



Comparison of the effects of maxillary expansion applying rapid maxillary expanders or clear aligners in mixed dentition

A 3D finite element study

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Abstract

Purpose To compare maxillary expansion achieved through the use of a rapid palatal expander (RPE) or clear aligner systems (incorporating variable buccal and palatal attachments) during mixed dentition.

Methods The study employed the ANSYS SpaceClaim (SpaceClaim Corporation, Concord, MA, USA) software for reverse engineering and computer-aided design (CAD) tasks, utilized the ANSYS workbench for model adaptation and mesh generation, and applied the LS-DYNA solver for the resolution of the finite element model. The posterior cap splint RPE, clear aligners with buccal attachments on teeth 55, 65, 16, and 26 (CAB), and clear aligners with palatal attachments on teeth 16 and 26 (CAP) were used in the study. The appliances were modeled based on two distinct scenarios: (1) an expansion of 0.2 mm per activation of the RPE splint or per aligner; (2) a total expansion of 8 mm. The results were evaluated using finite element analysis.

Results In the first scenario (0.2 mm activation), maximum stresses on the first molars for the RPE, CAB, and CAP models were 47.649, 26.653, and 14.040 MPa, respectively. In the second (8 mm total activation) scenario, they were 1854.022, 665.629, and 559.368 MPa. Across all models, stress levels ranked in descending order at the Z point, PNS, ANS, and A point, with RPE showing the highest overall stress values.

Conclusion The RPE induced greater stress (indicated by red zones) on the palatal region, particularly on the palatal and buccal surfaces of the buccal segments and on the gingival area of the incisors, compared to the other two appliances. Only the RPE group showed high stress distribution in the region of the midpalatal suture. Stress on the teeth was more pronounced following the RPE compared to aligners.

Keywords Finite element analysis · Dental stress analysis · Maxillary expansion · Computer simulation · Palatal expansion techniques

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Vergleich der Auswirkungen einer maxillären Expansion im Wechselgebiss mit schnellen Gaumennahterweiterungsgeräten oder mit Alignern

Eine 3D-Finite-Elemente-Studie

Zusammenfassung

Ziel Vergleich der maxillären Expansion mit einem RPE („rapid palatal expander“) oder mit Clear-Aligner-Systemen (mit variablen bukkalen und palatinalen Attachments) während der Wechselgebissphase.

Methoden In der Studie verwendet wurden die ANSYS SpaceClaim-Software (SpaceClaim Corporation, Concord/MA, USA) für Reverse Engineering und computergestützte Designaufgaben (CAD), die ANSYS Workbench für Modellanpassung und Netzgenerierung sowie den LS-DYNA-Solver zur Lösung des Finite-Elemente-Modells. Eingesetzt wurden der Posterior Cap Splint RPE, Clear Aligner mit bukkalen Attachments an den Zähnen 55, 65, 16 und 26 (CAB) und Clear Aligner mit palatinalen Attachments an den Zähnen 16 und 26 (CAP). Die Apparaturen wurden basierend auf 2 verschiedenen Szenarien modelliert: (1) eine Expansion von 0,2 mm pro Aktivierung des RPE-Splints bzw. pro Aligner und (2) eine gesamte Expansion von 8 mm. Die Ergebnisse wurden mittels Finite-Elemente-Analyse ausgewertet.

Ergebnisse Im ersten Szenario (0,2 mm Aktivierung) betragen die maximalen Spannungen an den ersten Molaren für die RPE-, CAB- und CAP-Modelle 47,649 MPa, 26,653 MPa und 14,040 MPa. Im zweiten Szenario (8 mm Gesamtaktivierung) lagen die Werte bei 1854,022 MPa, 665,629 MPa und 559,368 MPa. In allen Modellen waren die Spannungsniveaus in absteigender Reihenfolge an den Punkten Z, PNS, ANS und A zu beobachten, wobei RPE die höchsten Gesamtspannungswerte aufwies.

Fazit Der RPE erzeugte eine größere Spannung (gekennzeichnet durch rote Zonen) im palatinalen Bereich, insbesondere auf den palatinalen und bukkalen Oberflächen der bukkalen Segmente sowie im gingivalen Bereich der Schneidezähne, verglichen mit den anderen beiden Apparaturen. Nur die RPE-Gruppe zeigte eine hohe Spannungsverteilung im Bereich der medianen Gaumennaht. Die Spannung auf den Zähnen war nach der Anwendung des RPE ausgeprägter als bei den Alignern.

Schlüsselwörter Finite-Elemente-Analyse · Analyse der dentalen Belastung · Oberkiefererweiterung · Computersimulation · Gaumennahterweiterungstechniken

Introduction

Epidemiological studies have reported that the incidence of transverse maxillary deficiency during the mixed dentition period ranges from 2.7 to 9.6%, with a higher prevalence observed in females [1, 2]. A narrowed maxilla, commonly observed during the primary or mixed dentition, has been associated with systemic disorders, abnormal pressure habits, and oral respiration, highlighting its potential clinical implications [1, 3]. Delaying rapid maxillary expansion (RME) until the early permanent dentition is one common treatment approach [4]. It has also been suggested that if the midpalatal sutures have already partially fused, the orthopedic effects of the treatment may diminish, resulting in greater dental effects [3]. To achieve a skeletal effect, various rapid palatal expander (RPE) devices have been developed, one of which is the hyrax rapid palatal expander (HRPE), a tooth-supported expansion device. Compared to other devices, the HRPE offers potential advantages related to retention during the mixed dentition phase [5].

Clear aligners, which have recently gained popularity for adult treatment, have also provided an alternative for use in children during the mixed dentition period with the introduction of the Invisalign First® system by Align Tech-

nology (Santa Clara, CA, USA) in 2018 [6]. The removable appliance, with a thickness of 0.75 mm, is made from a polyurethane foil and is shaped to achieve tooth movement ranging from 0.15 to 0.25 mm per aligner [6, 7]. A recent study reported no statistically significant differences between the planned and achieved maxillary expansion using the Invisalign First® system, demonstrating an efficiency of $62.6\% \pm 18.3\%$ for maxillary expansion [8].

Transverse maxillary arch development with the Invisalign® (Align Technology, San Jose, CA, USA) First® system has been the subject of only a little research, with some studies offering comparisons to rapid palatal expansion (RPE) [8–15]. While both methods are effective for maxillary expansion, aligner therapy was noted to produce a greater improvement in arch shape compared to RPE in certain contexts [10–12]. However, RPE has demonstrated superior efficiency in increasing intermolar width, particularly at the gingival level, which may have attributed to less buccal tipping of the molars compared with aligner treatment [13, 14]. This suggests that while Invisalign First®, when combined with smaller amounts of total movement, may provide better control of crown angulation for the upper first molars, it may also contribute to an increase in

palatal area [13], and RPE might offer advantages in addressing severe maxillary transverse deficiencies [15].

Bruni et al. [14] highlighted a significant increase in palatal volume, surface area, and maxillary arch width with both clear aligners and RPE in the mixed dentition. However, they emphasized that RPE generally achieved better outcomes, including greater skeletal and dental effects, such as buccal tipping and increased widths in the intercanine and first molar regions. Lu et al. [15] similarly concluded that while Invisalign First® is a viable option for mild to moderate deficiencies, RPE remains the preferred choice for severe cases due to its superior expansion efficiency.

Finite element method (FEM) analysis has emerged as a valuable tool for evaluating the biomechanical effects of orthodontic appliances, offering precise simulations of stress and displacement distributions in craniofacial structures [16–19]. FEM enables the creation of consistent 3D models to compare the expected dental and skeletal effects of different expanders, allowing for a nuanced understanding of their clinical applications. By leveraging FEM, clinicians can make informed decisions for selecting the most appropriate treatment method for individual cases, considering the unique stress distributions and predicted outcomes associated with each appliance.

The primary objective of the present study was to employ FEM to compare the effects of a routine RPE protocol and clear aligner systems on the maxillary complex in the mixed dentition. A secondary objective was to evaluate the extent of tooth displacement induced by these appliances. The null hypothesis proposed for this study was that no differences would exist between the effects of the expansion protocols utilizing clear aligner systems and those employing RPE.

Materials and methods

This study was conducted in collaboration between the Faculty of Dentistry at Istanbul Kent University and Tinus Technologies (Ankara, Turkey). Since an open-source material was used with patient consent in the text, and based on previous studies and consultation with the university's ethics committee, it was concluded that ethical approval was not required. An open-source [20] archival cone beam computed tomography (CBCT) image of a 9.5-year-old girl in the mixed dentition stage was used as the model, and the patient's upper jaw was symmetrically mirrored from the left side.

The CBCT data in DICOM format was processed using 3DSlicer software (Slicer Community, MA, USA) according to suitable Hounsfield Unit values (threshold range 426.50–3193.04). The region of interest (ROI) was specified, and artifacts were eliminated using the 'Erase' and

'Scissors' tools, which helped to further remove unwanted areas and establish the appropriate threshold range.

The segmented data were converted into 3D models through a "segmentation" operation, and the resulting 3D models were exported in Standard Triangle Language (STL) format. The arrangement of the 3D mesh architecture, its conversion into a mathematically compatible solid mesh structure, the development of the 3D finite element analysis models, and the execution of finite element stress analysis were performed using HP workstations equipped with INTEL Xeon E-2286 processors at 2.40 GHz and 64 GB ECC memory. 3DSlicer software was utilized to obtain the bone model data and generate STL model files from the tomography data.

ANSYS SpaceClaim (SpaceClaim Corporation, Concord, MA, USA) software was utilized for reverse engineering and three-dimensional CAD operations, while ANSYS Workbench was used to adapt solid models to the analysis environment and to create an optimized mesh network. The LS-DYNA (SpaceClaim Corporation) solver was employed to analyze the generated finite element models.

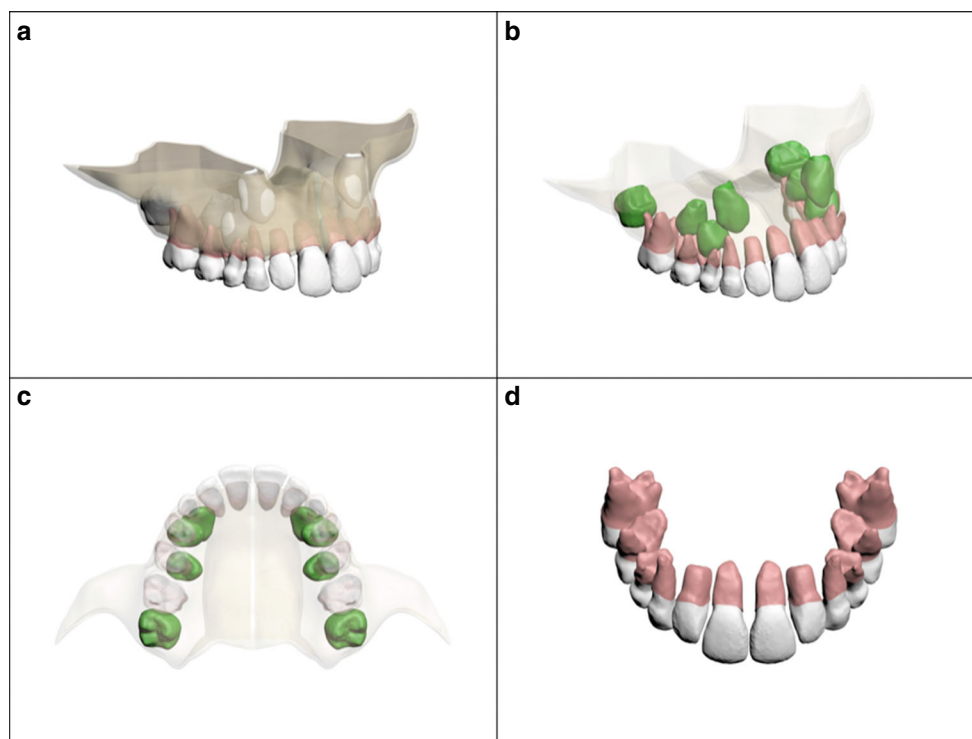
The study consisted of three groups: a posterior cap splint rapid palatal expansion (RPE) group, a clear aligner group with buccal attachments on teeth 55, 65, 16, and 26 (CAB group; first scenario: 0.2 mm of expansion per aligner/second scenario: after the expansion is completed), and a clear aligner group with palatal attachments on teeth 16 and 26 (CAP group; first scenario: 0.2 mm of expansion per aligner/second scenario: after the expansion is completed). The RPE appliance was modeled with a daily expansion protocol (the protocol in which the screw is activated once per day) of 0.2 mm (first scenario), resulting in a total expansion (after the expansion is completed) of 8 mm (second scenario).

Although a specific conventional attachment type has not yet been defined for expansion performed in the mixed dentition, a literature review was conducted to guide the creation of the CAB model (buccal conventional horizontal rectangular attachments on teeth 55, 65, 16, and 26) [21], designed to transmit force to the permanent molar and primary molar. Due to the short clinical crown length and the fact that it is reported as the most retentive region in the literature, a conventional horizontal rectangular attachment was added to the palatal surface of the permanent molar to create the CAP model [22].

The CAB and CAP treatments were modeled to produce 0.2 mm of expansion per aligner, reaching a total expansion of 8 mm. The von Mises stress, which is a scalar value used to assess material failure under complex loading, distributions at the teeth, midpalatal suture, and specific skeletal landmarks—including the Z point (deepest point of maxillozygomatic curvature at the zygomaticomaxillary junction), A point, anterior nasal spine (ANS), and posterior

Fig. 1 Three dimensional (3D) finite element model displaying the geometry of bone (a), tooth germ (b, c), permanent teeth (b, d), primary teeth (b, d), and periodontal ligaments. This model illustrates the spatial relationships among these structures for the simulation

Abb. 1 3D-Finite-Elemente-Modell zur Darstellung der Geometrie von Knochen (a), Zahnkeimen (b, c), bleibenden Zähnen (b, d), Milchzähnen (b, d) und Parodontalligamenten. Das Modell veranschaulicht die räumlichen Beziehungen zwischen diesen Strukturen für die Simulation



nasal spine (PNS)—were analyzed, along with the initial displacements of teeth in three spatial directions, using the finite element method (FEM).

Modeling of bones, teeth, and periodontal ligament

The geometry of the bone, permanent teeth, and deciduous tooth germs was modeled using ANSYS SpaceClaim software. The external surfaces of the deciduous teeth were used as references to model the periodontal ligaments, which were assigned a thickness of 0.2 mm (Fig. 1; Table 1).

Modelling of working models RPE, CAB, and CAP

The RPE appliance used in the study was modeled using ANSYS SpaceClaim software. The clear aligners, with a thickness of 0.38 mm [23], were also modeled in the software. The buccal and palatal attachments, each measuring 5 mm in length, 2 mm in width, and 1 mm in thickness, were modeled accordingly (Fig. 2; Table 1; [23–27]).

Obtaining mathematical models

In the process of creating mathematical models, the geometric models were segmented into basic and compact sections known as meshes. Once the modeling phase was completed in ANSYS SpaceClaim software, the models were mathematically formulated and prepared for analysis using AN-

SYS Workbench software (ANSYS, Inc., Canonsburg, PA, USA). For analysis purposes, these mathematical models were then transferred from ANSYS Workbench to the LS-DYNA solver (SpaceClaim Corporation).

Material definitions

In the analyses, materials with specified elastic modulus and Poisson's ratio were assigned linear material properties. The material properties used in the model are summarized in Table 1 [23–27].

Table 1 Material lists with their assigned elastic modulus and Poisson's ratio, employing linear material properties

Tab. 1 Liste der verwendeten Materialien mit zugewiesenem Elastizitätsmodul und Poissonzahl unter Verwendung linearer Materialeigenschaften

Material	Elastic modulus (MPa)	Poisson's ratio
Cortical bone [24]	15,000	0.30
Dental follicle [24]	12	0.45
Tooth [24]	18,600	0.31
PDL (periodontal ligament) [24]	12	0.45
Suture [27]	98.5	0.4
RPE (rapid palatal expander) [25]	200,000	0.33
Acrylic resin [26]	2000	0.3
Clear aligners [23]	528	0.36
Attachment [23]	12,500	0.36

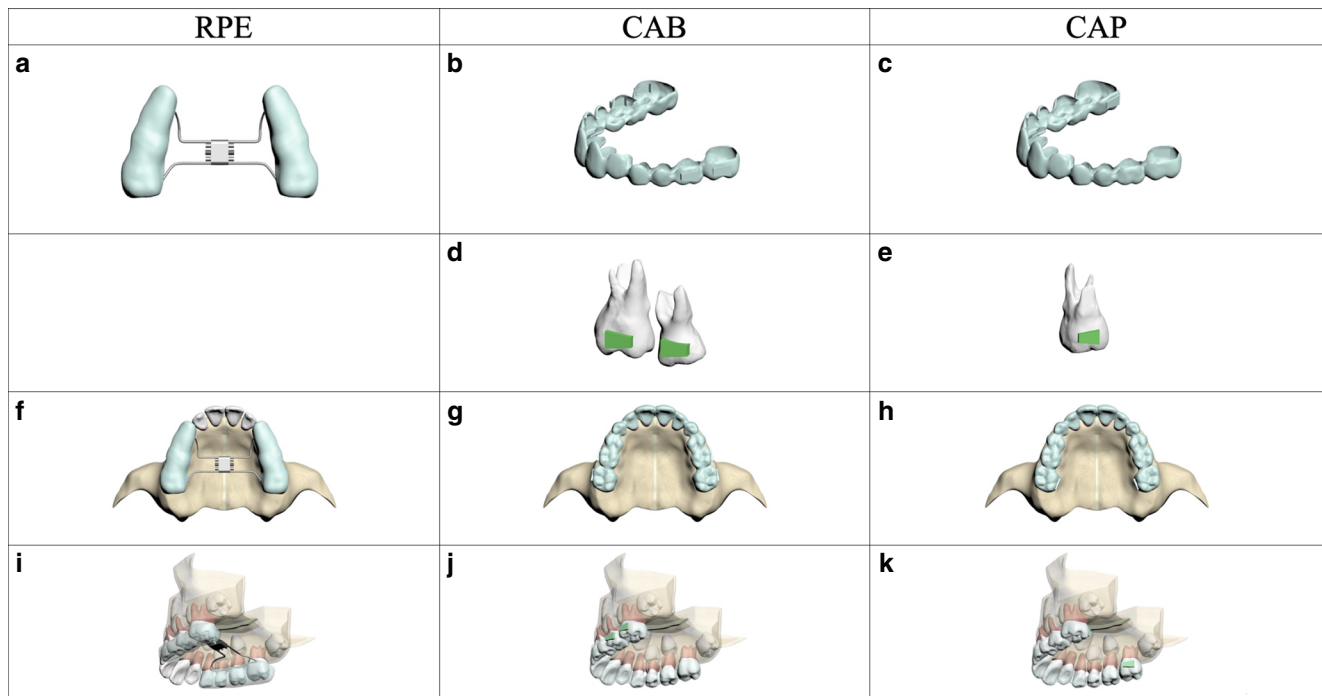


Fig. 2 **a** Rapid palatal expander (RPE) appliance; **b** clear aligners with buccal attachments (CAB); **c** clear aligners with palatal attachments (CAP); **d** buccal attachments on the permanent molar and primary molar; **e** palatal attachment on the permanent molar for retention; **f** bone structures and mixed dentition with the RPE appliance; **g** bone structures and mixed dentition with the CAB; **h** bone structures and mixed dentition with CAP; **i** RPE appliance with bone, periodontal ligament, and tooth models; **j** CAB appliance with bone, periodontal ligament, and tooth models; **k** CAP appliance with bone, periodontal ligament, and tooth models

Abb. 2 **a** RPE („rapid palatal expander“)-Apparatur; **b** Clear Aligner mit bukkalen Attachments (CAB); **c** Clear Aligner mit palatinalen Attachments (CAP); **d** bukkale Attachments am bleibenden Molar und am Milchmolar; **e** palatinales Attachment am bleibenden Molar zur Retention; **f** Knochenstrukturen und Wechselgebiss mit der RPE-Apparatur; **g** Knochenstrukturen und Wechselgebiss mit CAB; **h** Knochenstrukturen und Wechselgebiss mit CAP; **i** RPE-Apparatur mit Knochen-, Parodontalligament- und Zahnmodellen; **j** CAB-Apparatur mit Knochen-, Parodontalligament- und Zahnmodellen; **k** CAP-Apparatur mit Knochen-, Parodontalligament- und Zahnmodellen

Loading scenarios and boundary conditions

For the RPE model, an expansion force corresponding to a 0.2 mm displacement was applied. For the CAB and CAP models, an expansion force corresponding to a 0.2 mm initial displacement was applied to the palatal surfaces of the teeth with attachments. In this study, an 8 mm lateral displacement was simulated in the maxilla using RPE and aligner appliances. In the RPE appliance, expansion was achieved with a plate surrounding the primary molars and the first permanent molars on both the right and left sides, along with an appliance placed at the center of the palate to mimic the expansion movement. In the aligner models, loading was applied to all surfaces covered by the appliance to simulate the displacement. The method used to simulate displacement involved applying force based on the mechanical properties and constraints of the system. In all models, the nodal points in the superior region of the bone were fixed by constraining all degrees of freedom to restrict movement along all three axes. In models 1, 2, and 3, the total number of nodes were 988,610, 1,353,397, and 1,360,847, respectively, while the number

of elements were 3,793,705, 5,141,225, and 5,190,571, respectively. Three nonlinear static analyses were sequentially executed for each of the three analysis models under the prescribed forces and boundary conditions.

Integration of systems and interpart connections

To conduct analyses in the created mathematical models and obtain accurate results, the surface relationships between the components comprising the model had to be defined in the analysis program. A nonlinear frictional contact with a coefficient of friction of $\mu=0.2$ was defined at the aligner–tooth interface and the aligner–attachment interface. For the components in contact with each other, a bonded contact type was defined. This methodology assumes that the components move in perfect synchrony during their motion.

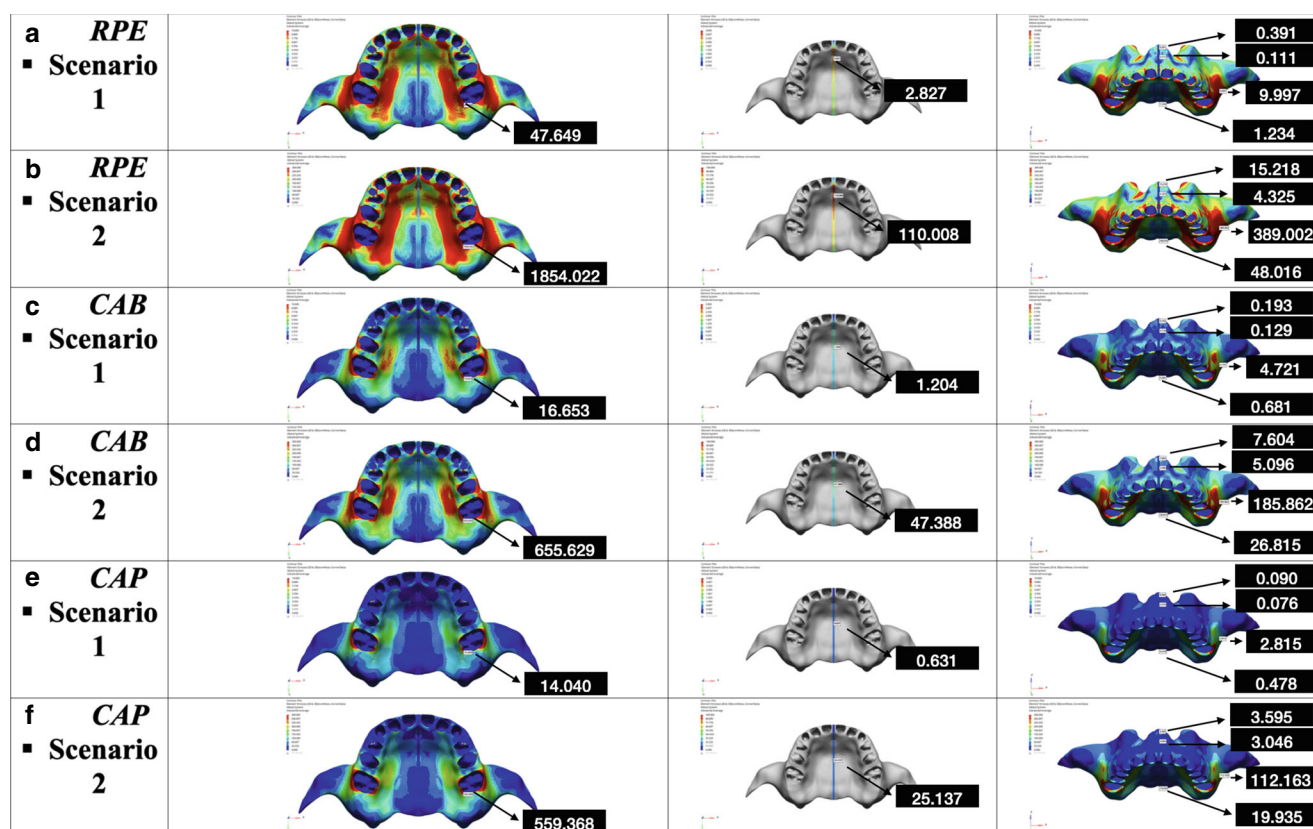


Fig. 3 Stress distribution on the skeletal parameters: **a** rapid palatal expansion (RPE) using a 0.2 mm daily expansion protocol, **b** RPE using a 0.8 mm daily expansion protocol, **c** clear aligners with buccal attachments (CAB) using a 0.2 mm daily expansion protocol, **d** CAB using a 0.8 mm daily expansion protocol, **e** clear aligners with palatal attachments (CAP) using a 0.2 mm daily expansion protocol, **f** CAP using a 0.8 mm daily expansion protocol. Z point zygomaticomaxillary junction's deepest point, A point; ANS anterior nasal spina, PNS posterior nasal spina

Abb. 3 Verteilung der Belastung auf den skelettalen Parametern. **a** RPE („rapid palatal expander“) mit einem täglichen Expansionsprotokoll von 0,2 mm, **b** RPE mit einem täglichen Expansionsprotokoll von 0,8 mm, **c** CAB („clear aligners with buccal attachments“) mit einem täglichen Expansionsprotokoll von 0,2 mm, **d** CAB mit einem täglichen Expansionsprotokoll von 0,8 mm, **e** CAP mit einem täglichen Expansionsprotokoll von 0,2 mm, **f** CAP mit einem täglichen Expansionsprotokoll von 0,8 mm. Z-Punkt: tiefster Punkt der zygomaticomaxillären Verbindung, A-Punkt, ANS „anterior nasal spina“, PNS „posterior nasal spina“

Results

Stresses on the skeletal parameters

A visual analysis of the bone and suture structures was conducted to evaluate the von Mises stress distribution, using a color map. In this map, red denotes the areas of highest stress concentration, while dark blue represents regions of lowest stress concentration. The stresses on the skeletal parameters, including the Z point (the deepest point of the maxillozygomatic curvature at the zygomaticomaxillary junction), A point, ANS, and PNS, are shown in Fig. 3. In the first scenario (0.2 mm expansion), as seen above, the maximum stresses for the upper first molars' displacements for the RPE, CAB, and CAP models were 47.649, 26.653, and 14.040 MPa, respectively. In the second scenario (8 mm expansion), as seen above, they were 1854.022, 665.629, and 559.368 MPa. In both scenarios, with the application of RPE, maximum stress (red zone) was observed around the

permanent and primary molar teeth, both on the palatal and buccal sides, and in the palatogingival area of the incisors (Fig. 3). In the CAB model, a small red zone appeared on the buccal side of both permanent and primary molars in the first scenario, as seen above, which increased in the second scenario, as seen above, at the same locations. In the CAP model, a red zone was observed in the first scenario (0.2 mm activation) only around the buccal and palatal gingival areas of the permanent molars. When evaluating the von Mises stresses in the midpalatal suture, a red zone was observed in the first scenario, as seen above, for the RPE, with higher stresses compared to the first scenario, as seen above. In contrast, blue zones representing low stresses were seen in the other two applications, indicating less stress in those regions (Fig. 3). For the anatomical landmarks of the maxilla, the stress values across all three applications, in descending order, were as follows: Z point, PNS, ANS, and A point. The highest stress values were observed for the RPE application (Fig. 3).

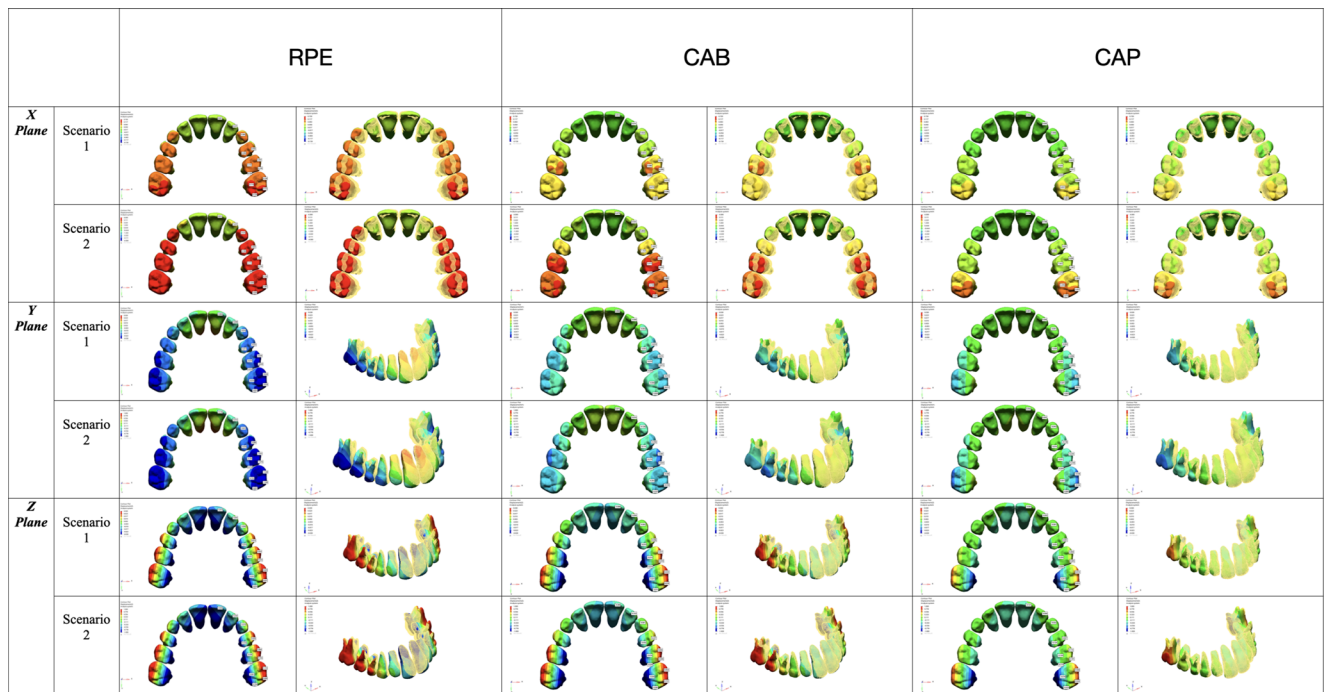


Fig. 4 The displacements of the teeth in the x, y, and z planes with rapid palatal expansion (RPE), clear aligners with buccal attachments (CAB), and clear aligners with palatal attachments (CAP)

Abb. 4 Die Verschiebungen der Zähne in den x-, y- und z-Ebenen mit RPE („rapid palatal expansion“), CAB („clear aligners with buccal attachments“) und CAP („clear aligners with palatal attachments“)

Initial displacement of teeth on models

The initial displacements of teeth across the three models along the x, y, and z planes are shown in Fig. 4 and detailed in Tables 2, 3, and 4. When evaluating the displacement of teeth along the x-plane (transversal), the RPE model exhibited the highest displacement values in both the first and second scenarios, while the CAP model showed the lowest displacement values in both scenarios (Fig. 4; Table 2). Regarding displacement along the y-plane (sagittal), no group displayed significant displacements (no red zone). In the z-plane (vertical), the RPE model showed the highest displacement values across all teeth in both scenarios, whereas the CAP model exhibited the lowest displacement values across all teeth in both scenarios. On the buccal side, red zones were observed, indicating intrusion, while blue zones on the palatal side represented extrusion, suggesting buccal tipping in the posterior region. In the first and second scenarios, the z-plane in the RPE model showed red zones in the upper first molars and first and second primary molars, while in the CAB model, red zones were observed in the upper first molars and second primary molars, and in the CAP model, red zones were found only in the upper first molars (Fig. 4; Table 4).

Negative values indicate movement opposite to the direction shown in the coordinate plane, while all teeth posi-

tioned symmetrically in the arch reflect the same displacement on the opposite side.

Discussion

The current FEM study compared the biomechanical effects of clear aligners with conventional horizontal rectangular attachments to those of RPE in the mixed dentition, revealing key differences in stress distribution, tooth movement, and tipping pattern. Stress in the midpalatal suture was highest with RPE, followed by CAB and CAP, with stress levels decreasing from the Z point to the PNS, ANS, and A points. Tooth displacement was greatest with RPE in all planes, showing maximum transverse and vertical movement, while CAP resulted in the least displacement and a more conservative effect.

RPE appliances, alongside posterior cap splints, have long been identified as a reliable expansion measure [4, 5]. RPE treatments may cause speech difficulties, feeding issues, and bad breath in children [28, 29]. Clear aligners, now widely used with advancing technology, have been proposed to offer similar effects to traditional expansion protocols [6]. A review of the literature on RPE [16–28] reveals some clinical and finite element studies, but no comparisons with clear aligner treatment in the mixed dentition have been identified. This study aimed to provide quanti-

Table 2 Displacement of teeth along the x-axis in the three models
Tab. 2 Verschiebung der Zähne entlang der x-Achse in den 3 Modellen

Appliance/tooth	RPE		CAB		CAP	
	0.2 mm Expansion	8 mm Expansion	0.2 mm Expansion	8 mm Expansion	0.2 mm Expansion	8 mm Expansion
26 (MP cusp)	0.119	4.660	0.079	3.139	0.057	2.295
26 (DB cusp)	0.123	4.801	0.080	3.149	0.061	2.427
65 (MP cusp)	0.105	4.115	0.086	3.415	0.026	1.042
65 (DB cusp)	0.106	4.154	0.086	3.120	0.027	0.898
64 (B cusp)	0.094	3.687	0.041	1.637	0.013	0.531
64 (P cusp)	0.096	3.760	0.044	1.757	0.015	0.580
63	0.088	3.425	0.023	0.894	0.008	0.307
22	0.037	1.437	0.014	0.544	0.005	0.189
21	0.021	0.812	0.012	0.479	0.004	0.158

CAB clear aligners with buccal attachments, CAP clear aligners with palatal attachments

Table 3 Displacement of teeth along the y-axis in the three models
Tab. 3 Verschiebung der Zähne entlang der y-Achse in den 3 Modellen

Appliance/ Tooth	RPE		CAB		CAP	
	0.2 mm Expansion	8 mm Expansion	0.2 mm Expansion	8 mm Expansion	0.2 mm Expansion	8 mm Expansion
26 (MP cusp)	-0.018	-0.722	-0.008	-0.302	0.001	0.047
26 (DB cusp)	-0.033	-1.260	-0.013	-0.510	-0.013	-0.534
65 (MP cusp)	-0.019	-0.750	-0.010	-0.376	-0.001	-0.041
65 (DB cusp)	-0.028	-1.013	-0.015	-0.603	-0.006	-0.250
64 (B cusp)	-0.023	-0.880	-0.010	-0.392	-0.003	-0.130
64 (P cusp)	-0.017	-0.659	-0.003	-0.116	0.000	-0.016
63	-0.016	-0.627	-0.003	-0.128	-0.001	-0.040
22	-0.008	-0.312	-0.000	-0.010	0.000	0.001
21	-0.003	-0.136	0.002	0.071	0.001	0.056

CAB clear aligners with buccal attachments, CAP clear aligners with palatal attachments

Table 4 Displacement of teeth along the z-axis in the three models
Tab. 4 Verschiebung der Zähne entlang der z-Achse in den 3 Modellen

Appliance/Tooth	RPE		CAB		CAP	
	0.2 mm Expansion	8 mm Expansion	0.2 mm Expansion	8 mm Expansion	0.2 mm Expansion	8 mm Expansion
26 (MP cusp)	-0.022	-0.861	-0.021	-0.830	-0.017	-0.670
26 (DB cusp)	0.021	0.808	0.018	0.721	0.013	0.524
65 (MP cusp)	-0.012	-0.468	-0.016	-0.616	-0.004	-0.169
65 (DB cusp)	0.019	0.746	0.018	0.656	0.005	0.181
64 (B cusp)	0.013	0.503	0.006	0.277	0.001	0.047
64 (P cusp)	-0.019	-0.725	-0.010	-0.402	-0.003	-0.134
63	-0.008	-0.319	-0.002	-0.621	-0.001	-0.033
22	-0.005	-0.202	-0.004	-0.163	-0.002	-0.066
21	-0.014	-0.555	-0.008	-0.300	-0.003	-0.121

CAB clear aligners with buccal attachments, CAP clear aligners with palatal attachments

tative evidence on the expected clear aligners' impact on maxillary structures and teeth. The null hypothesis was rejected, as significant differences were found between the effects of expansion protocols utilizing clear aligner systems and those employing RPE.

Both clear aligner treatments and the RPE protocol are known to cause buccal tipping of posterior teeth [14, 15]. Attachments play a critical role in aligner retention and expansion control. Takara et al. [22] highlighted the effectiveness of attachments, particularly noting that aligners are most easily removed from the lingual side of the first molar. While detailed reviews exist on attachment shapes and placements [21], limited data specifically address their role in Invisalign First treatment [30]. Moshiri et al. [30] reported that optimized attachments in the Invisalign G8 protocol (Align Technology, San Jose, CA, USA) were designed for posterior expansion, but no attachment type has been established for Invisalign First treatment. Studies, such as that from Karshi et al. [31], indicated that occlusally beveled attachments and addition of buccal root torque can minimize buccal tipping during aligner-based expansion. The current study evaluated clear aligners with conventional horizontal rectangular attachments, emphasizing the need for further research to refine attachment designs and minimize side effects.

Several studies have examined stress distribution, tooth displacement, and tipping effects in different expansion protocols, highlighting both, similarities and distinctions with the current research. Bruni et al. [14] and Lu et al. [15] reported buccal tipping with Invisalign First treatments, with torque control attachments mitigating this effect. While Bruni et al. [14] utilized two daily activations and a 6 mm movement, our study employed a single activation and an 8 mm movement, which likely influenced the observed stress and displacement patterns. Both studies identified lower stress accumulation in the midpalatal suture with clear aligners compared to RPE. Lione et al. [32] examined the effects of the Invisalign system on the permanent dentition, reporting a significant increase in both mesial and distal intermolar width in the region of the permanent first molars. They used attachments smaller than 2 mm that were placed mesiobuccally on the maxillary first molars. In a separate study, Lione et al. [11] evaluated the Invisalign First system in young patients, finding it effective for maxillary arch development and increasing transverse interdental width, particularly due to mesial rotation of the upper first molars. In the current study, significant displacements were also observed at the mesiopalatal cusps. The attachment design used in this study was 5 mm in length, 2 mm in width, and 1 mm in thickness, aimed at enhancing retention and minimizing buccal tipping. In the CAP model, attachments were reduced and placed only on the palatal side of the permanent first molars to im-

prove comfort and ensure effective retention. This model showed more homogeneous stress distribution in the palatal region compared to the CAB model. Although no direct comparisons exist analyzing palatal attachment placement, observational clinically data suggests it results in more parallel movement and reduces tipping, aligning with the findings of this study.

In the literature, previous studies have highlighted that asymmetrical RPE designs such as asymmetrically split acrylic plate with jackscrew (ASAPJ), NORD cross-bite expander, asymmetric maxillary expansion appliance (AMEX), asymmetrical rapid maxillary expansion (ARME) increase stress and buccal tipping, particularly in the canine and molar regions [33]. Additionally, Araújo et al. [34] showed that screw height affected buccal tipping, while positioning the screw above the center of resistance of the maxillary first molars reduced tipping. In this study, the symmetrical RPE design resulted in more even stress distribution, with variations in stress accumulation at the ANS and PNS, a fact that could be attributed to the design differences. Additionally, positioning the RPE screw near the center of resistance was intended to minimize tipping. While some clinical studies suggested that RPE caused less buccal tipping than aligners, this difference may be due to variations in screw placement [14, 15].

One study demonstrated lingual tipping of anterior teeth and buccal tipping of posterior teeth during expansion in adults [35]. Similarly, our findings revealed buccal tipping of posterior teeth, with intrusion of the anterior teeth in the RPE group and extrusion in the aligner group, reflecting distinct mechanical effects of the two protocols. Another study [36] that evaluated the RPE found minimal stress in the canine and premolar regions, with no red zones. In contrast, the current study, when simulating RPE, showed red regions primarily at the gingival margin of the canine and first deciduous molar, predominantly on the labial side, with minimal presence on the lingual side. This discrepancy may be attributed to differences in the developmental stage of the analyzed dentitions. The mixed dentition that was investigated in the current study likely differs morphologically from the permanent dentition in the referenced study. While findings across studies underscore the effectiveness of clear aligners and RPE in maxillary expansion, methodological and design variations influenced the respective outcomes such as stress distribution and tooth displacement.

As highlighted in the FEM study of Provatidis et al. [36], the human skull's maxillary base is pyramidal, with the apex at the posterior maxilla and the base in the region of the anterior teeth. The ossification of the midsagittal and median palatine sutures, which have a low elasticity modulus, is essential for effective maxillary expansion [35]. In line with the above findings, the RPE group experienced the highest stress accumulation in the anterior region, while the

CAB group showed stress progression to the midregion of the suture, and the CAP group to the posterior region. This suggests that RPE results in a triangular expansion pattern, whereas expansion with clear aligners follows a different trajectory. The variation in stress distribution between the CAP and CAB groups could be attributed to the all-encompassing nature of the aligner application. While the RPE screw delivers force from the median palatine suture region, aligners apply force to the dentition from both the palatal and buccal regions.

When examining the literature on arch form changes and dental effects, Lombardo et al. [12] observed that, compared to the Invisalign First® system, rapid palatal expansion (RPE) resulted in a more triangular arch form in the maxilla.

Based on these findings, the stress distribution observed in the current study, might have contributed to this arch form. It was higher in the posterior palatal region in the RPE group, whereas a more uniform distribution with lower stress concentrations in the palatal bone was observed in the clear aligner groups. Geramy et al. [37] reported higher buccal tipping of the molars and increased crestal stress with removable expansion devices in their FEM study. In contrast, the current study observed less buccal tipping and lower crestal stress for the clear aligners compared to RPE. This difference may be attributed to the thinner design of the aligners, which produce weaker forces, and the use of a mixed dentition model, which could have influenced the results. In another study, Martina et al. [38] in a clinical study found no significant differences between slow and rapid expansion protocols, although slow expansion was associated with less pain and discomfort. In this FEM study, clear aligner application, when compared to RPE, resulted in more homogeneous force distribution, which might theoretically be clinically accompanied with reduced pain and discomfort.

One limitation of this study was the reliance on instantaneous results from the FEM analysis. Despite efforts to simulate real-time FEM and sutural opening, software limitations hindered the accuracy of this approach. Additionally, the use of a low Field of View (FOV) scan to minimize radiation exposure prevented a full head scan from being obtained, which limited the ability to visualize stress distribution in the cranial region and buttress areas. Another limitation was the lack of a clearly defined ideal attachment type. In addition, there was no group with a palatal attachment with exactly the same design as the buccal attachments. Future research should focus on addressing this issue and may be conducted with different attachment designs during the mixed dentition phase, thus, contributing further to the literature on this topic. This study utilized a single CBCT model, which may not fully represent individual variations in bone density, arch width, or malocclu-

sion, thereby limiting its generalizability to the wider population. Expanding the research to encompass variations in age, gender, and malocclusion type would provide a more comprehensive understanding and aid in guiding clinicians' selection of appropriate devices. Future prospective clinical studies are essential to further investigate the biological tissue responses to clear aligner expansion protocols in the mixed dentition.

Conclusion

When evaluating the results of the current study:

- Rapid palatal expansion (RPE) induced greater stress on the palatal and buccal bones around primary and permanent molars compared to the other devices. In cases where sutural opening is required due to excessive stress, RPE may be the preferable choice clinically.
- With RPE, stress was concentrated anteriorly along the suture, while in the other two groups, it shifted posteriorly. In cases with premaxillary defects, such as cleft lip and palate, clear aligner treatments may be preferred to direct stress posteriorly, minimizing the risk of a perforation in the suture area.
- Dental effects were most pronounced with the RPE group, reduced with clear aligners with buccal attachments (CAB) compared to RPE, and minimal with clear aligners with palatal attachments (CAP). Treatment choice should be made based on the desired movement, considering the specific skeletal and dental needs.

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Data Availability The data are protected on an encrypted computer and can be accessed when needed by making a request to the corresponding author.

Declarations

Conflict of interest M. Kurnaz and E. Dayan declare that the study was conducted in collaboration between the Faculty of Dentistry at Istanbul Kent University and Tinus Technologies (Ankara, Turkey). The authors declare that they have no competing interests.

Ethical standards This study was conducted in collaboration between the Faculty of Dentistry at Istanbul Kent University and Tinus Technologies (Ankara, Turkey). Since an open-source material was used with patient consent in the text, and based on previous studies and consultation with the university's ethics committee, it was concluded that ethical approval was not required. Since the material used is open-source and the patient has already given consent, no additional permission was required. The patient's existing tomography was used, and no intervention was performed.

References

- Gross AM, Kellum GD, Michas C, Franz D, Foster M, Walker M, Bishop FW (1994) Open-mouth posture and maxillary arch width in young children: a three-year evaluation. *Am J Orthod Dentofacial Orthop* 106:635–640. [https://doi.org/10.1016/S0889-5406\(94\)70089-3](https://doi.org/10.1016/S0889-5406(94)70089-3)
- Helm S (1968) Malocclusion in Danish children with adolescent dentition: an epidemiologic study. *Am J Orthod* 54:352–366. [https://doi.org/10.1016/0002-9416\(68\)90304-7](https://doi.org/10.1016/0002-9416(68)90304-7)
- Bishara SE, Staley RN (1987) Maxillary expansion: clinical implications. *Am J Orthod Dentofacial Orthop* 91:3–14. [https://doi.org/10.1016/0889-5406\(87\)90202-2](https://doi.org/10.1016/0889-5406(87)90202-2)
- Sari Z, Uysal T, Usumez S, Basciftci FA (2003) Rapid maxillary expansion. Is it better in the mixed or in the permanent dentition. *Angle Orthod*. [https://doi.org/10.1043/0003-3219\(2003\)073](https://doi.org/10.1043/0003-3219(2003)073)
- McNamara JA Jr, Sigler LM, Franchi L, Guest SS, Baccetti T (2010) Changes in occlusal relationships in mixed dentition patients treated with rapid maxillary expansion: a prospective clinical study. *Angle Orthod* 80:230–238. <https://doi.org/10.2319/040309-192.1>
- Ali SA, Miethke HR (2012) Invisalign, an innovative invisible orthodontic appliance to correct malocclusions: advantages and limitations. *Dent Update* 39:254–260. <https://doi.org/10.12968/denu.2012.39.4.254>
- Vlaskalic V, Boyd R (2001) Orthodontic treatment of a mildly crowded malocclusion using the Invisalign system. *Aust Orthod J* 17:41–46. <https://doi.org/10.2478/aoj-2001-0006>
- Gonçalves A, Ayache S, Monteiro F, Silva FS, Pinho T (2023) Efficiency of Invisalign first® to promote expansion movement in mixed dentition: a retrospective study and systematic review. *Eur J Paediatr Dent* 24:112–123. <https://doi.org/10.23804/ejpd.2023.1754>
- Levrini L, Carganico A, Abbate L (2021) Maxillary expansion with clear aligners in the mixed dentition: a preliminary study with Invisalign® first system. *Eur J Paediatr Dent* 22:125–128. <https://doi.org/10.23804/ejpd.2021.22.02.7>
- Phase BR (2019) I orthodontic treatment using Invisalign first. *J Clin Orthod* 53:73–83
- Lione R, Cretella LE, Paoloni V, Meuli S, Pavoni C, Cozza P (2023) Upper arch dimensional changes with clear aligners in the early mixed dentition. *J Orofac Orthop* 84:33–40. <https://doi.org/10.1007/s00056-021-00332-z>
- Lombardo EC, Paoloni V, Fanelli, Pavoni C, Gazzani F, Cozza P (2022) Evaluation of the upper arch morphological changes after two different protocols of expansion in early mixed dentition: rapid maxillary expansion and Invisalign® first system. *Life* 12:1323. <https://doi.org/10.3390/life12091323>
- Lombardo EC, Fanelli Y, Paoloni V, Cozza P, Lione R (2023) Maxillary response induced by rapid palatal expansion vs. Clear aligners: a short-term retrospective evaluation of the Dento-alveolar effects in mixed dentition. *Appl Sci* 13(15):8675. <https://doi.org/10.3390/app13158675>
- Bruni A, Ferrillo M, Gallo V, Parrini S, Garino F, Castroflorio T, Deregibus A (2024) Efficacy of clear aligners vs rapid palatal expanders on palatal volume and surface area in mixed dentition patients: a randomized controlled trial. *Am J Orthod Dentofacial Orthop* 166(3):203–214. <https://doi.org/10.1016/j.ajodo.2024.04.006>
- Lu L, Zhang L, Li C, Yi F, Lei L, Lu Y (2023) Treatment effects after maxillary expansion using Invisalign first system vs. acrylic splint expander in mixed dentition: a prospective cohort study. *Bmc Oral Health* 23(1):598. <https://doi.org/10.1186/s12903-023-03312-4>
- Jafari A, Shetty KS, Kumar M (2003) Study of stress distribution and displacement of various craniofacial structures following application of transverse orthopedic forces—A three dimensional FEM study. *Angle Orthod* 73:12–20. [https://doi.org/10.1043/0003-3219\(2003\)073\(0012:SOSDAD\)2.0.CO;2](https://doi.org/10.1043/0003-3219(2003)073(0012:SOSDAD)2.0.CO;2)
- MacGinnis M, Chu H, Youssef G, Wu KW, Machado AW, Moon W (2014) The effects of micro-implant assisted rapid palatal expansion (MARPE) on the nasomaxillary complex—a finite element method (FEM) analysis. *Prog Orthod* 15:52. <https://doi.org/10.1186/s40510-014-0052-y>
- Gautam P, Valiathan A, Adhikari R (2007) Stress and displacement patterns in the craniofacial skeleton with rapid maxillary expansion: a finite element method study. *Am J Orthod Dentofacial Orthop* 132:5e1–5e11. <https://doi.org/10.1016/j.ajodo.2006.09.044>
- Bouton A, Simon Y, Goussard F, Teresi L, Sansalone V (2017) New finite element study protocol: clinical simulation of orthodontic tooth movement. *Int Orthod* 15:165–179. <https://doi.org/10.1016/j.ortho.2017.03.001>
- <https://www.dicomlibrary.com?study=1.3.6.1.4.1.44316.6.102.1.2025010314734774.110787423506361295763>
- Jedliński M, Mazur M, Greco M, Belfus J, Grocholewicz K, Janiszewska-Olszowska J (2023) Attachments for orthodontic aligner treatment—state of the art—a comprehensive systematic review. *Int J Environ Res Public Health* 20(5):4481. <https://doi.org/10.3390/ijerph20054481>
- Takara Y, Haga S, Kimura H, Maki K (2022) Mechanical analysis of factors affecting clear aligner removability. *Dent Mater J* 41:534–544. <https://doi.org/10.4012/dmj.2021-493>
- Jiang T, Wu RY, Wang JK, Wang HH, Tang GH (2020) Clear aligners for maxillary anterior en masse retraction: a 3D finite element study. *Scientific Reports* 10(1):10156. <https://doi.org/10.1038/s41598-020-67158-1>
- Sarrafpour B, Swain M, Li Q, Zoellner H (2013) Tooth eruption results from bone remodelling driven by bite forces sensed by soft tissue dental follicles: a finite element analysis. *Plos One* 8(3):e58803. <https://doi.org/10.1371/journal.pone.0058803>
- Hartono N, Soegiharto BM, Widayati R (2018) The difference of stress distribution of maxillary expansion using rapid maxillary expander (RME) and maxillary skeletal expander (MSE)—a finite element analysis. *Prog Orthod* 19:1–10. <https://doi.org/10.1186/s40510-018-0224-0>
- Tanne K, Sakuda M, Burstone CJ (1987) Three-dimensional finite element analysis for stress in the periodontal tissue by orthodontic forces. *Am J Orthod Dentofac Orthop* 92(6):499–505
- Savoldi F, Xu B, Tsoi JK, Paganelli C, Matinlinna JP (2018) Anatomical and mechanical properties of swine midpalatal suture in the premaxillary, maxillary, and palatine region. *Sci Rep* 8(1):7073. <https://doi.org/10.1038/s41598-018-25379-0>
- Stevens K, Bressmann T, Gong SG, Tompson BD (2011) Impact of a rapid palatal expander on speech articulation. *Am J Orthod Dentofacial Orthop* 140:e67–e75. <https://doi.org/10.1016/j.ajodo.2011.02.017>
- Erhamza TS, Ozdiler FE (2018) Effect of rapid maxillary expansion on halitosis. *Am J Orthod Dentofacial Orthop* 154:702–707. <https://doi.org/10.1016/j.ajodo.2018.01.014>
- Moshiri M, Kravitz ND, Nicozisis J, Miller S (2021) Invisalign eighth-generation features for deep-bite correction and posterior arch expansion. *Semin Orthod* 27(3):175–178. <https://doi.org/10.1016/j.sodo.2021.07.001>
- Karslı N, Ocak I, Akyıldız M, Gögen H, Dalci O (2024) Evaluation of the effect of different attachment configurations on molar teeth in maxillary expansion with clear aligners—a finite element analysis. *BMC Oral Health* 24:921. <https://doi.org/10.1186/s12903-024-02195-5>
- Lione R, Paoloni V, Bartolommei L, Gazzani F, Meuli S, Pavoni C, Cozza P (2021) Maxillary arch development with Invisalign system: analysis of expansion dental movements on digital dental

- casts. *Angle Orthod* 91:433–440. <https://doi.org/10.2319/080520-687.1>
33. Hoque T, Srinivasan D, Chakravarthi S, Kannan R (2022) Evaluation and comparison of stresses and displacements generated by four different types of asymmetric maxillary expansion appliances in true unilateral crossbite using finite element method. *Int Orthod* 20:100668. <https://doi.org/10.1016/j.ortho.2022.100668>
34. de Sousa Araugi RM, Landre J Jr, Silva DDLA, Pacheco W, Pithon Oliveira MMDD, Oliveira DD (2013) Influence of the expansion screw height on the dental effects of the hyrax expander: a study with finite elements. *Am J Orthod Dentofacial Orthop* 143:221–227. <https://doi.org/10.1016/j.ajodo.2012.09.016>
35. Zhang Y, Hui S, Gui L, Jin F (2023) Effects of upper arch expansion using clear aligners on different stride and torque: a three-dimensional finite element analysis. *BMC Oral Health* 23:891. <https://doi.org/10.1186/s12903-023-03655-y>
36. Provatidis C, Georgiopoulos B, Kotinas A, MacDonald JP (2006) In vitro validated finite element method model for a human skull and related craniofacial effects during rapid maxillary expansion. *Proc Inst Mech Eng Part H: J Eng Med* 220:897–907. <https://doi.org/10.1243/09544119JEIM92>
37. Geramy A, Shahroudi AS (2014) Fixed versus removable appliance for palatal expansion; a 3D analysis using the finite element method. *J Dent (tehran)* 11:75
38. Martina R, Cioffi I, Farella M, Leone P, Manzo P, Matarese G, Cordasco G (2012) Transverse changes determined by rapid and slow maxillary expansion—a low-dose CT-based randomized controlled trial. *Orthod Craniofac Res* 15:159–168. <https://doi.org/10.1111/j.1601-6343.2012.01543.x>

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