Original Article

Maxillary arch development with Invisalign system: *Analysis of expansion dental movements on digital dental casts*

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ABSTRACT

Objectives: To evaluate tooth movements during maxillary arch expansion with clear aligner treatment.

Materials and Methods: The study group included 28 subjects (16 females, 12 males, mean age 31.9 ± 5.4 years) collected prospectively from January 2018 to May 2019. Inclusion criteria were European ancestry, posterior transverse discrepancy of 3–6 mm, permanent dentition stage, presence of second permanent molars, mild or moderate crowding, and good compliance with aligners. Treatment protocol included nonextraction strategies, application of Invisalign clear aligner system, and no auxiliaries other than Invisalign attachments. Linear and angular measurements were performed before treatment (T1), at the end of treatment (T2), and on final virtual models (T2 ClinCheck). A paired *t*-test was used to compare T2-T1 and T2-T2 ClinCheck changes. The level of significance was set at 5%.

Results: Statistically significant differences were found for all measurements, except for ones at the upper second molars. The greatest increase in maxillary width was detected at the upper first and second premolars: +3.5 mm for the first premolar and +3.8 mm for the second premolar at T2. Comparison of T2-T1 angular outcomes showed statistically significant changes in the inclinations of all teeth except for the second permanent molars. T2-T2 ClinCheck showed significant differences for both linear and angular measurements for maxillary canines, resulting in poor predictability.

Conclusions: Maxillary arch development revealed a progressive reduction of the expansion rate and buccal tipping in the anterior, lateral, and posterior regions, with the greatest net increase at the first and second premolars. Clinical attention should be paid to maxillary canine movements, and overcorrection should be planned for them during dentoalveolar expansion. (*Angle Orthod.* 2021;91:433–440.)

KEY WORDS: Clear aligner technique; Maxillary expansion; Dental movement; Digital cast analysis

INTRODUCTION

Arch width development obtained by means of different orthodontic approaches has been extensively examined in the literature.[1–5] Dentoalveolar expansion can be achieved using fixed appliances such as the quadhelix device[1,6,7] or broader archwires with both

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self-ligating and conventional bracket systems.[5,8–11] For nonextraction treatment, the management of moderate crowding and constricted maxillary arches requires an increase in arch perimeter by means of both transverse expansion and proclination of the incisors.[12,13] In addition, the achievement of a stable and functional upper transverse dimension represents one of the main objectives of orthodontic treatment, allowing occlusal stability and esthetic outcome.[14] Several studies[3,4,8,10–15] conducted on fixed appliance effects showed a general tendency toward a more pronounced expansion in the premolar region and a smaller increase in the intermolar width.

The ongoing search for innovation in orthodontics has boosted the emergence of appliances designed to offer patients more comfort, a shorter treatment time, ability to secure better oral hygiene, and greater patient acceptance.[16] Since the introduction of clear aligner treatment (CAT) as an esthetic alternative to traditional orthodontics, it has been reported[17–25] that CAT was able to correct dentoalveolar crossbite and to achieve interarch transverse coordination. With conventional fixed appliances, maxillary expansion occurs by tipping the teeth in a buccal direction, both in the posterior and the anterior regions.[5,6,8] On the contrary, the CAT system allows digital planning of upper arch expansion using a combination of two dental movements: buccal dental tipping and bodily translation of the posterior teeth. However, several authors have agreed that more dental tipping than bodily translation was clinically observed,[18,24] with no common ground regarding the predictability of clear aligners in such complex movements.[19,20] Thus, the current study aimed to evaluate tooth movements during maxillary arch expansion with CAT to provide guidelines during the digital planning phase.

MATERIALS AND METHODS

This project was approved by the Ethical Committee at the University of Rome 'Tor Vergata' (protocol No. 163.20), and informed consent was obtained from the subjects before their inclusion in the study.

Subjects

The study group included a sample of 28 subjects (16 females, 12 males) with a mean age of 31.9 $\pm$ 5.4 years collected prospectively from January 2018 to May 2019. The patients were selected according to the following inclusion criteria: European ancestry (white), posterior transverse discrepancy between maxillary and mandibular arches of a minimum of 3 mm and maximum of 6 mm, permanent dentition stage, presence of second permanent molars, mild or moderate crowding, and good compliance with aligners. Exclusion criteria included multiple and/or advanced caries, tooth agenesis, supernumerary teeth, cleft lip and/or palate, and other periodontal diseases.

The posterior transverse discrepancy was obtained based on the difference between the maxillary intermolar width (distance between the central fossae of right and left first maxillary molars) and the mandibular intermolar width (distance between the mesiobuccal cusps of right and left first mandibular molars).[26]

Treatment Protocol

The treatment protocol for all selected patients included nonextraction strategies, the application of the Invisalign clear aligner system, and the absence of any auxiliaries other than Invisalign attachments. Upper arch expansion with Invisalign was planned to correct the transverse discrepancy and crowding. The ClinCheck for each patient was planned consistently with the same standardized expansion protocol: arch expansion of 0.15 $\pm$ 0.5 mm per stage, mesiobuccal rotation of upper molars according to Rickett's line,[27,28] and an additional 10° of buccal root torque for upper molars and premolars. The achievement of a parabolic arch form was required as an indication for expansion procedures in the prescription form. All subjects were instructed to wear each aligner full time, excluding during meals and tooth brushing. Each aligner was changed every 10 days. Every four stages the clinician checked for good aligner fit and the position of the attachments. At the delivery appointment, the patients understood that they were part of a research study and that honest reporting of their compliance was critical. Patient compliance was noted in the clinical diary.

A single investigator conducted a face-to-face interview with each patient to assess his/her cooperation. Compliance was appraised with a 3-point Likert-type scale ("poor," "moderate," or "good").[29] Poor compliance was reported when the patient wore the aligners less than 16 h/d, moderate when worn between 16 and 20 h/d, and good when the patient wore the aligners full time, as suggested by the clinicians.

The last data collection occurred in May 2019. The mean number of aligners per arch was 35 maxillary and 32 mandibular aligners. Both arches averaged eight attachments each and less than 2 mm of interproximal reduction (IPR). The average time between the initial and final scans was 12.5 months.

Measurement Protocol

Pretreatment (T1) and posttreatment (T2) digital models (.stl files), created from an iTero scan, were collected from the 28 selected patients. Then the .stl files were uploaded in Viewbox 4 software (dHAL

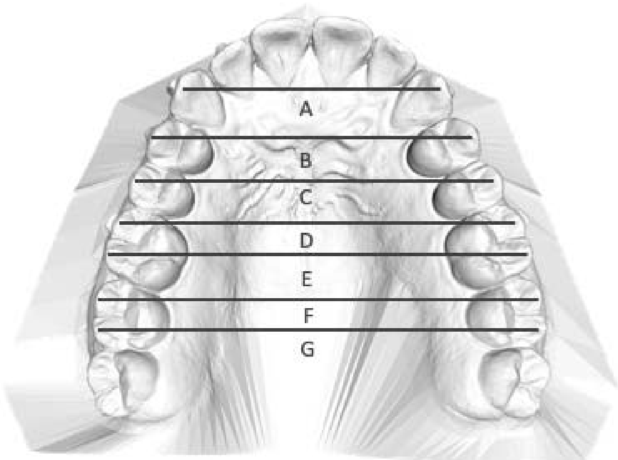

Figure 1. Upper maxillary arch widths measured on T1 and T2 models between the canine cusp tips (A), buccal cusp tips of first premolars (B), buccal cusp tips of second premolars (C), mesiobuccal cusp tips of first molars (D), distobuccal cusp tips of first molars (E), mesiobuccal cusp tips of second molars (F), and distobuccal cusp tips of second molars (G).

software, Kifissia, Greece) to digitize the casts and perform the arch change evaluation. The final position of the corresponding ClinCheck representation was also collected to establish the predictability of the final virtual model (T2 ClinCheck) with respect to the movements observed in the posttreatment model.

The following transverse linear values were measured only on the upper arch for each T1 and T2 model and the T2 ClinCheck model, as described in Figures 1 and 2:

- Intercanine width: linear distance between cusp tips of canines (A);
- First premolar width: linear distance between the buccal cusp tips of first premolars (B);
- Second premolar width: linear distance between the buccal cusp tips of second premolars (C);
- Mesial first molar width: linear distance between the mesiobuccal cusp tips of first molars (D);
- Distal first molar width: linear distance between the distobuccal cusp tips of first molars (E);
- Mesial second molar width: linear distance between the mesiobuccal cusp tips of second molars (F);
- Distal second molar width: linear distance between the distobuccal cusp tips of second molars (G);
- Transpalatal first molar width: linear distance between the groove of the first molars at the mucosa (H); and
- Transpalatal second molar width: linear distance between the groove of the second molars at the mucosa (I).

Upper canine, premolar, and first and second molar inclinations were determined using digital models at T1

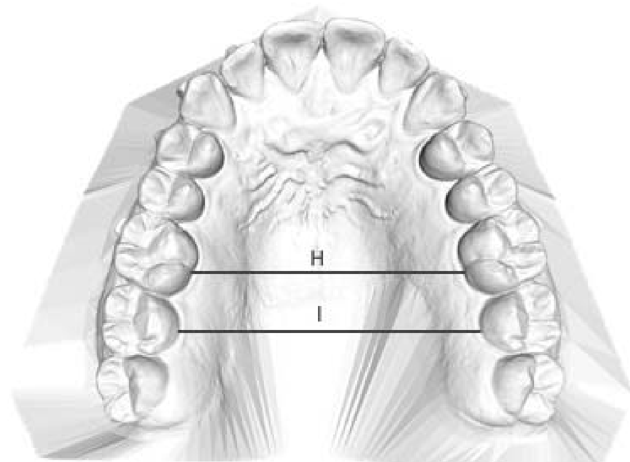

Figure 2. Upper maxillary arch widths measured on T1 and T2 models at the groove of the first molars at the mucosa (H) and at the groove of the second molars at the mucosa (I).

and T2 and T2 ClinCheck models. To evaluate the tooth inclination, a best-fit occlusal plane was set passing through the buccal cusp tips of the first and second molars, first and second premolars, canines, and the incisal edges of lateral and central incisors (Figure 3). This plane was used as a reference for generating one additional reference plane: ie, the para-coronal plane. The upper arch was divided into four sectors: from the second left molar to the first left premolar, from the first left premolar to the lateral left incisor, from the lateral right incisor to the first right premolar, and from the first right premolar to the second right molar. For each sector, the para-coronal plane was obtained perpendicular to the occlusal plane. For every analyzed tooth, a curve passing through the long axis was drawn, and the best fit line was set using the most occlusal and the most gingival points of the curve as references. Tooth inclination was

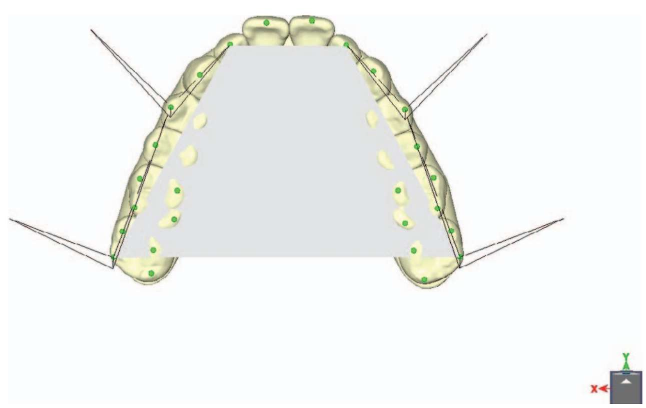

Figure 3. Best-fit occlusal plane passing through the buccal cusp tips of first and second molars, first and second premolars, canines, and the incisal edges of lateral and central incisors.

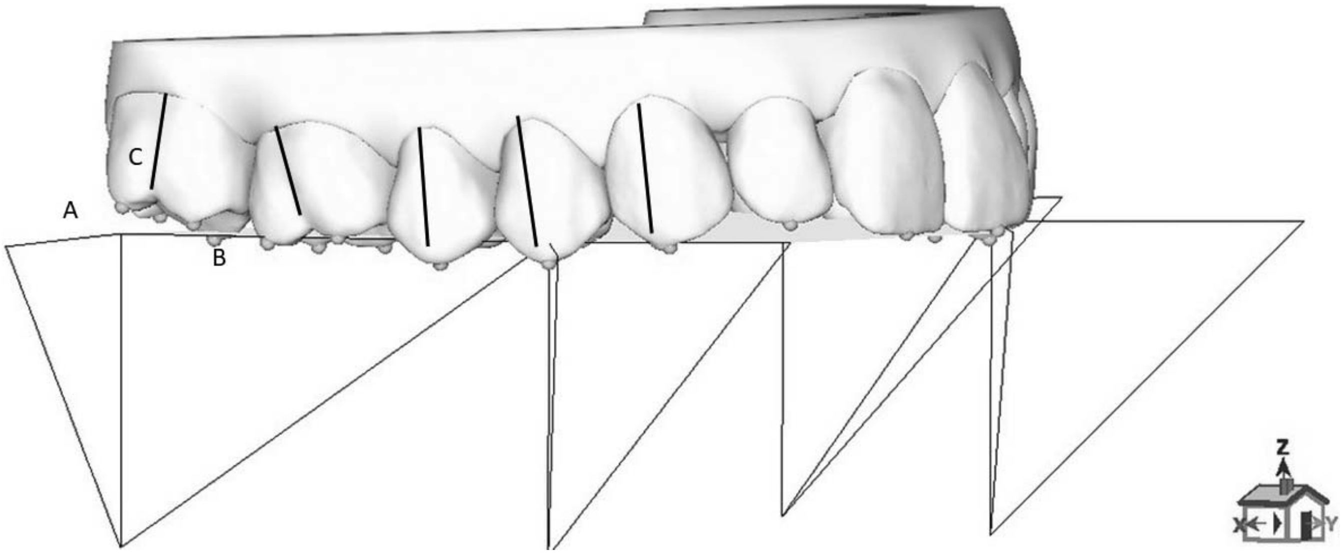

Figure 4. For each sector, the para-coronal plane (A) was obtained perpendicular to the occlusal plane (B). For every tooth analyzed, a curve passing through the long axis was drawn, and the best-fit line was set using the most occlusal and the most gingival points of the curve as references. Tooth inclination was obtained by the angle formed between the best-fit line of each tooth and the para-coronal plane (C).

obtained by the angle formed between the best-fit line of each tooth and the para-coronal plane (Figure 4).

Statistical Analysis

In a pilot study, eight patients were used to calculate the reproducibility and the sample size. Approximately 26 patients were needed to estimate crown inclination with a 95% confidence interval (CI), a maximum error of 2.3°, and a standard deviation (SD) of 5.5°, with a power of 80%.

To test intraexaminer reliability, the sample was measured again 2 weeks after the first assessment. The reliability of the measure was assessed by means of an interclass correlation coefficient (ICC). Sample normality was tested using the Shapiro-Wilk test.

In the presence of normally distributed data, a paired *t*-test was used to compare the T2-T1 changes and the T2-T2 ClinCheck differences. The level of significance was set at 5%.

SPSS (Statistical Package for the Social Sciences), version 18.0 (IBM Corp, Chicago, Ill) was used to analyze the data.

RESULTS

The analysis of compliance of the treated subjects (use of aligners) showed that none had poor cooperation; eight demonstrated moderate compliance and therefore were not included in the study group; 28 had good compliance. Cooperation was therefore good in 78% of the treated patients, and only the data from those subjects were included.

Crossbite of one tooth was present in four patients and three subjects had crossbite of two or three teeth, while 21 patients had no crossbite. None had bilateral crossbite.

The ICC test showed almost perfect agreement, with scores of 0.97 and 0.98 for linear and angular measurements, respectively.

Table 1 summarizes differences between initial upper arch dimensions and final outcomes. For every maxillary measurement, there was a statistically significant difference between pretreatment values and final outcomes, except for measurements at the second upper molars. The greatest increase of maxillary width was detected at the upper first and second premolars, with a net expansion of +3.5 mm for the first premolar and of +3.8 mm for the second premolar at T2. A decreasing expansion gradient was observed moving from the anterior to posterior part of the arch. No significant differences were detected at the second upper molars at either the occlusal or the transpalatal level.

The results for changes in crown inclination are described in Table 2. The comparison of T2-T1 angular outcomes showed statistically significant changes in the inclinations of all teeth except for the second permanent molars. In particular, the mean buccal inclination increased from the canines to the second premolars on both sides, while it decreased from the second premolars to the first permanent molars. No statistically significant difference was found in the changes in the second permanent molar crown inclination measures on either side.

Table 1. Descriptive Statistics and Statistical Comparisons of the Pretreatment to Posttreatment Changes: Linear Measures (Paired *t*-Test)[a]

Variables	Pretreatment (n = 28)		Posttreatment (n = 28)		diff	95% CI	*P*-Value
	Mean	SD	Mean	SD			
Linear measurements, mm							
Intercanine width (3-3)	31.4	2.8	33.6	2.2	2.2	−3.087 to −1.313	***
First interpremolar width (4-4)	37.7	3.3	41.3	2.6	3.5	−4.575 to −2.525	***
Second interpremolar width (5-5)	43.2	3.2	47.1	3.0	3.8	−4.767 to −2.848	***
First intermolar width (6-6 mesial cusps)	49.7	3.8	52.3	3.5	2.6	−3.383 to −1.789	***
First intermolar width (6-6 distal cusps)	51.6	3.7	53.8	3.7	2.2	−2.800 to −1.557	***
First intermolar width (6-6 transpalatal)	33.6	2.6	35.2	2.9	1.6	−2.132 to −1.053	***
Second intermolar width (7-7 mesial cusps)	57.2	3.8	57.9	3.9	0.7	−1.548 to 0.219	NS
Second intermolar width (7-7 distal cusps)	58.1	4.5	58.4	4.7	0.3	−1.121 to 0.236	NS
Second intermolar width (7-7 transpalatal)	39.4	3.5	39.7	3.9	0.5	−0.970 to 0.299	NS

[a] SD indicates standard deviation; CI, confidence interval; and NS, not significant.
*** $P < .001$.

The predictability of ClinCheck of the Invisalign software was determined after completion of treatment (Tables 3 and 4) by comparing between the final expansion achieved in the digital models (T2) and the planned expansion (T2 ClinCheck). For linear measurements, statistically significant differences were detected only for the intercanine width, with 1.6 mm of discrepancy between predicted and achieved movements, reflecting poor predictability between the virtual recreation by ClinCheck and observed treatment outcomes.

Regarding the angular variables, the canine inclinations showed low predictability between the changes predicted by ClinCheck and the changes observed after the completion of treatment. The amount of change planned was not associated with the obtained outcome.

DISCUSSION

Although the Invisalign methodology has been successfully improved in recent years, knowledge related to the appliance is significantly limited in terms of scientific evidence.[18–21] Thus, the purpose of this investigation was to assess the expansion movement pattern of CAT when planning transverse changes in order to provide a suitable protocol for achieving predictable and stable results. An adult population was chosen to participate in this study to avoid bias due to normal transverse growth of the jaws. Traditional dentoalveolar expansion devices mainly result in expansion of the upper arch by means of an increase in posterior buccal tipping, with subsequent bone modeling,[6] obtained through broadened arches or repeated activations of a quadhelix appliance.[7] In the digital set-up for transverse expansion with CAT, a combination of both dental tipping and bodily translation of posterior teeth is usually planned, and the predicted values tend to be variable depending on the teeth involved.

Only a few previous studies[18,19,22,23] analyzed dentoalveolar expansion with CAT. In 2001, Vlaskalic and Boyd[30] reported that buccal expansion can be achieved within a range of 2 to 4 mm in each quadrant to reduce the risk of gingival recession and relapse. In the present study, a progressive reduction of the expansion rate

Table 2. Descriptive Statistics and Statistical Comparisons of the Pretreatment to Posttreatment Changes (T1-T2): Angular Measurements (Paired *t*-Test)[a]

Variables	Pretreatment (n = 28)		Posttreatment (n = 28)		diff	95% CI	*P*-Value
	Mean	SD	Mean	SD			
Angular measurements, °							
13 crown angulation	7.6	2.7	3.1	1.2	4.5	−1.122 to −0.121	***
14 crown angulation	10.3	4.4	4.5	2.9	5.8	−1.113 to −0.498	***
15 crown angulation	6.4	3.6	0.4	1.1	6.0	−1.130 to −0.444	***
16 crown angulation	10.2	2.5	6.9	2.8	3.3	1.283 to 5.317	**
17 crown angulation	1.0	1.6	−0.6	1.8	1.6	−1.325 to −0.525	NS
23 crown angulation	3.8	1.5	0.3	1.2	3.5	−2.107 to −0.393	**
24 crown angulation	8.2	4.5	1.4	0.8	6.8	−0.655 to 0.927	*
25 crown angulation	6.1	2.9	0.9	1.1	5.2	−1.519 to 0.419	**
26 crown angulation	9.5	2.7	4.8	1.9	4.7	2.625 to 6.732	***
27 crown angulation	3.6	1.3	0.5	0.2	3.1	−2.422 to 0.079	NS

[a] SD indicates standard deviation; CI, confidence interval; and NS, not significant.
* $P < .05$; ** $P < .01$; *** $P < .001$.

Table 3. Descriptive Statistics and Statistical Comparisons Between the Actual Posttreatment and the Predicted Post-treatment ClinCheck Changes: Linear Measures (Paired *t*-Test)[a]

	Posttreatment (n = 28)		Posttreatment ClinCheck (n = 28)				
Variables	Mean	SD	Mean	SD	diff	95% CI	*P*-Value
Linear measurements, mm							
Intercanine width (3-3)	33.6	2.2	35.2	2.3	1.6	0.121 to 1.122	*
First interpremolar width (4-4)	41.3	2.6	41.6	3.0	0.3	−0.498 to 1.113	NS
Second interpremolar width (5-5)	47.1	3.0	47.4	3.0	0.3	−0.459 to 1.130	NS
First intermolar width (6-6 mesial cusps)	52.3	3.5	52.2	3.4	−0.2	−1.153 to 0.768	NS
First intermolar width (6-6 distal cusps)	53.8	3.7	54.2	3.4	0.4	−0.525 to 1.325	NS
First intermolar width (6-6 transpalatal)	35.2	2.9	35.5	2.4	0.3	0.393 to 2.107	NS
Second intermolar width (7-7 mesial cusps)	57.9	3.9	57.8	3.7	−0.1	−0.927 to 0.655	NS
Second intermolar width (7-7 distal cusps)	58.4	4.7	59.0	4.7	0.6	−0.419 to 1.519	NS
Second intermolar width (7-7 transpalatal)	39.7	3.9	40.9	3.4	1.2	−0.079 to 2.422	NS

[a] SD indicates standard deviation; CI, confidence interval; and NS, not significant.
* $P < .05$.

from the anterior to the posterior segments, resembling a "drawbridge expansion model," was observed. Greater expansion of maxillary width of 3.5 mm and of 3.8 mm at the first and second premolars, respectively, was reported, corresponding to a mean increase of 8.5% with respect to initial values. The "drawbridge pattern," characterized by different amounts of expansion in the canine (6.5%), premolar (8.5%), and posterior regions (5% for first molars, 1% for second molars), led to development of the maxillary arch from a V-shape to a more parabolic form. In particular, it was possible to observe that premolars had a greater tendency to be expanded because they are located on a straight line, while the canines are arranged on the arc of a circle, the radius of which is determined by the dimensions of the incisors and canines, and while the molars are curving toward the midline. The decision to quantify different percentage values of expansion was related to the possibility of using not only the parabolic arch form but also some numeric parameters as predictors of how much dentoalveolar expansion should be achieved during treatment.

Finally, the results of this study showed that CAT can achieve arch expansion with a minimum amount of buccal tipping. However, in the present study, 10° of additional buccal root torque for upper premolars and molars were planned with the objective of reducing excessive tipping of the teeth planned for maxillary expansion. Zhou and Guo[22] reported that the ratio of the expansion movement between the root and crown was approximately 2:5. For this reason, during digital planning, different buccal root torque should be added according to the amount of expansion. In the present investigation, tooth inclination significantly increased for all maxillary teeth except for the second molars, following the same decreasing gradient from anterior to posterior that is observed for transverse width. Indeed, the greatest buccal tipping was detected for first and second premolars, ranging from +5.2° to +6.9°, while maxillary molars tipped with a mean value of +4° at the end of expansion. Those values were in agreement with those of previous studies,[18,19,22] despite using different measurement strategies, confirming that the mechanical efficiency for delivering effective buccally

Table 4. Descriptive Statistics and Statistical Comparisons Between the Actual Posttreatment and Predicted Posttreatment ClinCheck Changes (T1-T2): Angular Measurements (Paired *t*-Test)[a]

	Posttreatment (n = 28)		Posttreatment ClinCheck (n = 28)				
Variables	Mean	Mean	Mean	SD	diff	95% CI	*P*-Value
Angular measurements, °							
13 crown angulation	3.1	1.2	4.2	0.9	1.1	−1.122 to −0.121	***
14 crown angulation	4.5	2.9	4.8	2.2	0.3	−1.113 to −0.498	NS
15 crown angulation	0.4	1.1	0.9	1.3	0.5	−1.130 to −0.444	NS
16 crown angulation	6.9	2.8	7.3	2.6	0.4	1.283 to 5.317	NS
17 crown angulation	−0.6	1.8	0.2	0.8	0.6	−1.325 to −0.525	NS
23 crown angulation	0.3	1.2	1.2	1.1	0.9	−2.107 to −0.393	*
24 crown angulation	1.4	0.8	1.8	0.4	0.4	−0.655 to 0.927	NS
25 crown angulation	0.9	1.1	1.4	1.3	0.5	−1.519 to 0.419	NS
26 crown angulation	4.8	1.9	5.1	1.1	0.3	2.625 to 6.732	NS
27 crown angulation	0.5	0.2	0.8	0.4	0.3	−2.422 to 0.079	NS

[a] SD indicates standard deviation; CI, confidence interval; and NS, not significant.
* $P < .05$; *** $P < .001$.

directed force by the aligner decreases from anterior to posterior.

Regarding the predictability of digital planning, particular attention should be paid to the maxillary canines. As reported in Tables 3 and 4, significant differences for both linear and angular measurements were found between planned and actual outcomes. This was most likely the result of the greatest amount of change planned for the anterior part of the arch to obtain alignment, leveling, and space closure. More lingually tipped maxillary canines at the end of treatment need to be considered for functional and esthetic reasons by planning for overcorrection during dentoalveolar expansion.

CONCLUSIONS

- The development of the maxillary arch showed a progressive reduction in the expansion rate in the canine, premolar, and posterior regions, with the greatest net increase at the first and second premolars.
- The Invisalign system can increase arch width by increasing the buccal tipping of maxillary teeth.
- Buccal tipping followed the same decreasing gradient from anterior to posterior that was observed for transverse width changes.
- The Invisalign system showed poor predictability between the virtual recreation by ClinCheck and observed treatment outcomes for the maxillary canines. An overcorrection of upper canine movements should be planned during dentoalveolar expansion.

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