacement decreased with increased sutural ossification and the resulting stresses demonstrated elevation. In adult models, the hybrid device generated reduced stress, especially around the orbital compartments.

Conclusion: Based on these findings, it is proposed that the orbital compartments may serve as a clinically relevant site for measuring the increased intracranial pressure during RME treatment. To prevent possible side effects, RME should be performed at an early age, and if ossification is suspected to be increased, bone-supported expansion devices are recommended.

Keywords: Hybrid HYRAX, orbital compartment stress, FEA, RME

INTRODUCTION

Transversal maxillary deficiency is among the most common skeletal problems in the craniofacial region.[1] The concept of separating the maxillary halves through rapid maxillary expansion (RME) was first introduced by E.H. Angell in 1860. Currently, a variety of appliances are used for this purpose, including tooth-supported, tooth-and-tissue-supported, hybrid (tooth-and-bone-borne), and bone-supported appliances. During tooth-supported RME, orthopedic forces of up to 100 N have been reported,[2] with effects transmitted not only to the maxilla but also to adjacent cranial bones through their associated sutures.[3] In animal studies involving rhesus monkeys, increased cellular activity was observed not only in the maxilla but also in the nasal, zygomaticomaxillary, and zygomaticotemporal sutures adjacent to the maxilla.[4] Furthermore, sutural separation has been observed even

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in the lambdoid and parietal sutures, and spheno-occipital synchondrosis.[5]

Maturation of the midpalatal suture, which progresses with the completion of growth, reduces the potential for transverse expansion.[6] As this maturation increases, the forces generated during RME are increasingly transmitted to surrounding craniofacial structures. One region that may be particularly susceptible to these stresses is the eye-maxillary complex, including the orbital floor, infraorbital rim, and maxillary sinus, where even minor skeletal changes could potentially affect orbital support and surrounding neurovascular pathways. Increased mechanical stress in these areas can lead to deformation of adjacent bones, elevated risk of fracture, and potential damage to critical vascular and nerve structures.[7] Reports have also indicated hemodynamic alterations within the brain during RME,[8] along with clinical observations of orbital volume increases and associated elevations in intracranial pressure (ICP), which may result in symptoms such as headache and diplopia.[9,10]

Given the complexity of these anatomical relationships, direct clinical evaluation of such effects remains challenging. Finite element analysis (FEA), an engineering method designed to calculate stress and deformation in complex structures, provides a reliable approach for evaluating these biomechanical changes. It has become a widely applied tool in biomedical research and is increasingly used in orthodontics to model craniofacial responses under various treatment modalities.[11]

Previous FEA studies have assessed the impact of both conventional tooth-supported (acrylic-coated HYRAX) and tooth-bone-supported (hybrid HYRAX) devices on cranial structures. However, their specific effects on the orbital compartment have not been systematically examined. One of the most accessible and non-invasive methods for evaluating changes in ICP is the measurement of the optic nerve sheath diameter (ONSD).[12]

Because the orbital compartment is closely related anatomically to the maxilla and serves as the most clinically feasible site for noninvasive ICP assessment, evaluating its response to RME is essential for determining whether such measurements accurately reflect pressure changes induced by expansion. Therefore, this study aimed to evaluate the effects of acrylic and hybrid HYRAX devices on stress distribution within the orbital compartment during RME at two distinct stages of midpalatal suture maturation.

METHODS

This study was approved by the Marmara University Faculty of Dentistry Clinical Research Ethics Committee (approval no.: 2022/40, date: 24.02.2022). For the creation of the maxilla and craniofacial bone model, computed tomography (CT) data were selected from the visible human project.[13] Tomography data were reconstructed with a slice thickness of 0.1 mm and were then imported into the 3DSlicer software in DICOM (.dcm) format. CT data in DICOM format were separated according to appropriate Hounsfield unit values (Supplementary Table 1) in 3D Slicer software and converted into a three-dimensional model through a segmentation process. The model was exported in STL format.

The three-dimensional model was imported into the ALTAIR Evolve software, where maxillary cortical and cancellous bone and tooth geometries were modeled. The periodontal ligaments (PDLs) were modeled with optimal thickness with reference to the outer surfaces of the teeth. Perimaxillary sutures were developed using cutting surfaces in ALTAIR Evolve, based on bone models obtained from tomography. Both acrylic and hybrid HYRAX devices were also modeled in the same software. In both devices, a 10 mm HYRAX expansion screw was incorporated (Forestadent Snap Lock Expander, Pforzheim, Germany). The hybrid HYRAX device included two 2x8 mm mini screws, two mini screw sleeves, and extensions to the premolars, which represented a modification adopted to enhance anchorage (Tasarımmed, İstanbul, Türkiye). Mini-screws were placed 2 mm laterally to the midpalatal suture in the region of the third palatal ruga, which has been identified in the literature as the most suitable site for screw placement. This location is also anatomically close to the center of resistance of the nasomaxillary complex.[14]

All models were prepared using material properties defined by their Young's modulus and Poisson's ratio values (Table 1) and placed in the correct coordinates in 3D space (Figure 1). The total number of nodes and elements that the models consist of is given in Table 2. To enable force transfer between models, mesh matching was performed in ALTAIR Hypermesh software.

In this study, a mesh convergence test was conducted to ensure the finite element model's reliability and accuracy, aiming for an error rate below 3% while maintaining computational efficiency. To maintain consistency in comparison, each mesh with element sizes ranging from coarse to fine was generated

Table 1. Poisson's ratio and Young's modulus determining the biomechanical properties of the materials in the study[19]

Materials	Young's modulus (MPa)	Poisson's ratio
Hybrid device and acrylic device	110000	0.3
Tooth	20000	0.3
Cancellous bone	1370	0.3
Cortical bone	13700	0.3
PDL	1.18	0.3
Suture	0.68	0.45

PDL, periodontal ligament.

Table 2. Total node and element numbers of models

	Acrylic device	Hybrid device
Total nodes	530,016	706,614
Total elements	2,065,964	2,827,372

and analyzed under identical loading and boundary conditions. The variation in the evaluation metric was observed through comparing results from successive mesh refinements. The relative error between two consecutive meshes was calculated. The process was repeated until the relative error dropped below the 2-3% threshold. Triangular 2D and tetrahedral 3D meshes were used for their suitability in capturing complex geometries and curved surfaces in bone models. Mesh quality was evaluated for skewness angles over 80° and a minimum element length of 0.001, with necessary refinements applied when either criterion was not met.

Activation forces simulating 0.25 mm, and 5 mm displacement along the X-axis (transverse direction) were applied to both acrylic and hybrid devices across all models (Figure 1). These values correspond clinically to activations of 1/8 turn and 5 turns, respectively. The load was transmitted to the maxilla via the expansion appliance. Distinct analysis scenarios were established for adult and non-adult variations using the same model: adult scenarios were simulated with closed sutures, and non-adult scenarios with open sutures. A total of eight static analyses were solved linearly under the specified loading conditions.

To calculate the stress and strain effects created by the externally applied force on the model, three boundary conditions were applied in this study:

• Boundary condition shown in blue: The models were fixed at the nodes around the foramen magnum by restricting all degrees of freedom to prevent movement in all three axes (Figure 2).

• Boundary condition shown in red: A boundary condition was applied on the X-axis normal, symmetrical with respect to the Y-Z plane (Figure 2).

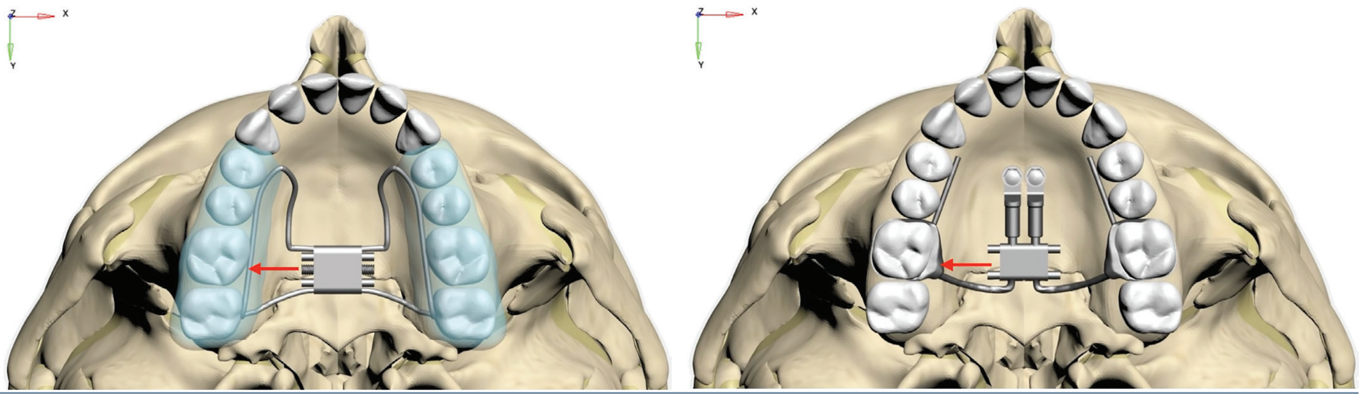

Figure 1. A) Acrylic HYRAX device placed in the correct coordinates in 3D space and activation forces simulated along the X-axis. **B)** Hybrid HYRAX device, including two 2x8 mm mini screws and two sleeves, placed in the correct coordinates in 3D space and activation forces simulated along the X-axis

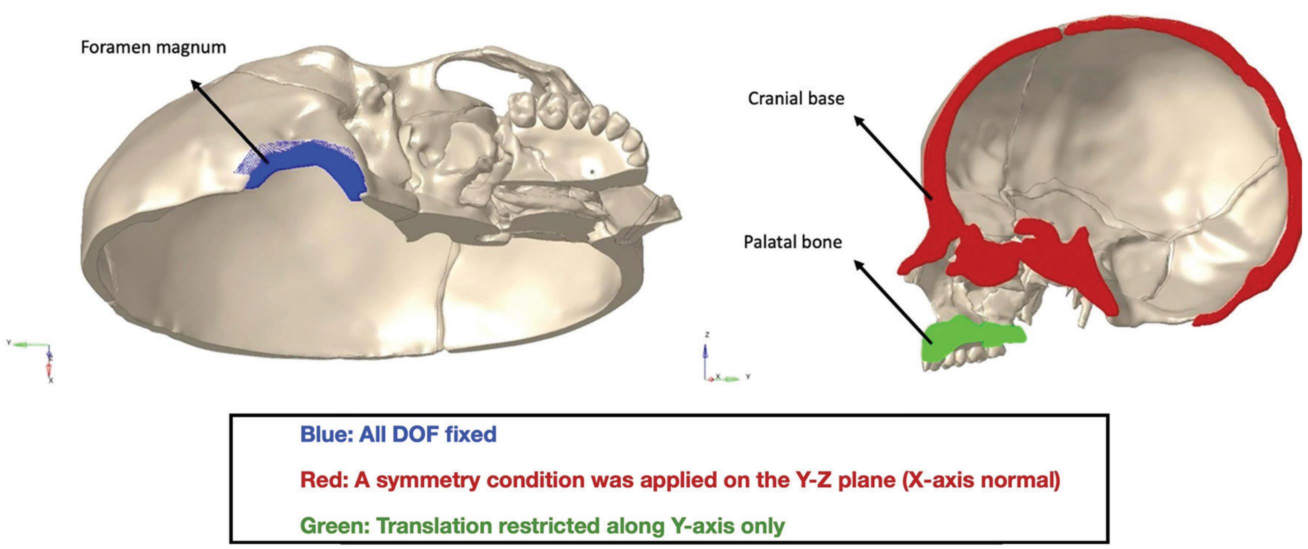

Figure 2. Boundary condition shown in blue: The models were fixed at the nodes around the foramen magnum by restricting all degrees of freedom (DOF) so that the movement in all three axes is prevented, Boundary condition shown in red: The palatal bone was modeled as two unconnected segments separated by the vertical plane of symmetry, permitting unrestricted lateral movement relative to this plane (X-axis normal, symmetrical with respect to the Y-Z plane) , Boundary condition shown in green: All cranial points on the symmetry plane (Y-axis) were constrained from motion perpendicular to it, except for the palatal bone, which remained fully unconstrained

• The boundary condition shown in green is applied to restrict motion in the Y-axis only (Figure 2).

A FREEZE type contact was defined in the bone-suture and bone-PDL-tooth contact areas, based on the assumption that these areas move in full correlation during displacement.

After obtaining the mathematical models, we solved the FEA using Nastran-based ALTAIR Optistruct (2021, Altair Engineering, Inc., Troy, MI, USA) implicit solver.

Through FEA, the 0.25 mm and 5 mm displacement amounts in the models were measured in millimeters (mm), along the X (transversal plane), Y (anteroposterior plane), and Z (vertical plane) axes. Von Mises stress values were calculated in megapascals (MPa=N/mm^2) and presented as color-mapped images. Each color in the obtained images represents a stress range, and the color scale is displayed to the left of each image.

RESULTS

In this study, von Mises stresses resulting from the initial activation of 0.25 mm, and the displacement amounts resulting from a total expansion of 5 mm for both acrylic and hybrid devices in adult and non-adult models were evaluated. Given that the forces generated during RME do not increase cumulatively as screw activation increases, additional investigation into the impact on bone remodeling is necessary. Therefore, von Mises stresses resulting from 5 mm expansion were not evaluated as they do not accurately represent clinical scenarios. The values resulting from a 0.25 mm expansion were also excluded from evaluation due to their negligible amounts.

0.25 mm Activation

When the Von Mises stresses after 0.25 mm expansion in the non-adult models are examined (Figure 3); the highest total craniofacial stress was observed in the acrylic device (18.97 MPa), followed by the hybrid device (10.38 MPa). Stress at the lateral orbital tubercle was also higher in the acrylic device (3.63 MPa) than in the hybrid device (1.88 MPa). While stress in the optic foramen was higher than in the infraorbital foramen with the acrylic device, the stress in the optic foramen was lower with the hybrid device (Table 3).

When the Von Mises stresses after 0.25 mm expansion in the adult models were examined (Figure 4), the total craniofacial stress was once again the highest in the acrylic device (106.68 MPa), followed by the hybrid device (18.58 MPa). Stress in the lateral orbital tubercle was significantly greater in the acrylic device (21.23 MPa) compared to in the hybrid device (3.35 MPa). While stress in the optic foramen was higher than in the infraorbital foramen with the acrylic device, it was lower in the hybrid device (Table 4).

In both devices, stress values were higher in the adult models compared to the non-adult models following 0.25 mm expansion.

5 mm Activation

When the resultant displacements after 5 mm expansion in the non-adult models were examined (Figure 5), total resultant displacement across all craniofacial structures was highest with the acrylic device (40.89 mm), followed by the hybrid device (21.72 mm). The greatest resultant displacement was observed at the zygomaticomaxillary suture (1.86 mm) in the hybrid device, and at the pterygoid hamulus (6.92 mm) in the acrylic device. Total resultant displacement was higher in an acrylic device, particularly in regions surrounding the orbital area. Although the junctional displacements in the optic foramen and superior orbital fissure were similar between devices, they

Table 3. Von Mises stresses (MPa) at 0.25 mm expansion in non-adult models with both devices

	Acrylic	Hybrid
Lateral orbital tubercle	3,6396	1,8885
Zygomaticomaxillary suture	2,7924	1,5132
Optic foramen	0.9088	0.536
Foramen rotundum	0.9083	0.5327
Infraorbital foramen	0.6781	0.5474
Medial pterygoid lamina	0.6102	0.3098
Carotid canal	0.569	0.3498
Foramen ovale	0.3897	0.2156
Superior orbital fissure	0.2166	0.1528
Lateral pterygoid lamina	0.2099	0.1157

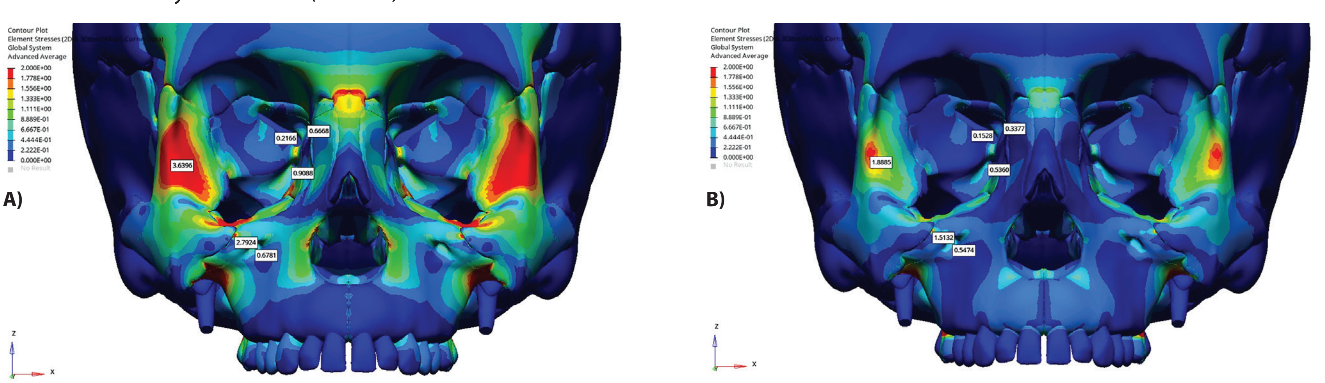

Figure 3. A) Von Mises stresses in the non-adult model given an expansion force of 0.25 mm with Acrylic device. **B)** Von Mises stresses in the non-adult model given an expansion force of 0.25 mm with Hybrid device

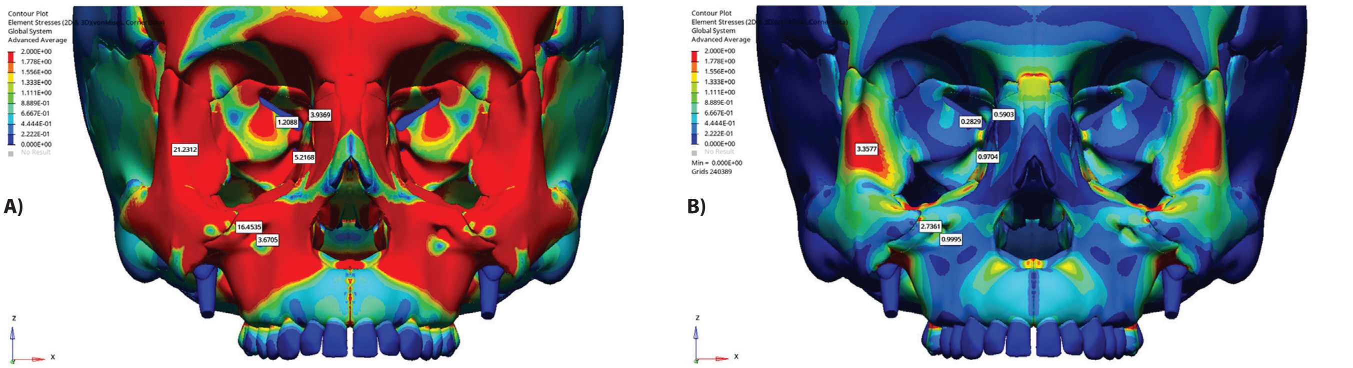

Figure 4. A) Von Mises stresses in the adult model given an expansion force of 0.25 mm with Acrylic device. **B)** Von Mises stresses in the adult model given an expansion force of 0.25 mm with Hybrid device

Table 4. Von Mises stresses (MPa) at 0.25 mm expansion in adult models with both devices

	Acrylic	Hybrid
Lateral orbital tubercle	21,2312	3,3577
Zygomaticomaxillary suture	16,4535	2,7361
Foramen rotundum	5,2291	0.9636
Optic foramen	5,2168	0.9704
Medial pterygoid lamina	3,6964	0.5562
Infraorbital foramen	3,6705	0.9995
Carotid canal	3,2436	0.6455
Foramen ovale	2,2409	0.3876
Lateral pterygoid lamina	1,2159	0.2104
Superior orbital fissure	1,2088	0.2829

was greater with the acrylic device. In the adult models, the resultant displacement at the infraorbital foramen was notably higher with the acrylic device (1.42 mm) compared to the hybrid device (0.43 mm) (Table 6).

In both devices, displacement were higher in the non-adult models compared to the adult models, following 5 mm expansion.

DISCUSSION

Numerous clinical and animal studies have investigated the effects of RME on skeletal and dental tissues.8 In addition, many studies using finite element analysis have been published, examining these effects.[15,16] Published studies consistently report that the effects of RME are not limited to the dentoalveolar region and midpalatal suture but extend to more extensive craniofacial structures through the sutures, potentially impacting critical neurovascular structures.[5] In two case reports, patients were reported to experience symptom resolution after the discontinuation of RME treatment, which they had undergone due to ocular symptoms.[17,18] Since the ocular region is considered the most clinically accessible and non-invasive site for ICP monitoring,[12] the potential effects of RME on this area warrant careful evaluation. The FEA method

Unlike previous FEA studies, this study employed an acrylic and a modified hybrid device, with extensions to the premolars, selected for their ability to produce greater skeletal effects and reduce dental side effects compared to traditional banded tooth-supported HYRAX devices.[15,22,23] This modification was incorporated based on clinical experience, which emphasized the need to enhance anchorage support in the event of miniscrew failure, thereby allowing the appliance to continue functioning as a tooth-supported device if necessary.

In order to standardize all anatomical factors except sutural maturation, a single CT dataset was modeled; the sutures designated as open for non-adult models and closed for adult models, representing two different age groups. Although the timing of midpalatal suture fusion varies significantly among individuals, with some patients retaining an open suture into early adulthood and others showing partial or complete fusion in their mid-teens 6, the general clinical approach is to perform RME as early as possible to reduce the risk of adverse effects, increased resistance, and relapse associated with delayed treatment.[24]

Von Mises Stress Findings

Regardless of whether the sutures were open or closed, the total Von Mises stresses were found to be higher in the acrylic device than in the hybrid device, consistent with findings from previously published studies. It has been demonstrated that because the hybrid device provides expansion force from a location closer to the center of resistance of the maxilla, the resulting stresses do not spread to the deep tissues of the facial skeleton as much as with the acrylic device.[19]

For both devices, the stresses observed in the adult models were higher than those in the non-adult models. This finding supports the understanding that the elasticity of sutures and bones may decrease with increasing age, thereby increasing the risk of complications that may occur during RME treatment in adult patients.[7]

In this study, the highest stress between the sutures was found to occur in the zygomaticomaxillary suture, as reported

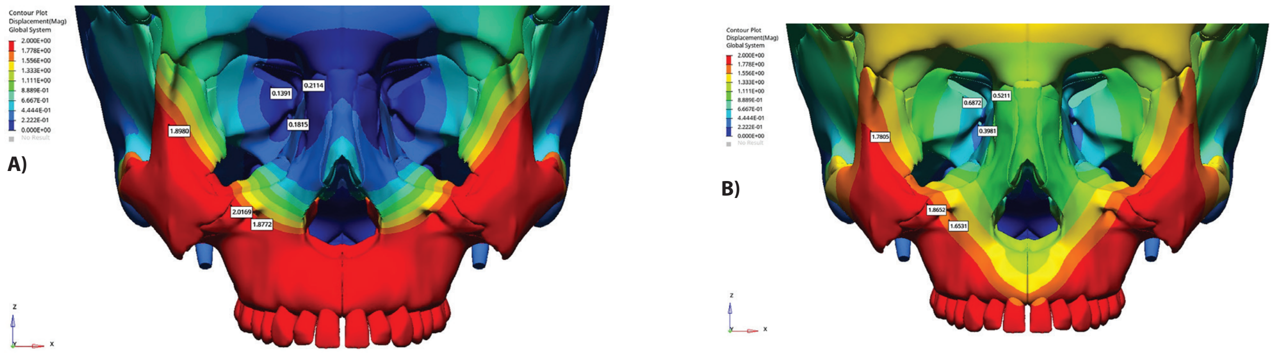

Figure 5. A) Resultant displacement in the non-adult model given 5 mm expansion force with Acrylic device. **B)** Resultant displacement in the non-adult model given 5 mm expansion force with Hybrid device

Table 5. Resultant displacement (mm) at 5 mm expansion in non-adult models with both devices

	Acrylic	Hybrid
Pterygoid hamulus	6,9238	1,7904
Lateral pterygoid lamina	5,138	1,592
Zygomaticomaxillary suture	3,8062	1,8652
Infraorbital foramen	3,523	1,6588
Lateral orbital tubercle	3,0767	1,7805
Medial pterygoid lamina	1,7329	0.4924
Carotid canal	0.6297	0.2047
Optic foramen	0.5478	0.5211
Superior orbital fissure	0.4839	0.4443
Foramen rotundum	0.3992	0.4056
Foramen ovale	0.3216	0.3024

in previous studies.[25] It has also been reported that clinical microcracks may occur due to limited displacement in this region.[26]

It was observed that stresses also occurred in the wings of the sphenoid bone, and pterygoid laminae. There was significant stress at points where important nerves and vascular bundles pass, such as the foramen ovale and foramen rotundum. Particularly in the adult models, the stress that was observed in the foramen rotundum after expansion with the acrylic device (5.22 MPa) was substantially higher than expansion with the hybrid device (0.96 MPa). Holberg and Rudzki-Janson[27] who reported similar results, emphasized that attention should be paid to hypersensitivity in the areas innervated by cranial nerves and temporary ocular movement limitation due to the stresses of RME treatment. They recommended that if rapid expansion treatment is to be performed in adults, surgical assistance should be considered, and the pterygomaxillary junction should be separated prior to expansion.[27]

Around the orbital compartments, the highest stress occurred at the lateral orbital tubercle in all models. In adult models, the acrylic device caused significant stress around the eye (31.32 MPa), whereas, in both adult and non-adult models, the hybrid device was found to cause less stress. Stress around the infraorbital foramen was slightly higher than around the optic foramen in all hybrid models, whereas in all acrylic models, stresses around the optic foramen exceeded those around the infraorbital foramen. However, MacGinnis et al.[19] reported that stresses around the infraorbital foramen were higher than those around the optic foramen in both devices. This discrepancy is thought to be due to the absence of acrylic in the conventional HYRAX device used in their study. Another FEA study yielded similar findings, demonstrating significant stress at the optic foramen and superior orbital fissure. These findings may provide a biomechanical basis for previously reported case studies describing ocular manifestations associated with RME.[7]

The results of this study correlate with the stress findings around the orbital compartments and with previously published case reports of dizziness and tension in the under-eye and cheekbone area during RME treatment.[17]

Resultant Displacement Findings

As in a previous thesis study, the total resultant displacements observed in this study were found to be higher in the acrylic devices under all sutural conditions.[28] The total resultant displacement was found to be higher in the non-adult model than in the adult model for both devices. Although this finding is consistent with previous studies,[7] there is also literature reporting contradictory results.[28] It can be assumed that in adult models, due to increased rigidity of bones and sutures, the amount of displacement caused by expansion forces decreases compared to non-adult models, while the resulting stresses in adult models increase.

In both device models, significant displacements of the lateral and medial pterygoid laminae were observed, consistent with previous studies.[29] Displacements in these regions were consistently greater in the acrylic device across all sutural conditions. Particularly in the adult model, the amount of displacement observed in the hybrid device was substantially lower than that observed in the acrylic device. This finding supports the hypothesis proposed by researchers who have suggested that in adult patients, the use of tooth-bone supported devices, as opposed to tooth-supported devices alone, can reduce complications during RME treatment.[19]

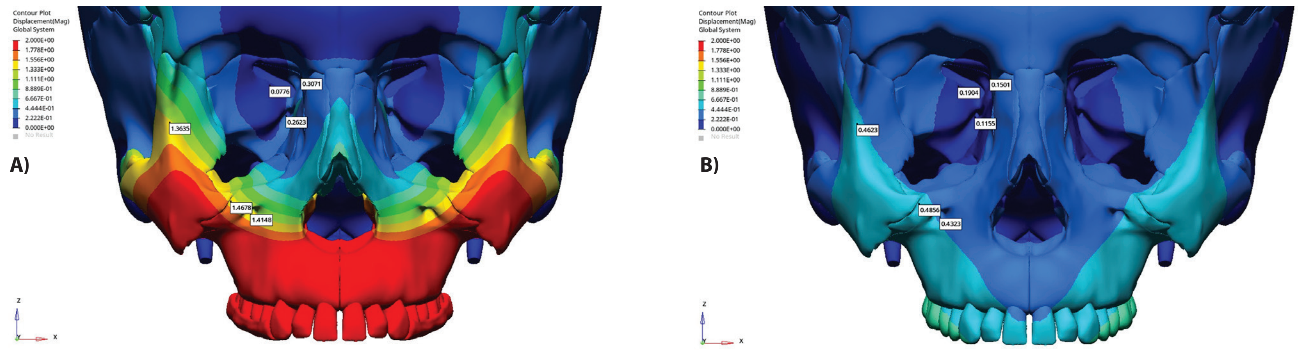

Figure 6. A) Resultant displacement in the adult model given 5 mm expansion force with Acrylic device. **B)** Resultant displacement in the adult model given 5 mm expansion force with Hybrid device

Table 6. Resultant displacement (mm) at 5 mm expansion in adult models with both devices

	Acrylic	Hybrid
Pterygoid hamulus	2,6681	0.4401
Zygomaticomaxillary suture	1,4678	0.4856
Lateral pterygoid lamina	1,9831	0.3985
Infraorbital foramen	1,4281	0.4323
Lateral orbital tubercle	1,3635	0.4623
Medial pterygoid lamina	0.6678	0.1277
Carotid canal	0.3324	0.0631
Optic foramen	0.3071	0.1501
Superior orbital fissure	0.2718	0.1266
Foramen rotundum	0.2567	0.1174
Foramen ovale	0.1239	0.0849

this study found that, particularly when examining the orbital compartment, the total amount of resultant displacement was higher in non-adult models. The acrylic device models caused more displacement around the orbital compartment, with the infraorbital foramen identified as the most significantly affected site. Consistent with previously published studies, significant displacements were also observed in the superior orbital fissure, infraorbital foramen, and optic foramen.[7,28,29] These displacements were notably reduced with the hybrid device, especially in adult models (Figure 6).

It was also observed that in RME-affected craniofacial bones, beyond the maxilla, considerable stress and displacement occurred particularly around the orbital compartment. In a previously published case by Romeo et al.,[17] it was noted that the symptoms, such as double vision and headache, during RME treatment, were caused by the protrusion of the optic nerve head and increased volume in the perioptic subarachnoid space. Additionally, idiopathic intracranial hypertension may develop due to elevated ICP.[17] The most prominent clinical symptoms of IHH include disturbances such as diplopia, headache, and papilledema, which can lead to blindness if not appropriately managed.[30] Therefore, clinical evaluation and reliable measurement of ICP are critical in patients at risk of IHH. Evensen and Eide[12] reported that one of the non-invasive methods for monitoring changes in ICP is ONSD measurement. Based on the findings of this study, the ability to visualize stress and displacement around the orbital compartments during RME, suggests that measuring ICP through the orbital compartment may yield clinically meaningful results.

Study Limitations

The main limitation of this study is the assumption that all anatomical structures, including cortical bone, sutures, and soft tissues, are isotropic and homogeneous, whereas in reality they are anisotropic and heterogeneous. In particular, the PDL exhibits non-linear and viscoelastic behavior, which may significantly influence stress distribution. Additionally, the assumption of bilateral symmetry and the use of a single time point analysis lead to the exclusion of time-dependent force dynamics, potentially limiting clinical applicability. Another limitation is the use of CT data from a single individual, which restricts generalizability, and the assumption of bilateral symmetry with a single time-point analysis, excluding time-dependent force dynamics. Furthermore, individual variability in suture maturation should be acknowledged, Despite these limitations, finite element analysis remains a valuable and comprehensive method for estimating the biomechanical effects of RME. Consequently, it is believed that the findings of this study may help guide future clinical research on the potential impact of RME on ICP.

CONCLUSION

In the expansion treatments performed with both devices, regardless of the suture ossification level, the highest stress was observed at the zygomaticomaxillary suture, rather than the midpalatal suture.

Significant stress and displacement also occurred at the pterygoid laminae of the sphenoid bone, suggesting that hybrid devices should be preferred to reduce neurovascular risks. Stress increased with enhanced sutural ossification, particularly around the orbital compartment, and this stress may be reduced by hybrid devices. During RME, stress were observed in the superior orbital fissure, and optic foramen, which may explain reported ocular symptoms. Based on these findings, it is suggested that the orbital compartments may be used as a clinically relevant site to assess ICP during RME.

As ossification increases, displacement decreases, while stresses increase. To avoid potential adverse effects, early expansion is recommended, and bone-supported devices should be considered in adults.

Ethics

Ethics Committee Approval: This study was approved by the Marmara University Faculty of Dentistry Clinical Research Ethics Committee (approval no.: 2022/40, date: 24.02.2022).

Informed Consent: Informed consent form wasnt taken since its not a clinical trial.

Footnotes

Author Contributions: Surgical and Medical Practices - A.E.; Concept - A.E.; Design - A.E.; Data Collection and/or Processing - A.E.; Analysis and/or Interpretation - A.E.; Literature Search - A.E.; Writing - A.E., A.A.D.

Conflict of Interest: The authors have no conflicts of interest to declare.

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Supplementary **Table 1.**

Tissue	Min. HU value	Max. HU value
Cortical bone	662	1988
Cancellous bone	148	661
Tooth	1200	3071

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Original Article

The Effects of Light and Vibration on the Correction of Lower Incisor Crowding with Aligners

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Main Points

- Low-frequency vibration and photobiomodulation applied separately did not significantly accelerate mandibular incisor alignment compared with the control.
- The combination of low-frequency vibration and photobiomodulation produced significantly greater short-term alignment.
- This combined protocol may be considered a promising adjunct to enhance the efficiency of clear aligner therapy in the early stages.

ABSTRACT

Objective: To compare the effects of low-frequency vibration (LFV), photobiomodulation (PBM), and their combination (HOT) on the rate of mandibular incisor alignment during clear aligner therapy.

Methods: This retrospective study included 89 patients treated with a single clear aligner system for mild-to-moderate mandibular anterior crowding. Patients were assigned to four groups: control (n=19), LFV (n=26), PBM (n=21), and HOT (n=23). LFV [30 Hz, 0.25 N (≈25 g)] and PBM (850 nm, 16×5 mm LEDs, ≈9.5 J/cm^2) devices were used daily for 20 minutes in relevant groups. The primary outcome was the change in Little's Irregularity Index at baseline (T0), 28 days (T1), 48 days (T2), and 62 days (T3). Statistical analyses included one-way ANOVA, repeated measures ANOVA, and Pearson's correlation.

Results: The HOT group showed significantly greater crowding reduction compared to all other groups ($p<0.05$). LFV and PBM alone were not significantly different from the control. Within-group analysis revealed significant reductions in all groups over time, with the HOT group showing consistent improvements at each interval. Correlation analyses revealed no significant associations between device usage or aligner wear time and crowding reduction.

Conclusion: Combining LFV and PBM during clear aligner therapy produced greater short-term acceleration of mandibular incisor alignment than either modality alone. Further randomized controlled trials are warranted to confirm long-term efficacy and safety.

Keywords: Orthodontics, clear aligners, low-frequency vibration, photobiomodulation, accelerated tooth movement

INTRODUCTION

Orthodontic treatment significantly enhances patients' quality of life by improving dental aesthetics, functional occlusion, and psychosocial well-being. Increasing aesthetic expectations, particularly among adult patients, has driven a growing preference for less visible treatment modalities such as lingual orthodontics and clear aligner therapy instead of conventional fixed appliances.[1,2] Although aesthetic brackets provide a better appearance than metal brackets, issues such as discoloration, increased friction, and enamel damage during debonding limit their clinical advantages.[3,4]

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Clear aligner therapy, first introduced by Kesling in 1945 and later digitized through advances in CAD/CAM technology, has evolved from a simple adjunctive tool into a comprehensive treatment modality for complex malocclusions.[5,6] The increased acceptance of clear aligners is largely due to their removability, improved aesthetics, and enhanced patient comfort. However, treatment duration remains a critical concern for both patients and clinicians. Prolonged orthodontic treatment, often lasting 24-36 months, may lead to decreased patient motivation, higher risk of enamel demineralization, gingival inflammation, and increased risk of root resorption .[7,8] Consequently, various approaches have been explored to accelerate orthodontic tooth movement (OTM), including pharmacological agents, surgical interventions, mechanical stimulation, and photobiomodulation.[9-11] These methods aim to either shorten the lag phase of tooth movement or enhance bone remodeling by modulating cellular and molecular processes within the periodontium. Understanding the biology of OTM is essential for evaluating these acceleration techniques. Tooth movement results from a sequence of mechanical, cellular, and biochemical events in the periodontal ligament (PDL) and alveolar bone. The PDL transmits orthodontic forces to the surrounding alveolar bone, leading to bone resorption in areas of compression and bone apposition in tension sites.[12] Multiple theories, including the pressure-tension theory, bone-bending theory, and piezoelectric theory, have been proposed to explain this process.[13,14] On a cellular level, osteoclasts, osteoblasts, and fibroblasts coordinate the remodeling process, while cytokines, prostaglandins, and the RANK/RANKL/OPG system regulate osteoclastic activity.[15] Efforts to accelerate OTM can broadly be categorized into surgical and nonsurgical methods. Surgical techniques, such as corticotomy, piezocision, and distraction osteogenesis, enhance tooth movement by altering alveolar bone resistance and stimulating a regional acceleratory phenomenon (RAP).[16-19] Nonsurgical methods include mechanical stimulation through vibration, low-level laser therapy, photobiomodulation, pharmacologic agents, and gene therapy.[20-23] Among these, mechanical vibration and photobiomodulation have gained attention as minimally invasive, patient-friendly approaches that can be integrated into clear aligner therapy without significantly increasing treatment complexity. This study aimed to compare the effects of vibration, photobiomodulation, and their combination on the rate of mandibular incisor alignment during clear aligner therapy. We hypothesized that adjunctive use of these modalities would result in faster resolution of crowding compared to clear aligner treatment alone.

METHODS

This retrospective observational study was conducted at the Department of Orthodontics, Faculty of Dentistry, Yeditepe University. Ethical approval was obtained from the Marmara University Clinical Research Ethics Committee (approval no: 2020-425, date: 30.06.2020) in accordance with the Declaration of Helsinki.

A total of 89 patients who had completed orthodontic treatment with clear aligners for mandibular incisor crowding between January 2018 and June 2020 were included. Inclusion criteria were the presence of mild to moderate crowding in the mandibular anterior region as assessed by Little's Irregularity Index (LII), completion of treatment using a single clear aligner system without mid-treatment appliance changes, absence of systemic or periodontal disease, good oral hygiene, and compliance with aligner wear protocol. Exclusion criteria were severe skeletal discrepancies requiring orthognathic surgery, a history of previous orthodontic treatment in the mandibular anterior region, the use of any adjunctive surgical acceleration techniques during treatment, and non-compliance with appliance usage protocols. The mean baseline mandibular anterior crowding across all groups was 5.6±0.4 mm, corresponding to mild-to-moderate irregularity according to Little's Index.

All patients were treated with the manufacturer's staging and refinement protocols. The initial impressions (T0) were taken at the beginning of treatment. Subsequent impressions followed at 28 days (T1), 48 days (T2), and 62 days (T3), with aligner change intervals of 14 days (T0-T1), 10 days (T1-T2), and 7 days (T2-T3) for all cases. Models were fabricated using Type IV dental stone from polyvinyl siloxane impressions. Although the study was retrospective in design, the impressions at T0, T1 (28 days), T2 (48 days), and T3 (62 days) were routinely obtained as part of the departmental clinical protocol for aligner follow-up. Therefore, interval measurements were possible without prospective recall, as these records already existed for all included patients.

Patients' records were assigned to four groups according to the acceleration device they used during their aligner treatment:

Group 1- Control group (n=19; 11 females, 8 males): received only clear aligner treatment without any adjunctive acceleration method.

Group 2- Vibration group (n=26; 14 females, 12 males): Received a 30 Hz, 0.25 N (≈25 g) mechanical vibration device

Group 3- Photobiomodulation (PBM) group (n=21; 12 females, 9 males): Received an 850 nm LED light device

Group 4- Combined group (HOT) (n=23; 14 females, 9 males): received a device integrating both vibration and PBM functions.

All patients in the experimental groups were instructed to use their respective devices for 20 minutes daily throughout the treatment period. Device usage was monitored through patient self-reported logs and compliance charts.

The acceleration devices were prototypes developed by Yeditepe University Faculty of Engineering and Architecture and Biomedical Engineering Department, and assembled from off-the-shelf components for research use. For the vibration device, oscillation frequency and force magnitude

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were standardized at 30 Hz; 0.25 N (≈25 g). The PBM device emitted continuous-wave 850 nm light via 16×5 mm red LEDs, delivering an energy density of ≈9.5 J/cm². For the combined device, both modalities were applied simultaneously within a single intraoral mouthpiece. The 850 nm near-infrared wavelength was selected based on its superior tissue penetration compared with visible light, and because previous clinical trials demonstrated favorable biostimulatory effects at this setting.[16-29] The applied energy density of ≈9.5 J/cm² was chosen within the range reported as effective in accelerating bone remodeling without adverse effects.

The vibration device (30 Hz; 0.25 N) was driven by a shaftless 10×3 mm vibration motor. The photobiomodulation device emitted 850 nm light via sixteen 5 mm red LEDs (PHOEBE module). The combined device integrated both modalities within a single mouthpiece. Devices were powered via USB with a 2000 mAh power bank. Digital measurements were performed using a 0.01 mm-precision caliper. Clear aligners were fabricated in-house using Orchestrate 3D planning software (Orchestrate 3D, Redlands, California, USA), models printed on a Uzaras Dreammaker 3D printer (Uzaras, İstanbul, Türkiye), and thermoformed on a Biostar® (Scheu Dental GmbH, Germany) pressure former with 0.75 mm polyethylene terephthalate glycol-modified (PETG) sheets.

Measurements were performed using a digital caliper with 0.01 mm accuracy by a single examiner (M.Ö.). Calibration and intra-examiner reliability were assessed by repeating measurements on 20 randomly selected models at two-week intervals. Method error was calculated using Dahlberg's formula. The primary outcome was the reduction in LII, representing the extent of correction. To evaluate the pace of treatment, we calculated the rate of change (ΔLII per day) between consecutive time intervals (T0-T1, T1-T2, T2-T3). This allowed the assessment of both the magnitude of alignment and the acceleration of tooth movement. Intra-examiner reliability, assessed using the Intraclass Correlation Coefficient (ICC) with 95% confidence intervals, indicated excellent agreement for all time points (Table 1).

Statistical Analysis

Statistical analyses were performed using SPSS Statistics for Windows, Version 26.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics were expressed as mean ± standard deviation. Group differences were assessed using One-Way ANOVA for normally distributed data, followed by Tukey's post-hoc test for pairwise comparisons. Repeated measures ANOVA was applied for within-group changes over time. Pearson's correlation coefficient was used to assess the relationship between device usage and changes in crowding (Table 2). Statistical significance was set at $p<0.05$. For multiple comparisons, Tukey's honestly significant difference (HSD) test was applied. This post-hoc procedure inherently controls for Type I error without the need for additional correction methods.

In the present study, the therapeutic effect achieved through the adjunctive use of photobiomodulation and vibration devices in combination with aligners was considered accelerated when a greater degree of crowding correction was observed within the same aligner replacement interval.

RESULTS

The distribution of age and gender across the four study groups showed no statistically significant differences ($p>0.05$), indicating homogeneity among groups (Table 3).

Table 1 presents the methodological error evaluation for crowding measurements at T0, T1, T2, and T3. The methodological error for LII measurements at T0, T1, T2, and T3 was assessed using Dahlberg's formula and found to be clinically negligible. Intra-examiner reliability was assessed

Table 1. Methodological error evaluation regarding the amount of crowding measurements at T0, T1, T2 and T3 times

Time point	ICC	95% CI (Lower-Upper)	p-value
T0	0.999	0.999-1.000	<0.001
T1	0.998	0.997-0.999	<0.001
T2	0.998	0.997-0.999	<0.001
T3	0.999	0.999-1.000	<0.001

Significance at p<0.05.
ICC: Intraclass Correlation Coefficient; CI, confidence interval.

Table 2. Evaluations of acceleration device and aligner usage

Group	Device usage (min/day) Mean±SD	Aligner wear (h/day) Mean±SD	r (Device vs. crowding change)	p-value
Control	-	21.6±1.6	-	-
LFV	17.9±2.4	21.5±1.5	0.329	0.101
PBM	17.2±2.5	21.6±1.4	0.110	0.636
HOT	18.6±2.1	21.7±1.3	0.419	0.051

Significance at p<0.05.
SD, standard deviation; HOT, combined LFV + PBM; LFV, low-frequency vibration; PBM, photobiomodulation.

using the ICC with 95% confidence intervals, which indicated excellent agreement for all time points (Table 1).

At baseline (T0), no statistically significant differences were observed in the initial crowding scores among the groups (p>0.05). By the end of the treatment period, analysis of crowding reduction revealed significant intergroup differences (p<0.05) (Table 4).

The HOT group demonstrated the greatest mean reduction in crowding from T0 to T3, with a statistically, greater reduction than that observed in the control, vibration, and PBM groups. The vibration group showed a modest reduction in crowding compared to the control group, but the difference was not statistically significant (p>0.05). The PBM group showed results comparable to the vibration group and, importantly, no statistically significant difference when compared to the control group.

Repeated measures ANOVA indicated significant reductions in LII within each group over time (p<0.05). Post-hoc pairwise comparisons (Table 5) showed that the HOT group exhibited significant reductions at each time interval (T0-T1, T1-T2, T2-T3). The vibration and PBM groups showed significant reductions between T0-T1 and T0-T3 whereas changes between consecutive intervals (T1-T2, T2-T3) were less pronounced. The control group showed a significant reduction only between T0-T3.

Post-hoc comparisons demonstrated that the HOT group exhibited significantly greater reductions. HOT vs Control: The largest improvement was observed in the HOT group, with a mean difference of -1.05 mm, which was highly significant (p<0.001). The effect size was large (η^2=0.32, Cohen's d=1.25), indicating strong clinical relevance. HOT vs. low-frequency vibration (LFV): The HOT group also outperformed the LFV group with a mean difference of -0.65 mm (p=0.010). The effect size was moderate to large (η^2=0.18, Cohen's d=0.80). HOT vs PBM: A significant advantage was also found for HOT, when compared with PBM, (-0.53 mm, p=0.025), with a moderate effect size (η^2=0.15, Cohen's d=0.65). LFV vs Control: Although LFV showed better results than Control, with a difference of (-0.40 mm), the difference was not statistically significant (p=0.070), and the effect size was small to moderate effect. PBM vs Control: PBM showed a borderline significant improvement compared to Control (-0.52 mm, p=0.050) with a small to moderate effect size. Overall, the HOT protocol produced the most pronounced acceleration of crowding resolution, with large effect sizes confirming not only statistical

Table 3. Evaluation of the groups in terms of age and gender

	Control	Vibration	PBM	HOT	p-value
Age Mean±SD	23.16±3.55	24.31±2.51	22.57±5.06	23.52±3.19	0.426[1]
Female n (%)	11 (57.9%)	14 (53.8%)	12 (57.1%)	14 (60.9%)	0.969[2]
Male n (%)	8 (42.1%)	12 (46.2%)	9 (42.9%)	9 (39.1%)	

[1]One-Way ANOVA test; [2]Chi-square test.
Significance at p<0.05.
SD, standard deviation; PBM, photobiomodulation.

Table 4. Evaluations of crowding amount measurements

	Control Mean±SD	Vibration Mean±SD	PBM Mean±SD	HOT Mean±SD	p-value
T0	5.66±0.47A,a	5.56±0.39A,a	5.75±0.41A,a	5.65±0.43A,a	0.476
T1	5.49±0.46A,b	5.39±0.39A,b	5.34±0.41A,b	5.16±0.42A,b	0.074
T2	5.31±0.48A,c	5.22±0.41 AB,c	4.95±0.41BC,c	4.68±0.42C,c	0.000*
T3	5.14±0.48A,d	5.06±0.39A,d	4.55±0.41B,d	4.19±0.42C,d	0.000*

One-Way ANOVA test
*Significance at p<0.05.
Uppercase letters in rows indicate intergroup variation, and lowercase letters in columns indicate intertemporal variation.
SD, standard deviation; PBM, photobiomodulation; HOT, combined LFV + PBM; LFV, low-frequency vibration.

Table 5. Post-hoc analysis results (Tukey HSD, effect sizes)

Comparison	Mean difference (mm)	95% CI (Lower-Upper)	p-value	n^2 (Eta squared)	Partial n^2	Cohen's d
HOT vs Control	-1.05	-1.32 - -0.78	<0.001	0.32	0.28	1.25
HOT vs LFV	-0.65	-0.90 - -0.40	0.010	0.18	0.16	0.80
HOT vs PBM	-0.53	-0.78 - -0.28	0.025	0.15	0.14	0.65
LFV vs Control	-0.40	-0.65 - -0.15	0.070	0.09	0.08	0.50
PBM vs Control	-0.52	-0.77 - -0.27	0.050	0.12	0.11	0.60

Significance at p<0.05. Post-hoc test; Tukey HSD. Effect size calculated as n^2.
Values are expressed as mean differences in millimeters (mm).
n^2: Eta squared effect size; Partial n^2: effect size from the model; Cohen's d: standardized mean difference.
HOT, combined LFV + PBM; LFV, low-frequency vibration; PBM, photobiomodulation.

but also clinical significance. LFV and PBM protocols showed some improvements over Control, but their effects were smaller and less consistent. These findings highlight that HOT could be considered the most effective adjunctive modality for enhancing aligner efficiency in resolving lower incisor crowding.

Mean daily usage of the acceleration devices was highest in the HOT group, followed by the vibration and PBM groups. Correlation analyses between device usage time and changes in crowding were not statistically significant in any group.

Clear aligner wear time, recorded via patient compliance charts, did not differ significantly among the groups (p>0.05). No significant correlations were found between aligner wear time and crowding reduction in any group.

When evaluating the combined effect of aligner wear time and device usage, usage metrics were comparable among the groups, and combined usage analyses did not yield significant correlations.

DISCUSSION

Over the past decade, LFV and PBM have attracted increasing attention in orthodontics, particularly regarding their potential to accelerate tooth movement and improve patient comfort. The evidence remains inconclusive, with discrepancies mainly attributed to variations in study design, intervention protocols, and outcome measures. The present study adds to this growing body of research by assessing, during the early alignment phase of mandibular incisors treated with clear aligner therapy, LFV, PBM, and a combined HOT approach.

Vibration has been proposed to enhance OTM by modulating the bone remodeling cycle through mechanotransduction and increased PDL fluid flow.[23] However, the effect of LFV (≤30 Hz) remains controversial. Pascoal et al.[24] and Akbari et al.[25] reported that LFV generally failed to significantly accelerate OTM in both aligner and fixed appliance therapies. In contrast, HFV (>90 Hz) has shown more promising effects, particularly in canine retraction and space closure. Our results are consistent with these findings. LFV alone (30 Hz, 0.25 N [≈25 g], 20 min/day) did not significantly outperform the control group over the 62-day period. This parallels the clinical observations of Woodhouse et al.[26] and Lombardo et al.[27] who also failed to detect a statistically significant difference in alignment rate with LFV in clear aligner patients under certain conditions. The modest, non-significant reduction observed in our LFV group might reflect biological limitations of low-frequency stimulation or the short observation period.

PBM, typically delivered via low-level laser therapy (LLLT) or light-emitting diodes (LEDs), acts through photonic stimulation of mitochondrial chromophores, primarily cytochrome c oxidase, leading to increased ATP production, modulation of reactive oxygen species, and altered cellular signaling. These effects can enhance osteoblastic and osteoclastic activity, potentially accelerating bone remodeling.[28] Our PBM-only group, which received 850 nm LED light at 9.5 J/cm^2 for 20 min/day, did not show statistically significant results compared with the control, though a trend toward greater crowding reduction was observed. This aligns with a recent systematic review, indicating that PBM's clinical effectiveness is dose-, wavelength-, and protocol-dependent.[29] Variability in energy density, application intervals, and movement type likely accounts for inconsistent outcomes across studies. For example, Kau et al.[16] reported significant acceleration using similar wavelengths but different usage protocols, while Farhadian et al.[30] observed smaller gains with LED compared to laser sources.

The HOT protocol, integrating both LFV and PBM in a single device, demonstrated significantly greater alignment over 62 days than either modality alone, or control. This suggests a potential synergistic effect, vibration may enhance PDL mechanotransduction and fluid dynamics, while PBM may upregulate cellular metabolism and accelerate the RANK/RANKL/OPG-mediated remodeling cycle. Although clinical evidence for such synergy remains sparse, the biological plausibility is supported by our results and by mechanistic insights from previous *in vitro* and *in vivo* studies.[24,25,28,29]

Although LFV and PBM individually failed to achieve statistical significance, their combination was effective. It is possible that simultaneous mechanical and photonic stimulation engages complementary pathways, compensating for the limitations of each modality. This is particularly relevant in the early alignment of mandibular incisors, where tooth size, morphology, and aligner fit may limit movement efficiency.

The resolution of anterior crowding is often a critical determinant of patient satisfaction in the early stages of treatment. In clear aligner therapy, maintaining tracking accuracy and minimizing refinements are essential for efficiency. Previous aligner-based studies have shown HFV can shorten aligner change intervals,[17] while PBM has demonstrated potential for reducing treatment duration,[16] though not consistently. The superior performance observed in the HOT group suggests that this approach may enable an earlier transition to the finishing stages without increasing adverse effects, consistent with the absence of reported root resorption or discomfort in our cohort.

The short follow-up (62 days) was deliberate, capturing the leveling phase while all patients were in active anterior alignment, but it prevents conclusions about total treatment time. Furthermore, the LFV parameter used (30 Hz) may be suboptimal compared to HFV protocols that have shown clearer benefits. Future studies should include longer follow-up, objective compliance monitoring, and direct comparisons of LFV+PBM versus HFV+PBM.

While surgical methods such as corticotomy, piezocision, and micro-osteoperforations can significantly accelerate OTM,[16-19] their invasiveness, need for anesthesia, and patient reluctance may limit their applicability. Non-invasive methods like HOT may offer a viable alternative, especially for patients unwilling to undergo surgery. Though the absolute acceleration in our study is lower than that of surgical approaches, the favorable safety and comfort profile may make HOT a more acceptable choice for aligner patients.

In aligner-only cohorts, previous studies have reported modest, but clinically significant reductions in LII during the first 6-10 weeks, findings that are consistent with the changes observed in our control group.[21,22] For low-frequency vibration (≈30 Hz), several randomized clinical trials did not demonstrate clinically meaningful acceleration compared with aligners alone,[26,27] and recent systematic reviews also reported mixed or negligible effects.[24,25] Photobiomodulation (PBM), on the other hand, has shown protocol-dependent outcomes; while some early studies suggested accelerated alignment with near-infrared wavelengths,[16] more recent systematic reviews emphasize heterogeneity and dose-response considerations.[28,29] Trials comparing LED and laser sources generally showed smaller effects for LED devices.[30] Against this background, the combined HOT protocol in the present study demonstrated larger between-group differences and effect sizes than aligners alone or either modality used individually (Table 5), supporting a potential synergistic benefit during the early alignment phase.

It is important to distinguish between the amount of correction and the pace of tooth movement. The reduction in LII reflects the absolute amount of alignment achieved, whereas treatment pace is represented by the rate of change in LII per unit of time (ΔLII/day). Previous studies on aligner-only protocols reported average alignment changes of approximately 0.5-0.8 mm per month during the early treatment phase,[21,22] which is consistent with the modest improvements observed in our control group. In contrast, patients in the HOT protocol showed greater reductions in LII within the same time intervals, resulting in higher rates of alignment per day. This indicates that the observed differences are not only in the magnitude of correction but also in the acceleration of the alignment process.

Thus, the HOT protocol not only resulted in a greater absolute reduction in LII but also accelerated the rate of alignment compared with aligners alone. In our control group, the mean reduction in LII corresponded to approximately 0.26 mm per month, which is in line with previously reported aligner-only outcomes of 0.5-0.8 mm per month.[21,22] By contrast, the HOT group demonstrated significantly higher rates of correction per day, indicating a true acceleration of treatment rather than only a larger correction amount.

From a clinical perspective, the combined HOT protocol offers a non-invasive and patient-friendly adjunct to aligner therapy, potentially reducing treatment duration without additional chair time or surgical procedures, thereby increasing the practicality of accelerated orthodontics in daily practice.

CONCLUSION

Within the limitations of this retrospective study, combining low-frequency vibration and photobiomodulation (HOT) during clear aligner therapy resulted in a greater short-term acceleration of mandibular incisor alignment than each modality alone or the control. These findings suggest a potential synergistic mechanism, warranting further randomized trials to confirm efficacy, optimize parameters, and assess long-term safety.

Ethics

Ethics Committee Approval: This retrospective observational study was conducted at the Department of Orthodontics, Faculty of Dentistry, Yeditepe University. Ethical approval was obtained from the Marmara University Clinical Research Ethics Committee (approval no: 2020-425, date: 30.06.2020) in accordance with the Declaration of Helsinki.

Informed Consent: Retrospective observational study.

Footnotes

Author Contributions: Concept - M.Ö., D.N.; Design - M.Ö., D.N.; Data Collection and/or Processing - M.Ö.; Analysis and/or Interpretation - M.Ö.; Literature Search - M.Ö.; Writing - M.Ö.

Conflict of Interest: The authors have no conflicts of interest to declare.

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Review

Clear Aligner Attachments: A Comprehensive Review

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Main Points

- Attachments play a critical role in facilitating complex tooth movements, including rotation, extrusion and torque.
- Current evidence indicates that optimized attachments may offer some benefits, though their superiority over conventional designs is not consistently demonstrated.
- Careful selection of attachment design and position is essential to balance biomechanical efficiency with esthetic and patient-related considerations.
- Attachment selection and staged planning are of critical importance in managing complex or combined tooth movements.

ABSTRACT

Clear aligner therapy has gained significant popularity in orthodontics due to its aesthetic advantages and patient comfort. However, achieving complex and precise tooth movements with aligners often necessitates the use of auxiliary features such as attachments. This review explores the biomechanical role of attachments in clear aligner therapy and evaluates their effectiveness in facilitating various orthodontic tooth movements, including rotation, extrusion, intrusion, torque, distalization, and arch expansion. Attachments serve as critical components for enhancing force delivery, ensuring aligner retention, and improving the predictability of tooth movement. The morphology, quantity, and positioning of attachments have a direct impact on movement efficiency, patient comfort, and overall treatment success. The article highlights the importance of selecting appropriate attachment shapes (such as rectangular, ellipsoidal, or optimized designs) based on the intended movement. It emphasizes the relevance of strategic placement relative to the tooth's center of resistance. Furthermore, for cases requiring complex or combined movements, strategies such as phased treatment planning and the use of multiple or combined attachments are discussed. While optimized attachments have shown biomechanical advantages in some movements, clinical studies suggest that in many instances, their superiority over conventional attachments is not statistically significant, leaving the choice of design largely to clinician preference. This review underscores the necessity of individualized attachment planning to optimize biomechanics and improve treatment outcomes in aligner-based orthodontics.

Keywords: Attachments, clear aligner, invisalign, invisible orthodontics

INTRODUCTION

Orthodontic treatment has made significant progress over the past few decades, with clear aligner therapy emerging as a popular alternative to traditional fixed appliances. Initially introduced as a solution for mild orthodontic issues, clear aligners have evolved into a sophisticated treatment method capable of addressing complex malocclusions.[1,2] Their aesthetic appeal, comfort, and ease of use have contributed to their widespread acceptance among patients.[3]

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In terms of aesthetics and comfort, clear aligners present a favorable alternative to traditional fixed orthodontic treatments. However, the literature also highlights concerns regarding the biomechanical limitations of clear aligners when compared to fixed treatments.[4] The biomechanical debate surrounding aligner therapy stems from differences in force transmission mechanisms and the need for additional mechanics to achieve certain tooth movements, such as mesialization or intrusion.[5] Unlike continuous force application in fixed appliances, aligners rely on intermittent forces that can diminish over time, making them less efficient in controlling specific types of movements. This challenge becomes more evident in root torque, bodily movement, and vertical control, all of which require more sophisticated biomechanics.[4]

A critical factor influencing the success of clear aligner treatment is the incorporation of auxiliary features, such as attachments, which are designed to enhance the biomechanical capabilities of the aligners. Attachments are small composite structures bonded to the teeth to improve appliance retention and facilitate specific movements, such as rotation, extrusion, or controlled tooth movements.[6] These adjuncts significantly increase the predictability of treatment outcomes by modifying the force application mechanism of the aligners.[7] Research has demonstrated that the placement, shape, size, and number of attachments can significantly influence the effectiveness of orthodontic treatment.[4] Each attachment's design must correspond precisely to the desired tooth movement, with considerations such as surface area contact, aligner deflection points, and resistance centers being critical to biomechanical success. Moreover, optimizing the attachment's orientation in relation to the aligner's insertion path can further improve force delivery.[5]

In this context, a deeper understanding of the forces and moments generated by different attachments, as well as their biomechanical principles, is essential for selecting the appropriate attachments and ultimately improving the effectiveness and efficiency of orthodontic treatment. Advances in digital orthodontics and artificial intelligence have enabled more precise customization of attachments to meet the specific biomechanical needs of each case. These technological innovations, in conjunction with ongoing research into material properties and force dynamics, continue to enhance the scope and efficacy of clear aligner therapy.[2,6] AI-powered treatment planning software can simulate and adjust force vectors based on patient-specific dental and periodontal conditions, offering a more personalized approach to attachment placement. This integration supports clinicians in developing evidence-based treatment plans that maximize efficiency and minimize complications.[8]

Clear aligners have yet to fully match the mechanical advantages offered by traditional bracket-based treatments. To mitigate the biomechanical limitations of aligners, particularly in complex cases, additional methods-such as attachments, buttons, power arms, precise cuts on the aligners, bite ramps, temporary anchorage devices, and intermaxillary elastics-are often employed. These auxiliaries, when applied strategically, can provide enhanced anchorage, better vertical and sagittal control, and facilitate movements that would otherwise be inefficient or unpredictable with aligners alone.[5]

This article aims to provide a comprehensive review of the biomechanical principles, design considerations, clinical applications, and potential limitations of attachments. By synthesizing the available evidence, the review seeks to emphasize the critical role of attachments in enhancing the effectiveness of clear aligner therapy.

Key Features and Clinical Implications of Attachments in Aligner Therapy

Attachments are composite additions that are temporarily bonded to the surfaces of teeth to enhance the interaction between the aligner and the tooth during clear orthodontic treatments.[8] The concept of attachments was originally introduced by Martz[9] in 1988, who described a removable device for positioning teeth and suggested using composite "buttons" as anchoring points for aligners to facilitate movement.

Attachments come in various shapes, sizes, and orientations, tailored to assist specific types of movements or to fit the natural contours of dental crowns. Initially, ellipsoidal and rectangular shapes were used,[10] with vertical and horizontal orientations as the primary options. These attachments can be placed on either the buccal or the palatal-lingual surfaces.

Attachments' Components

Attachments consist of three main components: an active surface, a passive surface, and a base. The active surface is the part that comes into contact with the aligner, enabling it to exert the necessary force vectors, for desired tooth movements. This means that the active surface receives the pushing forces from the aligner. The orientation of this surface determines the direction of the force vectors, with efficient vectors typically being directed perpendicularly to the active surface.

The passive surface is the part of the attachment that forms its buccal face, and provides stability and supports the fitting of the aligner with minimal interference. If the passive surface has a low volume, it can be detrimental as this increases the risk of fractures, wear, or detachment of the attachment, thereby compromising its durability. This is particularly important given that the composite materials used today for attachments are subject to gradual wear of their surface texture.

An additional concept related to attachment terminology is the bevel. A bevel refers to an angled cut at the edge or tip of an attachment, which changes its pointed end into a smooth, inclined surface. The idea of using a bevel emerged due to fitting challenges with rectangular attachments, which require the aligner to be fully seated over the attachment; as the angle of emergence at the junction between the tooth and the attachment forms a right angle. By incorporating a bevel, aligner adaptation becomes more seamless, as the aligner needs to fit over the corner of the beveled attachment.

The angle of emergence in a beveled attachment exceeds 90°, allowing the tooth to slide more easily into the aligner during the first few hours of wearing each new aligner. Conventional attachments, which have at least one beveled edge, are beneficial for both tooth movement and anchorage. Beveled attachments are designed to enhance biomechanical efficiency in aligner therapy by considering the direction of force and the center of resistance of the tooth. In cases where extrusion is required, gingivally inclined attachments are considered appropriate, while for rotated teeth, attachments inclined mesially or distally may be preferred. For both rotated and infra-positioned teeth, the attachment inclination can be designed to balance both axes (for example, inclined in the mesiogingival direction). Additionally, it has been reported that palatally positioned beveled attachments provide both an aesthetic advantage and more effective force transmission compared to labially positioned ones.[11]

Importance of Attachment Material

Attachments are critical components through which force is transmitted to the teeth, and for effective force transmission, both the attachment and the aligner must maintain contact under high stress. Therefore, it is crucial to minimize unwanted attachment debonding.

It has been observed that when more rigid and thicker attachment plates are used, the attachments are formed with higher accuracy; however, the risk of attachment breakage increases during plate removal after the attachments have been polymerized.[12] The effect of composite viscosity on attachment performance has been investigated, and it has been concluded that as the filler content of the composite increases, both shear strength and force transmission efficiency improve. However, when the filler content exceeds 72%, further increases do not result in a significant improvement in the bonding performance of the attachment.[13] As a result, flowable composites or orthodontic bonding composites are considered the most suitable materials for bonding attachments.[11]

Location of Attachments

The location of attachments is closely related to the optimal point of force application and the retention of the aligner. According to biomechanical principles, the farther the point of force application is from the center of resistance of the tooth, the greater the moment it generates. Attachments placed closer to the gingival margin produce less moment than those positioned near the occlusal surface. Studies have shown that in specific tooth movements such as extrusion, maximum retention can be achieved by placing the attachment closer to the gingival margin and using attachments without gingival inclination. In cases where maximum retention is not required, attachments facilitating appliance removal may be preferred.[14] Attachments should be placed at least 1.5 mm away from the gingival margin to prevent undesirable plastic deformation; this distance should also be maintained from other limiting surfaces.[15]

In rotational movements, attachments can be placed on the mesial and distal corners of the tooth to increase the rotational moment. For example, in a case requiring mesiopalatal rotation, the effectiveness of the movement can be enhanced depending on the position of the attachment. However, if not properly positioned, the applied force may cause tipping and lead to undesired tooth movement (Figure 1).[16]

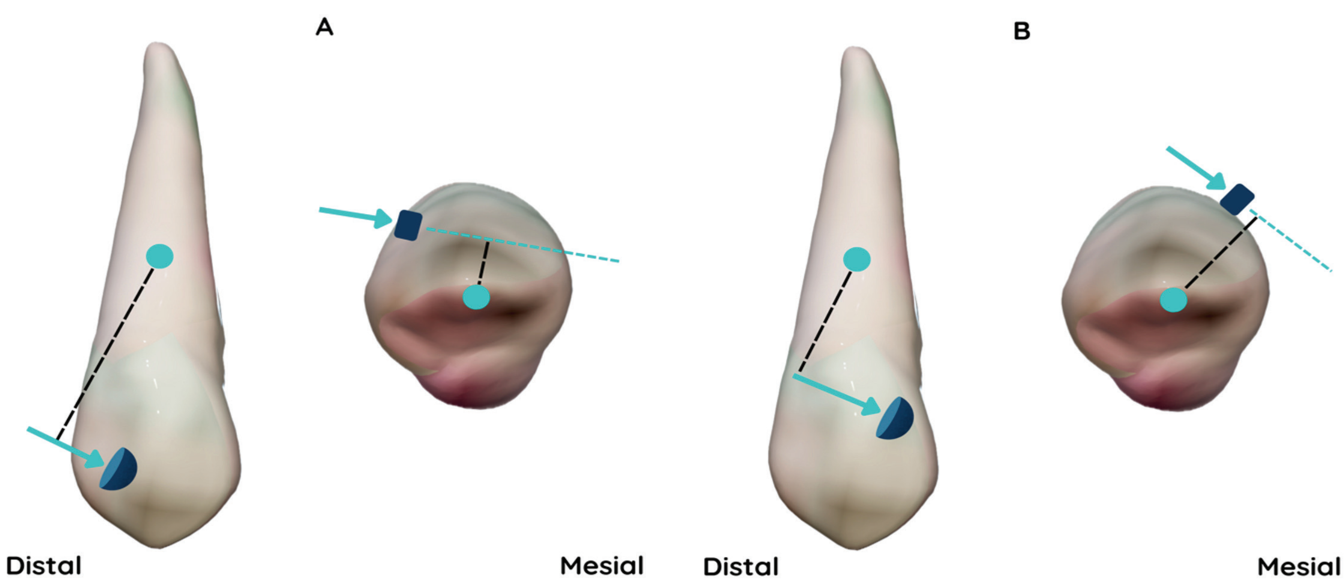


Figure 1. Schematic representation of the effect of attachment position on tooth movement. A) By placing the attachment in a more incisal and distal position, the distance between the direction of the force (blue arrow) and the center of resistance (blue dot) (black dashed line) increases in the labial view of the tooth, but remains negligible in the incisal view. As a result, more mesial tipping movement and less mesiopalatinal rotational movement have been observed. B) The attachment has been moved to a more gingival and mesial position, reducing the distance of the tipping force to the center of resistance (labial view). In the incisal view, the distance of the force responsible for rotating the tooth to the center of resistance has increased. Consequently, the moment responsible for tipping the tooth has been reduced, while the moment that rotates the tooth has been increased, thereby establishing a more efficient mechanism for derotation

A recent finite element analysis (FEA) study showed that placing horizontal rectangular attachments on the lingual surfaces of first molars, generates greater tipping moments than on the labial surfaces, especially during transverse arch expansion, highlighting the biomechanical importance of attachment positioning.[17]

Attachment Size

In achieving the desired tooth movements, the size of the attachments is as important as their location. As a general rule, more complex movements require larger attachments. However, it should be noted that larger attachments, especially in the anterior region, may pose aesthetic disadvantages. By optimizing the size of the attachments according to both aesthetic and functional needs, the treatment time can be reduced and the success rate increased.[18] The appropriate attachment sizes for different types of attachments are shown in Table 1.

According to the study by Ahmad et al.,[19] the effects of attachment size are listed as follows:

1. The force and the moment increase with the thickness, length, and width of the attachment.

2. The attachment size has only a mild effect on moment/force.

3. The direction of force is better aligned with the desired movement direction when a larger attachment size is used.

4. The appropriate force magnitude can be obtained by selecting the right attachment size.

Attachments' Classification

Attachments used in the aligner system are generally classified in two ways: according to their function or their optimization status.

Attachments According to Their Function

Attachments are classified as active or passive based on their function. Attachments can be added to increase the retention of the aligner (passive attachment) or to facilitate tooth movement (active attachment). Detailed information on the use of attachments in each situation is provided under the heading "Attachments' Function."

Conventional and Optimized Attachments

Another classification distinguishes between optimized and conventional attachments. The concept of optimized attachments is specific to the Invisalign system, and the shape of the attachment varies according to the morphology of each tooth and the type of movement.[20] Conventional attachments refer to the remaining attachments, which are not tooth- or movement-specific.

Conventional and Optimized Attachment Comparison

Several previous studies have compared and evaluated the effectiveness of optimized and conventional attachments in different tooth movements. The optimized rotation attachment was the first design introduced by Invisalign. Karras et al.[10] retrospectively compared the effectiveness of optimized rotation attachments and conventional attachments in correcting rotations of canines and premolars. The results showed that optimized attachments achieved slightly higher success rates, and these differences were statistically significant.

In a retrospective study by Hassanaly et al.[21] examining 147 incisors, divided into two groups-vertical and optimized attachment-it was found that optimized attachments were more effective for the rotation of lateral incisors. However, vertical conventional attachments were more successful in correcting mesiodistal angulation. For torque movements, horizontal attachments were reported to perform best.[21]

In a retrospective study by Burashed and Sebai[22] which investigated deep bite treatment with Invisalign using two groups-optimized and conventional attachments-it was found that optimized attachments were not more successful than conventional attachments in correcting overbite. The study also discussed the difficulty of correcting deep bite, independent of the type of attachment used. Anterior open bite correction was examined by the same researchers using horizontal conventional and optimized extrusion attachments in two groups. Both groups successfully corrected the open bite, but the study showed that optimized attachments reduced the treatment duration.[23]

Karras et al.,[10] analyzed the effectiveness of conventional designs compared to optimized extrusion attachments for the extrusion of anterior teeth using the Invisalign system. The results showed that while the mean extrusion achieved with optimized attachments was slightly higher (0.14 mm or 4.3%), there was no clinically or statistically significant difference. Similarly, in their study investigating traditional designs that assist rotation, they did not specify the characteristics such as location, size, orientation, or inclination of the conventional attachments used for extrusion.

In a retrospective study, Stephens et al.[24] compared two groups using optimized rotation attachments (changed weekly and biweekly) with another group using conventional vertical rectangular attachments (changed biweekly) to correct mandibular canine derotation with Invisalign aligners. The results showed that the group with optimized attachments that were changed weekly achieved the highest success rate (81.5%), followed by the group with optimized attachments that were changed every 14 days (76.5%). The group using conventional attachments had the lowest rotation movement expression rate ((63.1%), but this group also managed more severe rotations.

Table 1. Some commonly used attachments and their shapes

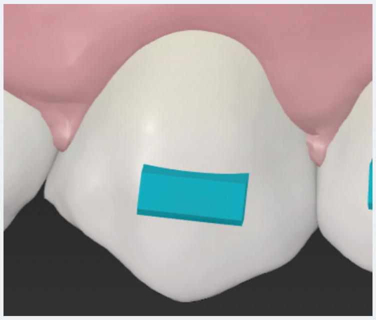
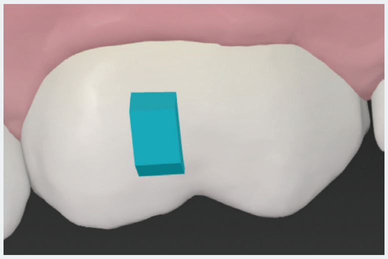
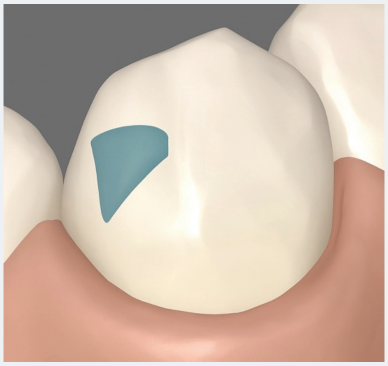
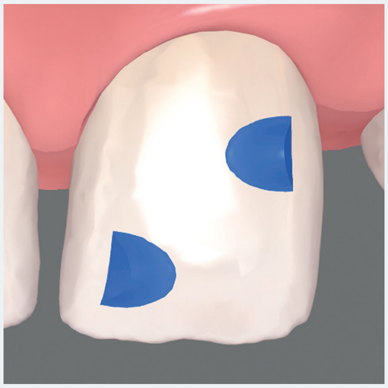
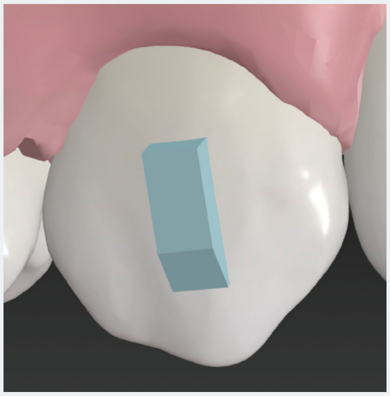
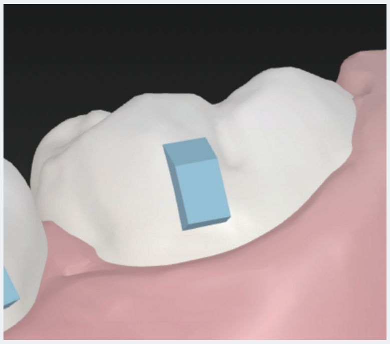
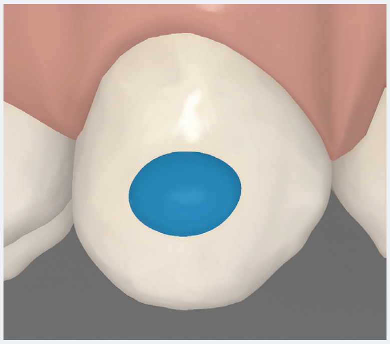
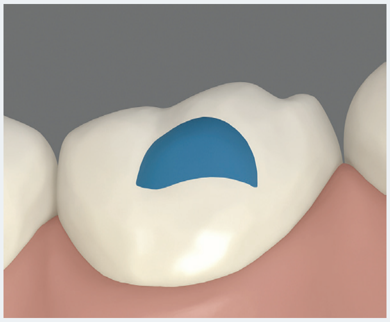
Attachment's name	Attachment's design	Dimension	
		Mesiodistal	Occlusogingival
Horizontal rectangular attachments		2-5 mm (It depends on the clinical conditions)	2-5 mm (It depends on the clinical conditions)
Vertical rectangular attachments		2-5 mm (It depends on the clinical conditions)	2-5 mm (It depends on the clinical conditions)
Rectangular attachments placed on the lingual surface		2-5 mm (It depends on the clinical conditions)	2-5 mm (It depends on the clinical conditions)
Optimized rotation attachments (invisalign)		Clear aligner provider determined based on planned tooth movement	Clear aligner provider determined based on planned tooth movement
Optimized Root control attachments (invisalign)		Clear aligner provider determined based on planned tooth movement	Clear aligner provider determined based on planned tooth movement

Table 1. continued			
Attachment's name	**Attachment's design**	**Dimension**	
		Mesiodistal	Occlusogingival
Incisally inclined attachments		2-5 mm (It depends on the clinical conditions)	2-5 mm (It depends on the clinical conditions)
Occlusally inclined attachments		2-5 mm (It depends on the clinical conditions)	2-5 mm (It depends on the clinical conditions)
Cylindrical/ellipsoid attachments		2-3,5 mm (It depends on the clinical conditions)	1-3 mm (It depends on the clinical conditions)
Optimized extrusion attachments (invisalign)		Clear aligner provider determined based on planned tooth movement	Clear aligner provider determined based on planned tooth movement

A FEA study by Goto et al.,[8] which examined the effects of optimized and conventional attachments on models with extraction spaces, used eight different optimized and three different conventional attachment models. No significant differences were found in the overall comparison of tensile force and tipping moment. However, it was revealed that larger conventional attachments generated 7% more tensile force and tipping moment compared to optimized attachments. However, this result did not result in a significant difference.[8]

When reviewing the existing clinical studies, no significant differences were observed in the effects of optimized and conventional attachments across nearly all types of movements. Therefore, it would be more accurate to conclude that using optimized attachments or alternative attachments depends on the doctor's preference.

Attachments Function

Attachments serve two primary functions: mobilization and retention.

Active Attachments

In cases where the appropriate tooth morphology is insufficient for tooth movement or when root movement cannot be achieved even if the appropriate morphology is present, active attachments are used. For example, if rotational movement is desired in conical premolar and canine teeth, or if extrusion movement is required in any tooth, the aligner would slip during the movement if the attachment is not added. This would prevent the planned movement from occurring. This phenomenon can be referred to as the "traffic cone effect." Traffic cones are designed to easily overlap and facilitate rotational movements due to their structure when placed on top of each other. If no attachment is used, the aligner will sit on the tooth like a cone, moving on its own, without applying force to the tooth during rotational or extrusive movements (Figure 2). This is where active attachments come into play. Tooth movements performed with aligners are as complex as those achieved in fixed orthodontic treatments. Below, we have summarized the relevant publications concerning these movements, with each movement presented under a separate heading. In addition, Table 2 provides a summary of which type of attachment is more suitable for each specific tooth movement.

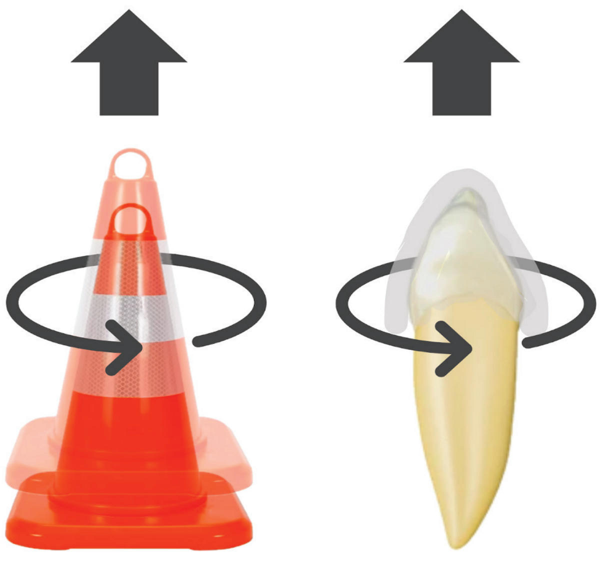


Figure 2. Traffic cone effect. When rotational and upward forces are applied to the upper cone of overlapping cones, the upper cone moves, while the lower cone remains stationary. Similarly, rotational and extrusive forces applied by the aligner to the canine tooth, as observed from the lateral side, cause the position of the aligner to shift, rather than the tooth itself

Table 2. Types of attachments that can be used for different types of movements

Type of movements	Attachments	Recommendations
Extrusion	Horizontal retrangular attachments optimized extrusion attachments	Focus should be on the apical part of the active surface during extrusion of incisors. Optimized designs may be preferred for symmetrical force transfer during attachment placement.
Intrusion	Horizontal rectangular attachments	Attachments can also be used on adjacent teeth to increase plate stability during intrusion. Large and wide surface attachments should be preferred to ensure balanced force distribution.
Expansion	Occlusally inclined attachments cylindrical attachments	Occlusally inclined attachments should be added to molars to prevent uncontrolled buccal tipping during arch expansion. Controlled movement of teeth should be provided with additional torque support when necessary.
Rotation	Vertical rectangular attachments optimized rotation attachments	In rotation movements, attachments optimized especially for lateral incisors can be used. Attachments providing flat surfaces should be preferred for conical teeth such as canines.
Distalization	Vertical rectangular attachments guideline attachments	Attachments should be placed on both buccal and palatal surfaces of upper molars during distalization. Double-sided attachments are recommended to prevent tipping during distalization.
Torque	Semi-ellipsoid attachments horizontal attachments power ridge	In torque movements of maxillary incisors, attachments placed close to the gingiva should be preferred. In canine teeth, cylindrical attachments placed palatally are more useful. In torque movements, it is necessary to plan the movement exaggeratedly, because in most cases, tooth movement lags behind the planning.

Rotational Movement

Rotational movements are among the most challenging movements for aligners to achieve. These movements are particularly difficult in teeth classified as "round" in the literature.[6] This is because for an aligner to apply an effective force, it requires a flat surface . When the tooth shape does not provide such a surface, attachments play a critical role. In incisors, the rectangular shape covered by the aligner provides a flat surface, allowing the aligner to apply force at the edges and rotate the tooth into the desired position.

Studies have shown that applying force in the correction of premolar rotation without attachments is minimally effective. Additionally, vertical rectangular attachments have been found to produce the most effective results.[25] Additionally, Fiorillo et al.[26] have confirmed that there is no significant difference between the use of optimized attachments and vertical rectangular attachments in rotation correction.

Extrusional Movement of Upper Incisors

Clear aligners, which accommodate teeth of varying shapes, move teeth sequentially to the desired position by applying thrust forces. However, some tooth movements, such as incisor extrusion, present challenges for clear aligners due to the lack of a sufficient thrust surface.

A study by Savignano et al.[27] concluded that extrusion of the upper central incisor is not possible without the use of attachments. The study also found that the position of composite attachments had a stronger effect on tooth movement, while different composite attachment shapes in the same position produced equal extrusion forces.[27]

In contrast, a study by Costa et al.[28] utilized specially designed composite attachments, modified from conventional attachments, to extrude the upper central incisor. The study demonstrated that different attachment designs produced significantly varying directions and magnitudes of force.[28]

Laohachaiaroon et al.,[29] used the finite element method to study the initial displacement of a 0.15 mm extrusion of the upper central incisor with different attachment shapes. The attachment shapes examined included a horizontal rectangular attachment with an active surface thickness of 1 mm and no slope, a horizontal rectangular attachment inclined toward the gingiva with an active surface thickness of 0.25 mm, and a horizontal ellipsoidal attachment with an active surface thickness of 0.5 mm. In all models, the primary pressure area of the aligner was located on the cervical surface of the attachments, and the stress distribution in the periodontal ligament was similar. The highest extrusion was achieved with the horizontal rectangular attachment model without slope, followed by the ellipsoidal attachment. The horizontal rectangular attachment inclined toward the gingiva (simulating an optimized extrusion attachment) showed the lowest degree of extrusion due to its smaller active surface area compared to the other models. However, these differences were not clinically significant.

Rossini et al.[30] demonstrated that rectangular horizontal attachments located on the buccal or palatal surfaces of the upper incisors constitute the most effective force system for incisor extrusion. Based on this, it can be concluded that attachments with an active surface on the apical part of the upper incisor extrusion can facilitate movement when used with aligners.

Intrusional Movement of Molars

Plates facilitate the intrusion of teeth by covering the entire surface of the teeth and exhibiting "block effect" on the molars.[31] Transparent aligners have been reported to provide excellent clinical vertical control, particularly on the molar.[32] These aligners have been especially prominent in open bite cases, where posterior teeth intrusion is used as part of the treatment.[33]

A study evaluating different attachments and intrusion without attachments found that intrusion with attachments was significantly more effective.[34]

FEA study[33] examined the effect of attachment location on the intrusion of the second molar, specifically focusing the first molars. Horizontal rectangular attachments were placed either buccally, palatally, or both buccally and palatally on the upper first molar to simulate second molar intrusion. The results showed that the most effective second molar intrusion and the least tipping were achieved using horizontal rectangular attachments, placed both buccally and palatally. Additionally, this attachment configuration exhibited the most balanced stress distribution. In cases where no attachment was added, or a buccal attachment was used, buccal tipping was observed, whereas palatal tipping occurred when a palatal attachment was added.[33]

Bodily Movement

As with all orthodontic mechanics, the distance between the applied force and the center of resistance of the tooth directly affects the moment of force applied with aligners. As this distance increases, the resulting moment increases proportionally. As a result, the direction of the net moment causes the tooth root to rotate in the direction of the applied force. Transparent aligner systems are inadequate in mesiodistal root positioning because these systems do not generate the necessary force couples. This limitation explains the difficulty in changing the angulation (tilt) of the anterior teeth. Therefore, to enhance second-order control, transparent aligner systems rely on special attachments that can generate equivalent force couples.[16]

In the existing literature, there are studies confirming that the use of attachments leads to bodily movement.[16] However, Goto et al.[8] reported that attachments had no effect on the tensile forces and tipping moments.

Torque Movement

Achieving torque movement in teeth using aligners is one of the challenges. While buccolingual tipping movements can typically be achieved easily, root torque in the anterior region presents a significant challenge in transparent aligner-based treatments. The structure of aligners causes a decrease in rigidity in the gingival area, preventing the transmission of the gingival force necessary for torque control. In the absence of attachments, the center of rotation shifts toward the apex, resulting in tipping rather than root movement. Studies using different attachment models have shown that ellipsoidal attachments and power ridges facilitate torque movement and reduce crown tipping. No significant differences were found between these two auxiliary mechanics, and horizontal rectangular and cylindrical attachments showed similar torque values to models without attachments.[6]

The torque control and retraction of the anterior teeth are dependent on the establishment of proper posterior tooth anchorage. This anchorage can be enhanced by adding attachments to the teeth from the canine to the second molar.[35]

For torque movements, attachments are placed on the lingual (palate side) or buccal (cheek side) surfaces to ensure the proper transmission of force to the tooth root. In a FEA study by Karsli et al.[36] on palatally positioned lateral teeth, labial (front surface) attachments showed less tipping compared to palatal (roof of the mouth surface) attachments. The study also revealed that positioning the combined labial attachment closer to the incisal edge and using it in conjunction with the palatal attachment minimized tipping.[36]

In a study conducted using cone beam computed tomography, the success rate for torque planning of more than 5 degrees was found to be approximately 47%.[37] It should also be noted that in movements exceeding 10 degrees, a torque loss of approximately 50% may occur.[6]

In conclusion, attachments and power ridges may not be sufficient to achieve the desired result in teeth requiring torque movement, and the need for overcorrection or refinement should not be overlooked.

Distalization Movement

A systematic review evaluating the predictability of orthodontic movements with clear aligners found that molar distalization was the most predictable movement.[1,2] A retrospective clinical study showed that molar distalization had the highest effectiveness of approximately 87%, outperforming movements like incisor torque and premolar derotation.[6]

It is correct to say that there is no consensus on the role of attachments in distalization movements with clear aligners. In one case-control study and another retrospective cohort study, it was concluded that attachments play a significant role in enhancing the effectiveness of molar distalization.[38] In contrast, a systematic review, an FEA study, and a prospective study emphasized that the role of attachments in distalization movements with clear aligners is minimal.[39] Ravera et al.[40] showed that in the distalization movement of the first and second molars, with distances of 2.25 mm and 2.5 mm, respectively, no significant distal tipping was observed. They attributed this lack of tipping to vertical rectangular attachments.[38] Similarly, in the case report by Yurdakul and Karsli,[39] which applied sequential distalization at two different rates with the same types of attachments used in each group, the distal tipping movement yielded results similar to those found in previous studies.

When evaluating all these studies, the following conclusion can be drawn: Although attachments may not directly affect the success of distalization movements with aligner systems, their use can be beneficial for predictable bodily movement and root control.

Passive Attachments

Passive attachments, which serve the retention function of attachments, are used to increase the retention of aligners. These attachments are especially useful in cases of microdontia, missing teeth, short crown lengths, and incompletely erupted teeth.[41] In some instances, even when teeth are of normal morphology and number, it may still be necessary to enhance the retention of the aligner. For example, patients with precise cuts made on their aligners and rubber bands used to engage these cuts may require additional retention. If a retaining attachment is not used in such cases, the aligner may be dislodged by the forces exerted by the rubber bands.

Increasing the retention of the aligner is also crucial for active movements. For instance, in intrusion cases, attachments are necessary on neighboring teeth. If intrusion is planned for the anterior teeth, the aligner will apply a force to push the anterior teeth apically. However, this force will cause the posterior region of the aligner to lift off the teeth. To prevent this, passive attachments added to the posterior part of the aligner will ensure that the plate remains stable, aiding the intrusion of the anterior teeth. As the number of attachments increases, the retention of the aligner is also enhanced.[42]

The shape and position of the attachments also play an important role in retention, in addition to the number of attachments. A study comparing horizontal rectangular attachments with occlusal and gingival inclination compared to a vertical rectangular attachment found that the vertical rectangular attachment provided the highest retention, followed by the horizontal rectangular attachment with occlusal inclination.[14] Attachments placed closer to the gingival area showed higher retention than those closer to the occlusal surface. The higher retention of the occlusal inclination attachment may be due to the design of providing a surface that is perpendicular to the extrusion movement. Consequently, the aligner with horizontal rectangular attachments with occlusal inclination is easier to attach and more difficult to remove. For similar reasons, the optimized extrusion attachment used by

Align Technology for anterior teeth features a gingival surface inclination. This design creates a less retentive area in the anterior gingival region, where the aligner is more rigid.[4]

However, it is important to note that too many attachments can be detrimental. Adding attachments to every tooth to increase retention can lead to undesirable effects if the planned movements do not occur. In such cases, the system may experience deformations, and the aligner may lose its effectiveness.[42]

Effect of Attachments on Aligner Retention and Gripping Force

Gripping force refers to the force applied to hold an object steady or prevent it from being displaced. In the case of clear aligners, although they are firmly attached to the teeth, their retention can be influenced by various factors, including tooth morphology and position, degree of malocclusion, aligner material, and the duration of appliance use.

To better control orthodontic tooth movement during aligner treatment, the placement of attachments has been recommended to strengthen the retention force of aligners. Various types of attachments have been developed to improve retention within these systems.

Studies have shown that thicker aligner materials increase retention, and longer aligner edges enhance it.[16] Increasing the number of attachments can make aligners more difficult to remove, reducing user comfort and potentially decreasing the amount of time patients wear their aligners.

In a study on gripping force by Takara et al.,[4] the force required for the removal of an aligner varied depending on the placement location and morphology of the attachments. It was demonstrated that increasing the thickness of the rectangular attachment placed on the lateral incisor and increasing the size of the semicircular attachment placed on the first premolar contributed to an increase in retention force on the labial side of the aligner. The study also found that the undercut area of the attachments played a significant role in enhancing the retention of the aligners. However, as the undercut area increased, the aligners also experienced more deflection in this region.[4]

Effect of Attachments on Expansion Movements

Since buccolingual tilting is one of the movements that are easier to achieve with clear aligners, clear aligners are commonly used in patients requiring mild to moderate tooth-alveolar expansion.[4]

When clear plates are used to expand the arches in individuals who have completed their growth period, correction involves buccal tipping of the posterior teeth, causing the palatal cusps to move in the occlusal direction. To minimize this tipping and provide more controlled movement of the teeth, torque compensation has been suggested by adding buccal root torque.[43,44]

The application of horizontal rectangular attachments to the posterior teeth has been suggested as one way to improve arch expansion with clear aligners.[20] Yao et al.[43] studied different attachment designs during expansion with clear aligners, including round, cubic, and cylindrical shapes with compensatory torque. The study found that torque transmission was nonlinear, with the cylindrical design being the most effective type among the attachments tested. However, this design is not commonly used in clinical practice.

Zhang et al.[44] used FEA to study the effects of additional torque and concluded that it was effective in controlling tipping, but it reduced the efficiency of maxillary arch expansion. In a study by Karsli et al.,[45] FEA was used to examine the effect of different attachments on tipping movement. The study found that expansion with clear aligners caused buccal and mesial tipping of maxillary molars, with the amount of buccal tipping increasing from the first to the second molars. The addition of occlusally inclined attachments and buccal torque compensation resulted in a significant reduction in the rate of uncontrolled buccal tipping.

Role of Attachments on Extraction Cases

Extraction cases treated with clear aligners are one of the challenges that aligners need to overcome. To close the extraction space, different anchorage methods and attachment designs have been proposed to achieve bodily movement of the anterior teeth without tipping and to ensure torque control. The common belief in this regard is that vertical or horizontal attachments placed on the canine, premolars, or molars are beneficial for anchorage retention and tooth movement.[46]

In extraction cases, the goal of the G6 protocol developed by Invisalign is to achieve torque control, bodily movement, and anterior vertical control. For this purpose, optimized attachments are preferred. To prevent anchorage loss in the posterior teeth, optimized anchorage attachments are used on these teeth, while optimized root control attachments are used to manage the angulation of the canines.[47] This is shown in Figure 3.

Attachment Hierarchy in Combined Movements

In clinical practice, it is rare to apply a single type of movement to a tooth. Typically, a combination of movements is required, such as torque, rotation, and angulation correction. Therefore, what type of attachments should be used in such cases?

Three different options arise when dealing with multiple movements. One approach is to prioritize the movement that is most dominant. For example, if both torque and angulation movements are involved, but torque is the more dominant movement (and is also more challenging to achieve), a horizontal attachment may be preferred. However, in this approach, the secondary movement may not be achieved as accurately.

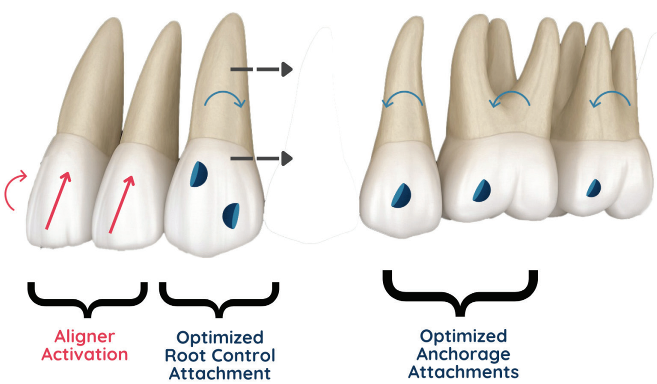


Figure 3. In the invisalign G6 protocol, the attachment procedure for extraction cases is as follows: To facilitate the parallel movement of the canine tooth in the extraction space, an optimized root control attachment (optimize retraction attachment) is used. This attachment allows for the correction of the canine tooth's angulation, represented by the blue arrow. To prevent anchorage loss in the posterior teeth, optimized anchorage attachments are employed. The effect of these attachments is also depicted by the blue arrow. Additionally, the central incisors are aimed to be retracted in a controlled manner through plaque activation

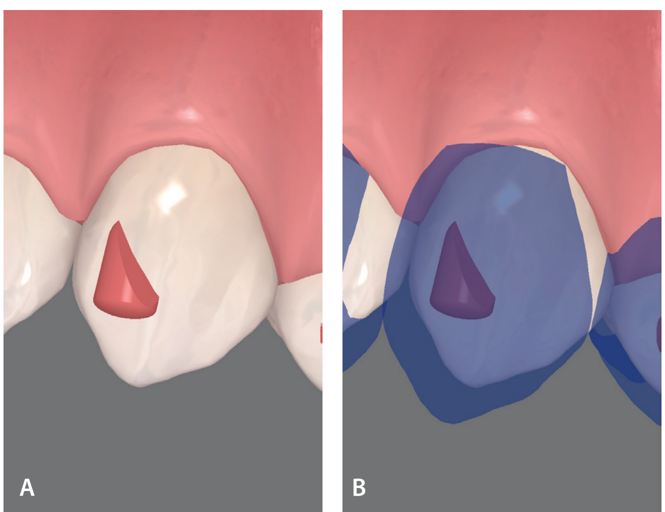


Figure 4. A) Optimized rotation attachment added to the upper left canine tooth in the Invisalign system. B) Final tooth position is simulated in blue. Rotational and extrusive movements were planned for the relevant tooth. In order to facilitate both rotation and extrusion, the active surface of the attachment was designed to face both the gingival and distal directions, rather than in a single direction. Note that the attachment position was moved to the mesial position due to the greater extrusion movement required in the mesial direction and the need for mesiopalatial rotation of the tooth.

A second approach involves changing the attachment geometry. The goal is to increase the surface area of the attachment to enhance force transmission.[48] This may involve using combined attachments, such as a horizontal attachment for torque and a vertical attachment for angulation. By combining attachments into a larger, angled attachment, the surface area is increased, improving the accuracy of the movements.

The third approach, seen in systems like Invisalign, involves using optimized attachments designed specifically for each tooth. These attachments are designed to apply combined movements in a single design. For example, Figure 4 shows an optimized rotation attachment applied to a canine tooth. The active surface of the attachment faces two different directions (gingival and distal), and the attachment is relatively large. This configuration allows for both rotational and extrusive movements to be performed effectively.

Attachments with more surface area provide more movement accuracy.[11,49,50] However, this situation may lead to an increase in the retention of the aligner and therefore to patients having more difficulty in putting on and taking off the aligners.[49] In addition, the use of larger attachments may cause a negative perception of the aesthetic. According to an eye screening study, people's attention is focused more on the oral area when using larger attachments.[50] This reduces the "unnoticeable" property of the aligners.

A third way of executing combined movements is to stage the movements and apply a different attachment type at each stage. This method gives more accurate results than the use of combined attachments.[48] Castroflorio et al.[49] stated that movement accuracy can be increased with three-dimensional planning and staging.

CONCLUSION

Attachments are crucial components of clear aligner treatments, directly influencing their effectiveness. Proper attachment selection and placement are essential for achieving predictable and accurate results. As treatment protocols continue to evolve, further research into attachment design and usage will improve the clinical efficacy and comfort of clear aligner systems. The information provided here offers valuable guidance for clinicians and researchers, helping to optimize treatment plans and contributing to the future development of these systems. The success of clear aligner treatments relies on the correct selection of attachments, thoughtful attachment design, and well-planned movement phases to the biomechanical challenges associated with them.

Footnotes

Author Contributions: Concept - A.Y., H.C.; Design - A.Y., H.C.; Data Collection and/or Processing - A.Y., M.S.; Analysis and/or Interpretation - M.S.; Literature Search - A.Y., M.S.; Writing - H.C.

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