Title

An Evaluation of Maxillary Expansion after Phase I Orthodontic Treatment with Clear Aligners using Model Analysis and Cone Beam Computed Tomography

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An Evaluation of Maxillary Expansion after Phase I Orthodontic Treatment with Clear Aligners using Model Analysis and Cone Beam Computed Tomography

by
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Abstract

An Evaluation of Maxillary Expansion after Phase I Orthodontic Treatment with Clear Aligners using Model Analysis and Cone Beam Computed Tomography

Kevin Y. Kai

The objective of this study was to utilize digital models and cone beam computed tomography (CBCT) radiographs to quantify the skeletal and dentoalveolar maxillary expansion in Phase I orthodontic treatment using clear aligner therapy. Fifty-four patients (22 female and 32 male) had measurements taken on both the pre-treatment intraoral scan and post-treatment intraoral scan from the mesiolingual cusps of the maxillary first permanent molars and the cusp tips of the maxillary primary canines to compare the amount of expansion of the dentition. This was compared with the planned amount of expansion seen in the ClinCheck setup. Twenty-nine patients (14 female and 15 male) had measurements taken on both the pre-treatment and post-treatment CBCT radiographs. The measurements included the upper first molar cusp width, upper first molar cementoenamel junction width, upper primary canine cusp width, upper primary canine cementoenamel junction width, the intermolar angle, and the intercanine angle. Samples were scanned with an iTero Element or iTero Element 2 intraoral scanner, and the CBCT radiographs were taken with an iCAT FLX (16x13cm field of view, 0.3mm voxel size, 623.9mGy/cm^2 exposure). The scans were measured using OrthoCAD version 5.9.0.36 and ClinCheck Pro 5. The CBCTs were measuring using Anatomage Invivo6. 2.4mm of posterior expansion was observed between the molars and 4.01mm of anterior expansion was observed between the primary canines. A comparison with the ClinCheck showed a percent yield of posterior expansion to be 51.15% and a

percent yield of anterior expansion to be 64.73%. The CBCT analysis displayed posterior expansion of 1.89mm between the molars, 1.87mm between the molar CEJs, an angle change of -1.16 degrees (buccal tipping) between the molars, anterior expansion of 3.64mm between the primary canines, 1.78mm between the canine CEJs, and an angle change of 24.73 degrees (facial tipping) between the canines. Thus, we demonstrated the impact of clear aligners in terms of maxillary expansion using models and CBCTs.

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Introduction

Palatal expansion has been a common practice for orthodontists to correct a maxilla with a transverse discrepancy and to aid in space generation to help correct crowding during Phase I orthodontic treatment. Traditionally, heavy orthopedic forces are applied to separate the midpalatal suture and other surrounding sutures to expand the maxilla (Angelieri et al. 2016). Indications for palatal expansion include the need to correct a posterior crossbite, to correct an arch-width discrepancy between the maxilla and the mandible, and more recently, to increase the size of the airway (McNamara et al. 2015).

Phase I orthodontic treatment is treatment of patients in mixed dentition, which means that the patient has both primary and permanent dentition (Proffit 2000). While it is not indicated in many situations, there are specific instances that children benefit from Phase I treatment (Proffit 2000; Klumper et al 2000). These include, but are not limited to, treatment of a posterior crossbite, severe overjet, impacted teeth, and an underbite (Proffit 2000; Klumper et al 2000). Because of the malleable bone structures and lack of interdigitation of maxillary sutures, orthodontists can take advantage of growth to generate skeletal changes in this patient population (Proffit 2000; Klumper et al 2000).

Posterior crossbite occurs when the maxillary dentition is more constricted relative to the mandibular dentition. The incidence of a posterior crossbite has been shown to be anywhere between 7.7 to 23.3% in children in primary and mixed dentitions without any type of craniofacial abnormality (Kutin et al. 1969; Gungor et al. 2016; Kurol et al. 1992). Specifically, unilateral posterior crossbites cause a functional shift in the position of the mandible, which can lead to skeletal asymmetry, condylar changes, and dental compensation (Hesse et al. 1997). To treat posterior crossbites, palatal expansion has been the treatment of choice using rapid maxillary expansion or slow maxillary expansion. (Martina et al. 2012)

To accomplish this palatal expansion, orthodontists have employed the use of various removable or fixed appliances during a critical period when children have not had their cranial sutures fused (Starnbach et al. 1966). Rapid palatal expansion has usually been defined as two activations per day, or about 0.5mm expansion (McNamara et al 2003). This has been shown to generate a force anywhere between 2 to 10 pounds for every one activation (Bell 1982). Rapid maxillary expansion is achieved by first causing the lateral tipping of the posterior maxillary teeth. This tipping causes the periodontal tissues to be compressed on the buccal side of the posterior teeth and to be stretched on the palatal side (Bell 1982). Subsequently, bodily translation occurs as the compressed buccal alveolar plate resorbs through repeated force application. If the applied transverse forces are of a sufficient magnitude to overcome the bio-elastic strength of the sutural elements of the maxilla, orthopedic separation of the maxillary segments occurs (Bell 1982). Following the separation, reorganization and remodeling of sutural connective and skeletal tissues proceed in the stabilization of the expanded maxillary arch. The posterior maxillary teeth are then able to upright in the newly expanded position (Bell 1982). Over time, this expansion does tend to decay and relapse closer to the original position of the maxilla. There has been a reported 20-55% loss of expansion between 2-5 years post-orthodontic treatment (Linder-Aronson & Lindgren 1979; Spillane et al. 1995).

In contrast to rapid maxillary expansion, slow maxillary expansion achieves a similar result with less force applied over a longer period of time. If using a jackscrew device, slow maxillary expansion is defined as 1 activation, or 0.25mm expansion, every other day (Proffit 2000). Examples of jackscrew devices include Hyrax, Schwartz, and Haas expanders. Other appliances that achieve slow expansion are quad-helices and activated transpalatal arches. The mechanism of action behind slow maxillary expansion is based on both the midpalatal suture and surrounding tissues. Instead of tearing and hemorrhaging the sutures during rapid maxillary expansion, slow maxillary expansion allows the tissues and sutures to adapt. (Linder-Aronson & Lindgren 1979; Langford 1982). Rapid maxillary expansion has also shown evidence of microtrauma to the temporomandibular joint and external root resorption. (Linder-Aronson & Lindgren 1979; Langford 1982). Theoretically, this suggests an improvement in the conservation of structures and in the stability of the expansion (Akkaya 1998). Loss of expansion due to relapse after slow maxillary expansion has been shown to be about 16-33% after two years of follow-up (Huynh et al. 2009). However, longitudinal studies suggest the stability of both rapid and slow maxillary expansion are comparable since the relapse has similar percentages (Pinheiro et al. 2014).

Given the variable efficacy and stability of expansion, there are factors that have been shown to impact success of expansion. Patient age is a critical factor in the success of traditional expanders (Proffit 2000). Because of increased interdigitation of the sutures, especially after puberty, expansion becomes less predictable as children get older (Baccetti et al. 2001). Younger patients are suspected to have an enhanced skeletal response due to increased cellular activity in the growing sutures (Brin et al.

1981). Brin et al. measured cyclic nucleotides as indicators of cellular activity and new bone formation and found that suture bone cells of young cats were more responsive (Brin et al. 1981). Specifically, cAMP and cGMP activity was higher in younger cats. Similarly, Ten Cate et al. found that sutural tissues of young growing rats were characterized by increased fibroblastic, fibroclastic, and osteoblastic activity following expansion (Ten Cate et al. 1977). Since girls reach skeletal maturity before boys, sex is also an indirect factor on the success of maxillary expansion (Proffit 2000). Melsen found that greater force is necessary to split the sutures in older individuals; this increased force can exceed the body's capacity for physiologic adaptation (Melson 1975).

In the event expansion cannot be predictably done with traditional expanders, surgical and bone-anchored options have become popularized. Multi-piece LeFort osteotomies and Surgically Assisted Rapid Palatal Expansion are methods used to generate orthopedic expansion when a patient has surpassed the age traditional expanders are effective (Chamberland & Proffit 2008). With the advent of mini-implants, non-surgical options to expansion have been utilized. Bicortical mini-implant anchorage on bone-bone palatal expansion can result in parallel expansion even in patients that have passed puberty (Lee et al. 2017; Brunetto et al. 2017).

While techniques and appliances have been created to increase the breadth of treatment options for expansion, advancements in radiography have been available to evaluate the efficacy of these techniques. To evaluate the sutural and dental expansion, cone beam computed tomography has been used to accurately quantify the effect of orthopedic expansion of both rapid and slow palatal expansion (Martina et al. 2012;

Pereira et al. 2017; Woller et al. 2014). Woller et al. took CBCT images immediately before and after rapid palatal expansion. This team discovered that expansion occurs at not only the midpalatal suture, but also the zygomaticomaxillary suture, frontonasal suture, and the intermaxillary suture (Woller et al. 2014). To compare rapid palatal expansion and slow palatal expansion, Pereira et al. measured the dentoalveolar changes (molar tipping) and skeletal changes (intermolar width) (Pereira et al. 2017). This team found that rapid maxillary expansion caused greater buccal tipping, the maxilla to move forward, the mandible to have backward rotation, and skeletal maxillary expansion. Slow maxillary expansion displayed significant dentoalveolar changes due to maxillary expansion but did not demonstrate skeletal maxillary expansion according to their measurement criteria, which measured the changes in the transverse alveolar distance compared to the apical bone base (Pereira et al. 2017). The buccal tipping was two times the magnitude in rapid maxillary expansion versus slow maxillary expansion (Pereira et al. 2017). Some authors have also found that slow maxillary expansion yields thinner buccal bone and thicker palatal bone as a result of translating the teeth through bone (Corbridge et al. 2011; Brunetto et al. 2013). However, other authors have reported equal amounts of skeletal expansion through their CBCT analysis of both expansion methods (Martina et al. 2012; De Almeida et al. 2016; Zheng et al. 2017). The differences in these papers can be due to measurement criteria, protocol, sample size, and more.

Within the last 30 years, clear aligners have become an integral component of orthodontic treatment. Invisalign, and now many other clear aligner systems, use gentle orthodontic forces to move permanent dentition. No evidence suggests that clear aligner systems are superior to traditional orthodontic treatment modalities (Proffit 2000; Zheng et al. 2017). Some studies suggest that aligner treatment does shorten appointment chair usage and treatment duration (Zheng et al. 2017). Anterior intrusive movements, posterior buccolingual inclination, and upper molar translation movements up to 1.5mm are well-controlled in clear aligner treatment (Rossini et al. 2015). However, anterior extrusion, anterior buccolingual movements, and rotations of rounded teeth are not as predictable with clear aligners (Rossini et al. 2015). Because aligners are able to be removed and individuals are able to floss between teeth, periodontal health has also been noted to be improved with clear aligner treatment (Rossini et al. 2014). Based on the increasing use of clear aligners by both orthodontists and general dentists, it is clear that clear aligner treatment will have a lasting impact in the dental field.

Given that dental caries is the most prevalent disease seen in young demographics (U.S. Department of Health and Human Services 2014), improved oral hygiene is an attractive benefit for aligner use (Ke et al. 2019). As a result, Invisalign and other aligner companies have expanded to provide Phase I treatment to pre-adolescent and adolescent children. Many studies have analyzed the benefits and impact of traditional means of palatal expansion, such as a Hyrax, quad helix, or Schwartz appliance. However, the efficacy of skeletal expansion and dentoalveolar movement resulting from Phase I Invisalign treatment has not been evaluated. Upper arch expansion and arch development for adults and individuals in permanent dentition has been studied, but expansion was only achieved through dentoalveolar tipping of the posterior teeth (Zhou & Guo 2019).

Central Hypothesis

We hypothesize that Phase I orthodontic treatment with clear aligners demonstrates predictable skeletal expansion through a combination of dentoalveolar movements and sutural expansion that is comparable to traditional expanders. Therefore, our null hypothesis is that clear aligners do not provide any expansion.

Specific Aims

1. To compare skeletal and dental expansion in Phase I orthodontic treatment with clear aligners with traditional palatal expanders as previously cited in literature
2. To do a model analysis on pre-treatment and post-treatment intraoral scans to determine total movement of the dentition
3. To compare the post-treatment intraoral scans with the planned treatment as seen in the Invisalign ClinCheck and obtain a percent yield of expansion in both the canine and the molar area
4. To do an analysis on pre-treatment and post-treatment CBCTs measuring molar tipping, intermolar distance, canine tipping, and intercanine distance

Materials and Methods

Patient Population

All patients were treated at one location, Gorton & Schmohl Orthodontics, between August 2016 and February 2020 with clear aligners through the Invisalign platform.

All patients had to fit certain inclusion criteria in order to be included in the model analysis aspect of this study. They had to have mixed dentition, no history of previous orthodontic treatment, before and after intraoral scans, had to have some kind of expansion planned, and had to be treated with clear aligners only.

Patients that had any craniofacial abnormalities, history of trauma, or were unable to complete treatment with clear aligners only were excluded from this study.

All patients had to fit certain inclusion criteria in order to be included in the CBCT analysis aspect of this study. They had to have mixed dentition, no history of previous orthodontic treatment, before and after intraoral scans, before and after CBCTs, need for some kind of expansion, and had to be treated with clear aligners only.

Patients that had any craniofacial abnormalities, history of trauma, or were unable to complete treatment with clear aligners only were excluded from this study.

Intraoral Scanning and Cone-Beam Computed Tomography

All intraoral scans were captured with an iTero Element or iTero Element 2 intraoral scanner. The iTero Element 2 replaced the iTero Element in 2018, so the patients who had scans after this year had them done on the iTero Element 2.

The CBCT used was an iCAT FLX taken using a 16x13cm field of view. The voxel size used was 0.3mm. Each scan takes 8.9 seconds and the exposure is 623.9mGy/cm^2. All patients are seated upright, their chin is positioned in the chin cup with adjustments made to the chair height to align the horizontal laser light to match the patient's smile line. All patients were informed to swallow, bite down into centric occlusion, and to not move. The occlusal plane was set to match the tragus-ala line in the horizontal dimension.

Clear Aligner Platform

All treatment rendered was done through Invisalign. Invisalign First was available for use in 2018. Therefore, Invisalign Teen was used for the cases that started before 2018. All patients had anywhere from 1 to 6 sets of aligners delivered over the course of treatment. The average number of aligner sets delivered was 2.44. Any warranty sets, sets that had no changes to the tooth movements but had to be sent for unforeseen circumstances (i.e. if a patient lost their aligners, if the aligners were defective, etc.) were not included in the sets that we tallied.

Morphometric Data Collection

All digital cast measurements were done through the measurement tool in OrthoCAD version 5.9.0.36 copyrighted by Align Technology in 2016. The intermolar measurements were done from the mesiolingual cusp of the 1st permanent molars on each side of the maxilla (Figure 1; Figure 2). The intercanine measurements were done from the cusp tip of the primary canines on each side of the maxilla (Figure 1; Figure 2). In the event one or both of the primary canines were missing on the initial or final intraoral scans, the measurement was done from the center of the alveolar ridge at the position where the primary canine would be.

All ClinCheck measurements of the teeth were done on ClinCheck Pro 5 and used the grid measurement tool to quantify to determine the planned interdental expansion. The intermolar measurements were done from the mesiolingual cusp of the 1st permanent molars on each side of the maxilla (Figure 3). The intercanine measurements were done from the cusp tip of the primary canines on each side of the maxilla (Figure 3). In the event one or both of the primary canines were missing on the initial or final intraoral scans, the measurement was done from the center of the alveolar ridge at the position where the primary canine would be. All planned measurements were taken from the last active aligner from the last refinement treatment plan accepted.

All CBCT measurements were done on Anatomage Invivo6 with a custom configuration. The plotted landmarks included:

- Basion (for CBCT positioning)
- Porion (for CBCT positioning)

- Nasion (for CBCT positioning)
- Right Orbitale (for CBCT positioning)
- Left Orbitale (for CBCT positioning)
- Mesiolingual Cusp of the upper right maxillary molar
- Mesiobuccal Cusp of the upper right maxillary molar
- Cementoenamel Junction of the upper right maxillary molar
- Mesiolingual Cusp of the upper left maxillary molar
- Mesiobuccal Cusp of the upper left maxillary molar
- Cementoenamel Junction of the upper left maxillary molar
- Cusp Tip of the upper right primary canine
- Root Tip of the upper right primary canine
- Cementoenamel Junction of the upper right primary canine
- Cusp Tip of the upper left primary canine
- Root Tip of the upper left primary canine
- Cementoenamel Junction of the upper left primary canine

The configuration inputted these landmarks to give specific measurements on the pre-treatment and post-treatment CBCTs. These measurements were:

- Upper 1st Molar Cusp Width (Figure 5)
- Upper 1st Molar Cementoenamel Junction Width (Figure 6)
- Intermolar Angle (Figure 7)
- Upper Primary Canine Cusp Width (Figure 8)
- Upper Primary Canine Cementoenamel Junction Width (Figure 9)
- Intercanine Angle (Figure 10)

Prior to landmarking any of the points, the Basion, Porion, Nasion, Right Orbitale, and Left Orbitale were used to orient each CBCT according to the Frankfort-Horizontal plane.

The intermolar width measurement was defined as the distance between the mesiolingual cusp of the 1st permanent molars on each side of the maxilla.

The intermolar cementoenamel junction width measurement was defined as the distance between the cementoenamel junction at the mesiolingual line angle of the 1st permanent molars on each side of the maxilla.

The intermolar angle was defined as the angle of intersecting lines tangent to the mesiobuccal and mesiolingual cusp tips of the maxillary right and left first permanent molars as described by Handelman and Handelman et al and used by Huynh et al. (Handelman 1997; Handelman et al. 2000; Huynh et al. 2009).

The intercanine width measurement was defined as the distance between the cusp tip of the primary canines on each side of the maxilla. In the event one or both of the primary canines were missing on the initial or final CBCT, the measurement was done from the center of the alveolar ridge at the position where the primary canine would be.

The intercanine cementoenamel junction width measurement was defined as the distance between the cementoenamel junction at the cingulum of the primary canines on each side of the maxilla. In the event one or both of the primary canines were missing on the initial or final CBCT, the measurement was done from the center of the alveolar ridge at the lingual boundary of the alveolar bone.

The intercanine angle was defined as the angle of intersecting lines following the long axis of the primary canines. In the event one of the primary canines were missing on the initial or final CBCT, a line was constructed from the center of the alveolar ridge to the cusp tip of the permanent canine. This line would then be used as an estimate for the long axis of the primary canine had it been present.

All measurements were conducted by two clinicians, Dr. Kevin Kai and student doctor Ronnel Azizollahi.

Statistical Analyses

All statistical analyses for both the model analysis and CBCT analysis were done by a statistician using Stata software.

For the model analysis aspect of the project, an exact Wilcoxon signed-rank test was used to compare the samples and assess whether the population mean ranks differ. This test was used to measure two aspects of the before and after models: the change of the intermolar distance and the intercanine distance from the planned expansion compared to the actual expansion. The null hypothesis was that the planned expansion was equal to the actual amount of expansion. Because multiple tests were performed on the same sample, Bonferonni’s method was used to correct for the traditional p-value threshold of $p<0.05$. Since a test was done for the intermolar distance and another test was done for the intercanine distance, the threshold for this test was set at $p<0.025$.

To compare the female and male samples, a two-sample Wilcoxon rank sum test was used for a gender analysis. The null hypothesis was that there is a significant difference between female and male samples, so gender is a significant predictor of success

To ensure the accuracy of the data collection, a Spearman rank correlation test was done to compare the two raters, Dr. Kevin Kai and student doctor Ronnel Azizollahi. The null hypothesis was that the correlation between the two raters was 0.

For the CBCT analysis aspect of the project, an exact Wilcoxon signed-rank test was again used to compare six measurements of the before and after CBCTs. These aspects were the change in the intermolar distance, the change in the intermolar angle, the change in the intermolar cementoenamel junction measurement, the change in the intercanine distance, the change in the intercanine angle, and the change in the intercanine cementoenamel junction measurement. The null hypothesis was that the post-treatment measurements were equal to the pre-treatment measurements. It is important to note that the p-value was not corrected for multiple comparisons.

Similar to the model analysis aspect of the study, a Spearman rank correlation test was done to compare the two raters, Dr. Kevin Kai and student doctor Ronnel Azizollahi to ensure the accuracy of the data collection. The null hypothesis was that the correlation between the two raters was 0.

Because 17 out of the 29 CBCTs were taken outside of one month of treatment completion, a nonparametric regression test with change as the outcome and time as the predictor was conducted to account for time was included in this project. Again, the six measurements of the before and after CBCTs were analyzed. These aspects were the change in the intermolar distance, the change in the intermolar angle, the change in the intermolar cementoenamel junction measurement, the change in the intercanine distance, the change in the intercanine angle, and the change in the intercanine cementoenamel junction measurement. The null hypothesis was that time between treatment completion and the post-treatment CBCT has no effect on changes. It is important to note that the p-value was not corrected for multiple comparisons.

Results

For the model analysis and comparison of the ClinCheck measurements, 54 patients were included in the sample. Of these 54 patients, 22 of them were female (40.74%) and 32 of them were male (59.26%). The age range for these patients were between 7 years, 7 months old and 11 years, 6 months old with an average of 8.77 years old. The estimated treatment time ranged from 6 months to 24 months with an average of 13.44 months. The actual treatment time ranged from 2 months, 27 days to 20 months, 22 days with an average of 10.11 months.

For the CBCT analysis, 29 patients were included in the sample. The decrease in the number of patients included in the sample was due to the lack of a post-treatment CBCT in the patients left out of the sample. Of these 29 patients, 14 of them were female (48.28%) and 15 of them were male (51.72%). The age range for these patients were between 7 years, 7 months old and 11 years, 6 months old with an average of 8.91 years old. The estimated treatment time ranged from 6 months to 24 months with an average of 13.86 months. The actual treatment time ranged from 5 months, 15 days to 20 months, 22 days with an average of 11.25 months. Of the 29 samples in this study, 12 of the samples had their post-treatment CBCT taken within 1 month of their treatment completion. The other 17 samples had variable amounts of time after treatment ended to when the CBCT was taken. The range for the 17 patients was between 3 months and 9 days to 28 months and 14 days. As a result, a statistical test to account for time was included in this project.

All 54 patients included in this study were able to complete their Phase I treatment with clear aligners. On average, the estimated treatment length for this patient population was 13.44 months. The average patient finished his or her treatment in 10.11 months. Therefore, the overall treatment time was decreased by an average of 3.33 months. Nevertheless, 7 out of the 54 patients (about 12.96%) went past their estimated treatment length.

Gender was not observed to be a significant predictor of expansion success. The intermolar change p-value=0.058 and the intercanine change p-value=0.329. Therefore, we reject the null hypothesis, and change values are similar for male and female patients on average.

Inter-Rater Reliability Results and P-Value Statistics

The Spearman rank correlation test for the model analysis aspect of this project showed that the intermolar distance measurements between the two raters had a p-value<0.001 and a correlation rho of 0.99. The intercanine distance measurement between the two raters had a p-value<0.001 and a correlation rho of 0.96. Therefore, the measurements between the two raters have a high degree of correlation. As a result, the average of the measurements was taken from both raters to analyze the results.

For the model analysis aspect of this project, the exact Wilcoxon signed-rank test displayed that the intermolar distance measurement had a p-value<0.001, and the intercanine distance measurement also had a p-value<0.001. Therefore, we reject the null hypothesis, and the planned expansion was significantly higher than the obtained expansion in both the intermolar and the intercanine dimension.

The Spearman rank correlation test for the CBCT analysis aspect of this project showed that all values had a p-value<0.001. The intermolar distance measurements between the two raters had a p-value<0.001 and a correlation rho of 0.90. The intermolar angle measurements between the two raters had a p-value<0.001 and a correlation rho of 0.67. The intermolar cementoenamel junction measurements between the two raters had a p-value<0.001 and a correlation rho of 0.89. The intercanine distance measurement between the two raters had a p-value<0.001 and a correlation rho of 0.95. The intercanine angle measurements between the two raters had a p-value<0.001 and a correlation rho of 0.87. The intercanine cementoenamel junction distance measurements between the two raters had a p-value<0.001 and a correlation rho of 0.91. Therefore, the measurements between the two raters have a high degree of correlation. As a result, the average of the measurements was taken from both raters to analyze the results.

For the CBCT analysis aspect of this project, the exact Wilcoxon signed-rank test displayed that the change in intermolar distance measurement had a p-value<0.001, the change in the intermolar angle measurement had a p-value=0.465, and the change in the intermolar cementoenamel junction distance measurement had a p-value<0.001. The change in intercanine distance measurement had a p-value<0.001, the change in the intercanine angle measurement had a p-value<0.001, and the change in the intercanine cementoenamel junction distance measurement had a p-value=0.005. Therefore, we reject the null hypothesis, and the observed changes in measurements were significant relative to the initial measurements except for the intermolar angle, which did not have a statistically significant change.

Statistical Analysis of CBCT Expansion with Time as a Predictor

The post-treatment CBCTs had a variable amount of time between when treatment ended and the post-treatment CBCT was taken. This was due to the treating orthodontist's prerogative in deciding when the CBCT was necessary in observing for any abnormalities, eruption of permanent dentition, and timing for Phase II orthodontic treatment. The nonparametric regression test with change as the outcome and time as the predictor displayed that the change outcome in the intermolar distance had a p-value=0.05, the change outcome in the intermolar angle measurement had a p-value=0.126, and the change outcome in the intermolar cementoenamel junction measurement had a p-value=0.002. The change outcome in the intercanine distance had a p-value<0.001, the change outcome in the intercanine angle measurement had a p-value=0.401, and the change outcome in the intercanine cementoenamel junction measurement had a p-value=0.003. Therefore, we accept the null hypothesis for the intermolar distance change outcome, the intermolar angle change outcome, and the intercanine angle change outcome. This means that time was not associated with the amount of change in these measurements. We reject the null hypothesis for the intermolar cementoenamel junction change outcome, the intercanine cementoenamel junction change outcome, and the intercanine distance change outcome. This means that longer time was associated with an increase in change in these measurements.

Digital Model Findings and Comparison with ClinCheck Setup

Using the landmarks (Figure 1 and 2) to measure the intermolar and intercanine distance, all 54 samples showed at least some amount of dentoalveolar expansion in the posterior region. The expansion ranged from 0.25mm to 6.10mm. When including all 54 samples, there was an average expansion of the maxillary molars of about 2.4mm (Figure 11).

Because not all patients necessitate expansion as part of the treatment, a percent yield of expansion was calculated to determine how predictable clear aligner treatment is at achieving planned expansion in the posterior region. From evaluating the planned ClinCheck expansion, it was seen that the average planned expansion was 5.22mm between the maxillary molars (Figure 11). In comparing the planned and actual expansion, we found the percent yield of maxillary molar expansion through the use of clear aligners to be 51.15% (Figure 12).

When analyzing the maxillary primary canine region, 53 samples out of the 54 showed dentoalveolar expansion in the anterior region (Figure 13). The expansion ranged from 0.15mm to 11.3mm. The one sample that did not show any expansion also did not show any constriction. This sample’s treatment plan was to maintain the intercanine dimension, which was reflected in a 100% yield of the planned movements. When including all 54 samples, there was an average expansion of the maxillary primary canines of about 4.01mm (Figure 13).

A percent yield of expansion was again calculated to determine how predictable clear aligner treatment is at achieving planned expansion in the anterior region. From evaluating the planned ClinCheck expansion, it was seen that the average planned expansion was 5.88mm between the primary canines (Figure 13). In comparing the planned and actual expansion, we found the percent yield of maxillary primary canine expansion through the use of clear aligners to be 64.73% (Figure 14).

Cone-Beam Computed Tomography Findings

Using the landmarks (Figure 5) to measure the intermolar distance, there was an average expansion of about 1.89mm (Figure 15) for the 29 samples. When accounting for time, there was about a 0.047mm decrease per month (Figure 21) after treatment was completed. However, the statistical analysis showed that this decrease over time was not significant.

Using the landmarks (Figure 6) to measure the intermolar cementoenamel junction distance, there was an average expansion of about 1.87mm (Figure 16) for the 29 samples. When accounting for time, there was about a 0.027mm decrease per month (Figure 22) after treatment was completed. The statistical analysis showed that this decrease may be correlated with time.

Using the landmarks (Figure 7) to measure the intermolar angle, there was an average decrease in angle of about 1.16 degrees (Figure 17) for the 29 samples. This means that the molars had tipped buccally by about 1.16 degrees after treatment on average. When accounting for time, there was about a 0.2 degree increase per month (Figure 23) after treatment was completed. This suggests that the molars uprighted gradually over time after treatment completion. However, the statistical analysis showed that this increase over time was not significant.

Using the landmarks (Figure 8) to measure the intercanine distance, there was an average expansion of about 3.64mm (Figure 18) for the 29 samples. When accounting for time, there was about a 0.12mm decrease per month (Figure 24) after treatment was completed. The statistical analysis showed that this decrease is in part due to time.

Using the landmarks (Figure 9) to measure the intercanine cementoenamel junction distance, there was an average expansion of about 1.78mm (Figure 19) for the 29 samples. When accounting for time, there was about a 0.21mm decrease per month (Figure 25) after treatment was completed. The statistical analysis showed that this decrease may be correlated with time.

Using the landmarks (Figure 10) to measure the intercanine angle, there was an average increase in angle of about 24.73 degrees (Figure 20) for the 29 samples. This means that the canines had tipped buccally by about 24.73 degrees after treatment on average. When accounting for time, there was about a 0.016 degree decrease per month (Figure 26) after treatment was completed. This suggests that the canines uprighted gradually over time after treatment completion. However, the statistical analysis showed that this increase over time was not significant.

Discussion

Digital Model and Comparison with ClinCheck Setup Discussion

When analyzing the samples, it is apparent that clear aligner treatment can yield dentoalveolar expansion. This study found that amount to be about 2.4mm in the posterior maxilla and about 4.01mm in the anterior maxilla. Other authors have found about 5mm of expansion from increased intermolar width through the use of slow maxillary expanders (Huynh et al. 2009; Hesse et al. 1997) and about 5.5mm from rapid maxillary expanders (Spillane & McNamara 1995; Moussa et al. 1995).

Therefore, on a model basis, clear aligner treatment can be seen to provide predictable expansion to some degree. Based on the results, the anterior maxilla at the canine region had about 1.61mm more expansion compared to the posterior maxilla. This pattern of expansion is similar to the triangular pattern seen in traditional rapid and slow maxillary expansion (Bell 1982).

The significance of the planned expansion seen in the ClinCheck setup can provide insight as to how much to program when trying to achieve predictable results. Our results showed that the intermolar percent yield of expansion was about 51.15% while the intercanine percent yield of expansion was about 64.73%. This means that a treating orthodontist can expect to gain anywhere from about half to about 65% of what the ClinCheck shows. One important aspect to consider is the instructions given to the Invisalign technician. Because of Invisalign’s customizable design, clinicians are able to specify how much expansion they would like. In our patient sample, the expansion varied for each patient. For example, the treating orthodontist specified 2mm of expansion bilaterally for some patients and 8mm of bilateral expansion for others.

Based on studies on relapse, the maxilla has a tendency to constrict regardless of expansion modality. Linder-Aronson and Lindgren found 3.6mm, or about 65.45%, of expansion remaining after 5.5mm of rapid maxillary expansion two years post-treatment (Linder-Aronson & Lindgren 1979). Boysen et al. found 3.6mm, or 72%, of expansion remained after 5mm of initial expansion immediately after treatment completion (Boysen et al. 1992) with slow maxillary expansion. Schiffman and Tuncay found 2.4mm of expansion remaining after 3.88mm of expansion a year after treatment completion in their meta-analysis (Schiffman & Tuncay 2001). Huynh et al found that about a third of expansion was lost after treatment completion (Huynh et al. 2009). They also noted that retention was critical in maintaining arch width, and decreased relapse by about 1mm two years after treatment completion (Huynh et al. 2009). In putting this into perspective with clear aligner treatment, it is feasible that 51.15-64.73% of expansion was maintained post-treatment compared to the ClinCheck set-up. Based on our results, it can be inferred that overtreating the expansion of the maxilla is warranted to achieve predictable results.

Cone-Beam Computed Tomography Findings Discussion

As stated in the materials and methods section, the post-treatment CBCTs were taken at variable times after treatment. When factoring this into account with past literature given relapse of expansion (Linder-Aronson & Lindgren 1979; Huynh et al.

2009; Boysen et al. 1992; Schiffman & Tuncay 2001), the average expansion shown in the CBCT aspect of our study should show a decreased amount of expansion compared to the model analysis. This was clear in both the intermolar and intercanine dimensions. There was an average expansion of 1.89mm in the intermolar distance, 1.87mm in the intermolar cementoenamel junction distance, 3.64mm in the intercanine distance, and 1.78mm in the intercanine cementoenamel junction distance. All values were decreased relative to the digital models that were taken immediately following treatment.

When plotting the average change in expansion over time where a line of best fit was constructed from a scatterplot of expansion observed from post-treatment CBCTs. The slope demonstrates the amount of change per month that can be expected as a result of relapse. Our results showed that it is possible to have about 0.047mm of relapse in the intermolar cusp dimension per month, 0.026mm of relapse in the intermolar cementoenamel junction dimension per month, 0.12mm of relapse in the intercanine cusp dimension per month, and 0.21mm of relapse in the intercanine cusp dimension per month. Of course, this has some confounding variables. First, none of the patients have post-retention records of their own to track how much expansion remains. Second, the protocol for each patient was variable, so comparing these samples may not be the best indication of potential relapse. Therefore, this observed decrease in arch dimension is simply a trend observed from our patient population, but future studies should take into account post-retention records to observe long term stability of expansion from the use of clear aligners.

From our data collection, the maxillary molars were shown to have an average buccal tipping of 0.58 degrees after treatment with clear aligners. This is significantly less than the 2.3 degrees seen with traditional slow maxillary expanders (Huynh et al. 2009) and the 3.7 degrees seen by the use of a hyrax (Schiffman & Tuncay 2001). Because clear aligners tend to have greater stability in maintaining buccolingual inclination (Rossini et al. 2015), this result is consistent with what the literature suggests. When examining the change in molar inclination over time, the trendline suggests that about 0.1 degrees of molar uprighting may occur per month after treatment occurs. Other studies have found the uprighting of molars to be about 6 degrees after two years of retention (Huynh et al. 2009) and 3.3 degrees of uprighting naturally when transitioning from mixed dentition to permanent dentition (Marshall et al. 2003).

The maxillary primary canines were seen to flare buccally by about 12.37 degrees (Figure 20). This change is seen to be relatively consistent despite time. There was only about a 0.0082 degree angle change per month seen based on our sample (Figure 26). A possible explanation for this higher degree of tip is due to the pattern of exfoliation of primary dentition. The maxillary canine usually erupts lingually relative to the maxillary primary canine (Litsas 2011). This pattern tilts the primary canine crown towards the cheek and increases the buccal crown flaring. Therefore, this angle is not very indicative of maxillary expansion.

Overall Clear Aligner Expansion Discussion

Admittedly, this study has some areas that can have impacted the results. First, there is no way to guarantee the patients were following the exact protocol set by the treating orthodontist. The efficacy of the aligners is highly based on proper use of the aligners, so we cannot guarantee all patients will have these similar results. Second, Invisalign uses the data collected by past aligner cases to improve their product. Given the range of data collection used in this sample was from 2016 to 2020, Invisalign certainly improved their product to optimize treatment efficiency. In addition, the treating orthodontist could have also changed their protocol for the cases as stated earlier in this discussion. Finally, not all of the patients included in this sample needed to have expansion done. This sample included patients that needed Class I, Class II, and Class III correction. Therefore, the treatment length and mechanics differ between each case.

It is also important to note that the case selection for these patients was such that the maxillary constriction was not clinically severe. Based on the measurement comparing the intermolar distance between the maxillary molars and the intermolar distance between the mandibular molars (measured from central fossa to central fossa), the average arch width discrepancy was 1.32mm. Given the novelty of clear aligner treatment in Phase I orthodontic cases, the treating orthodontist specifically chose cases without much of a significant discrepancy. Therefore, the amount of expansion shown in this sample size may not be indicative of the limit of what clear aligners can achieve.

On average, the estimated treatment length for this patient population was 13.44 months. The average patient finished his or her treatment in 10.11 months. Therefore, the overall treatment time was decreased by an average of 3.33 months. Nevertheless, 7 out of the 54 patients went past their estimated treatment length. 4 of the 7 patients that went past their estimated treatment length were male and 3 were female. This could have been due to a number of factors including: lack of use of the aligners, multiple refinement scans that prolonged treatment, and more. The shortened treatment length is a benefit for both the treating doctor and the patient, especially for Phase I treatment. Clear aligner therapy can be suggested as a treatment modality for patients with high caries risk given that patients tend to be able to keep their oral hygiene improved compared to fixed oral appliances (Ke et al. 2019).

Previous studies have demonstrated that patients treated for expansion at a younger age maintain their expansion more relative to those who were treated at an older age (Bell 1982; Huynh et al. 2009). This is possibly due to the increased interdigitation of sutures leading to patient's being more prone to expansion loss (Bell 1982; Hicks 1978). Given that clear aligners may be more tolerable for younger patients in comparison to traditional maxillary expanders (Alajmi et al. 2019), clear aligners can be a solution to provide treatment in that niche population that would not accept any other form of treatment.

Given the novelty of clear aligner therapy for Phase I orthodontic treatment, there are a multitude of future directions that this project can be taken. Much of the literature surrounding traditional slow maxillary expansion and rapid maxillary expansion has measurements taken multiple years after treatment is rendered (Huynh et al. 2009;

Spillane & McNamara 1995; Moussa et al. 1995; Hesse et al. 1997). This study did not include any examination of post-treatment records after several years. As such, relapse and retention of Phase I treatment with aligners is a future area of study. Clear aligners are highly customizable due to the ability to program movements digitally and create the aligners based on the digital movements. Therefore, another interesting area that can be examined is variable expansion if patients need to only have expansion in certain dimensions of their maxilla. Expansion has been cited to be more demonstrable and predictable in younger patients (McNamara et al. 2015; Gungor et al. 2016; Kurol & Berglund 1992; Proffit 2000), but other factors may contribute toward expansion success with clear aligner use. For example, more durable acrylic may provide a more stable result, an increased rate of switching to new aligners, or increased treatment time could contribute to more expansion. These are all areas of future study that can provide guidance on use of clear aligners for Phase I orthodontic treatment. An important inclusion criteria for future studies should also include a minimum amount of arch width discrepancy to necessitate expansion. Similar to the protocol by Woller et al., a post-expansion CBCT could also be taken immediately after the expansion phase to evaluate sutural expansion (Woller et al. 2014).

This master's thesis provides an overall introduction to the capabilities of Phase I orthodontic treatment with clear aligners and has shown that dentoalveolar and skeletal expansion does occur through the use of clear aligners. Further research into this area with a more specific sample population can provide useful information going forward.

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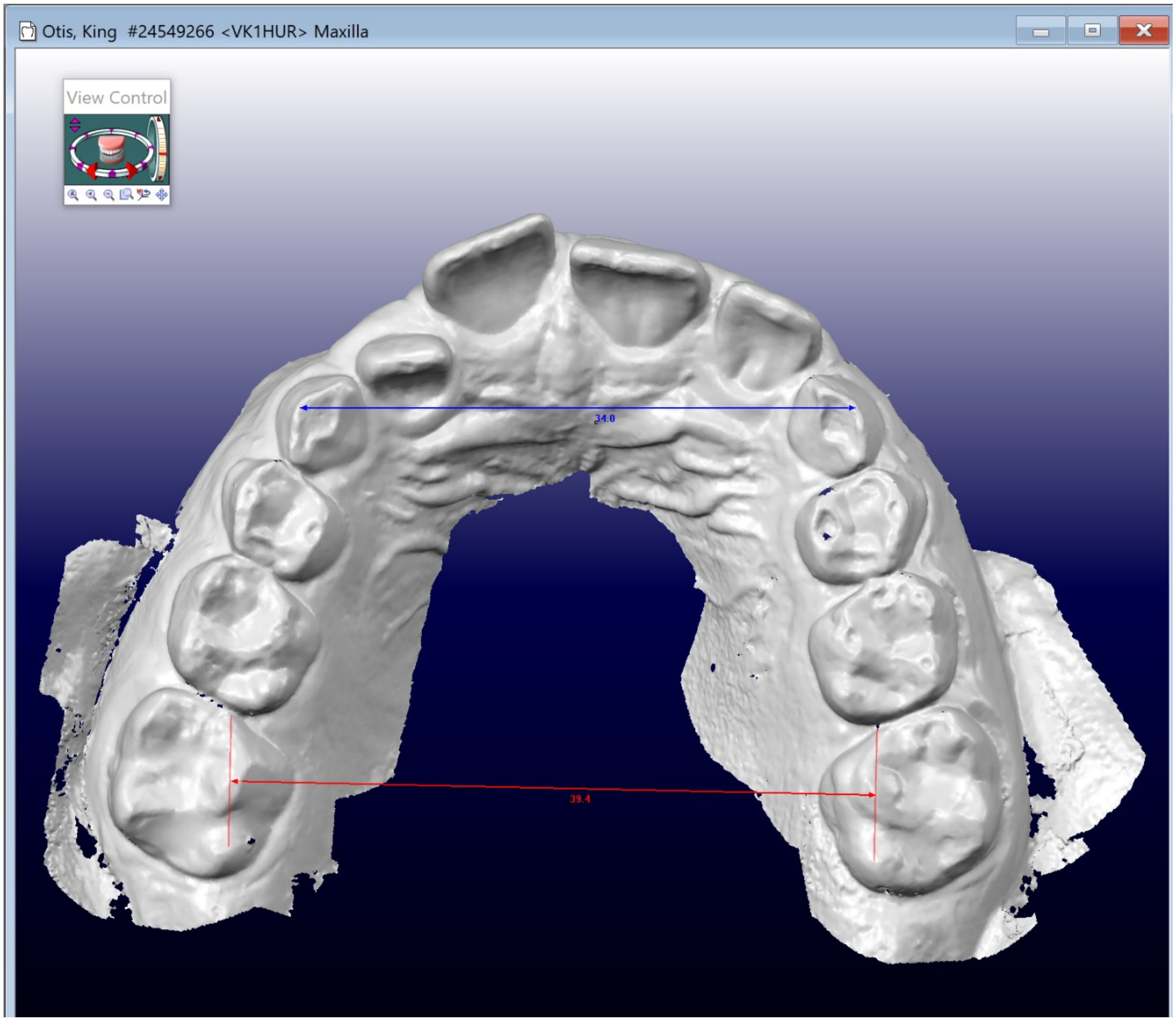

Figure 1 (Pre-Treatment Digital Cast Intermolar and Intercanine Width)

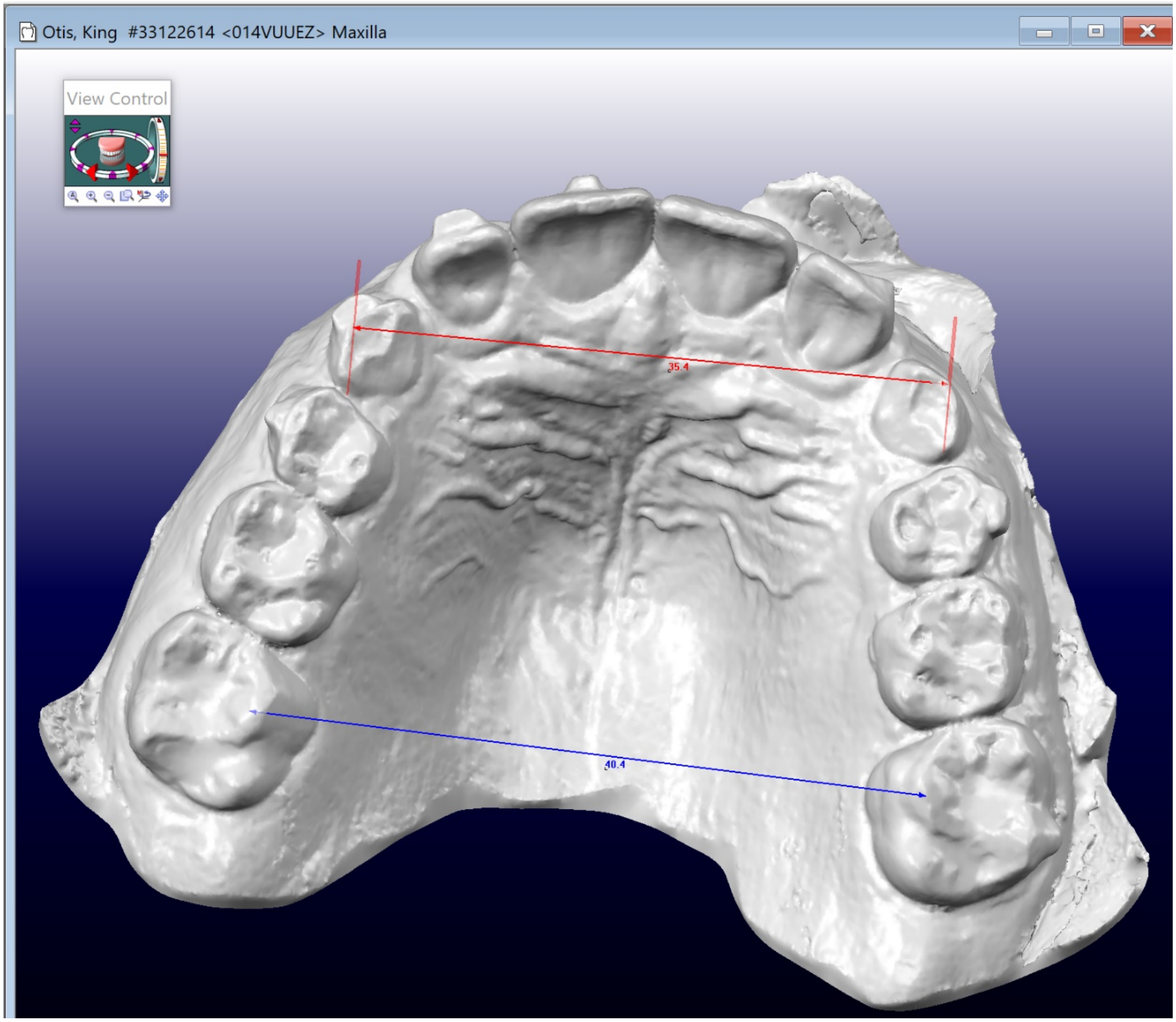

Figure 2 (Post-Treatment Digital Cast Intermolar and Intercanine Width)

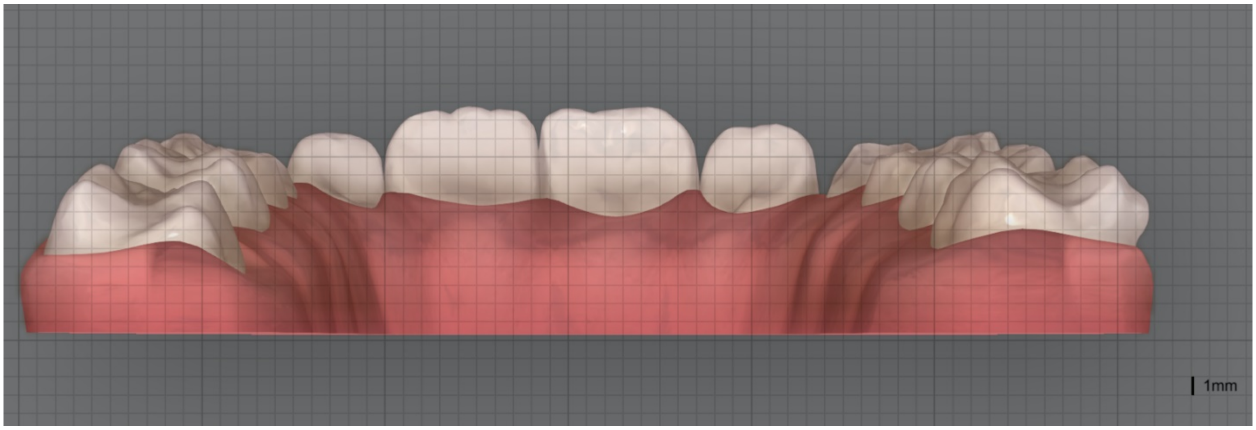

Figure 3 (Planned Expansion based on ClinCheck)

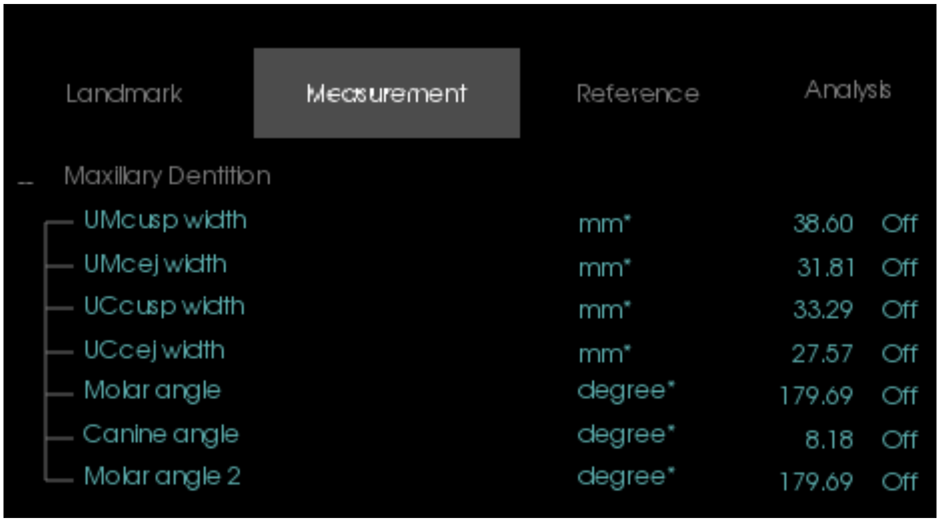

Figure 4 (Measurement Table constructed in Anatomage)

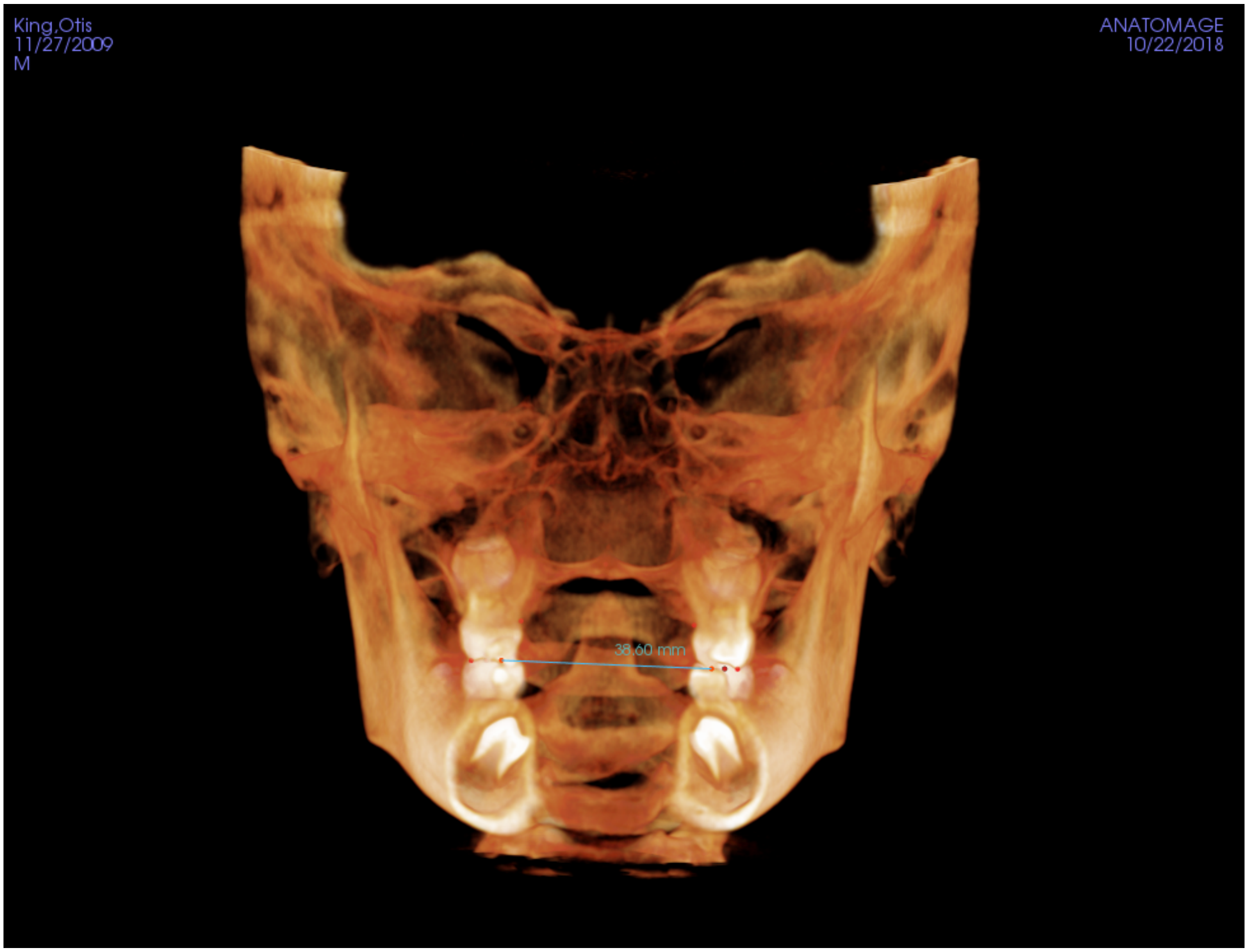

Figure 5 (Molar Intercuspal Width)

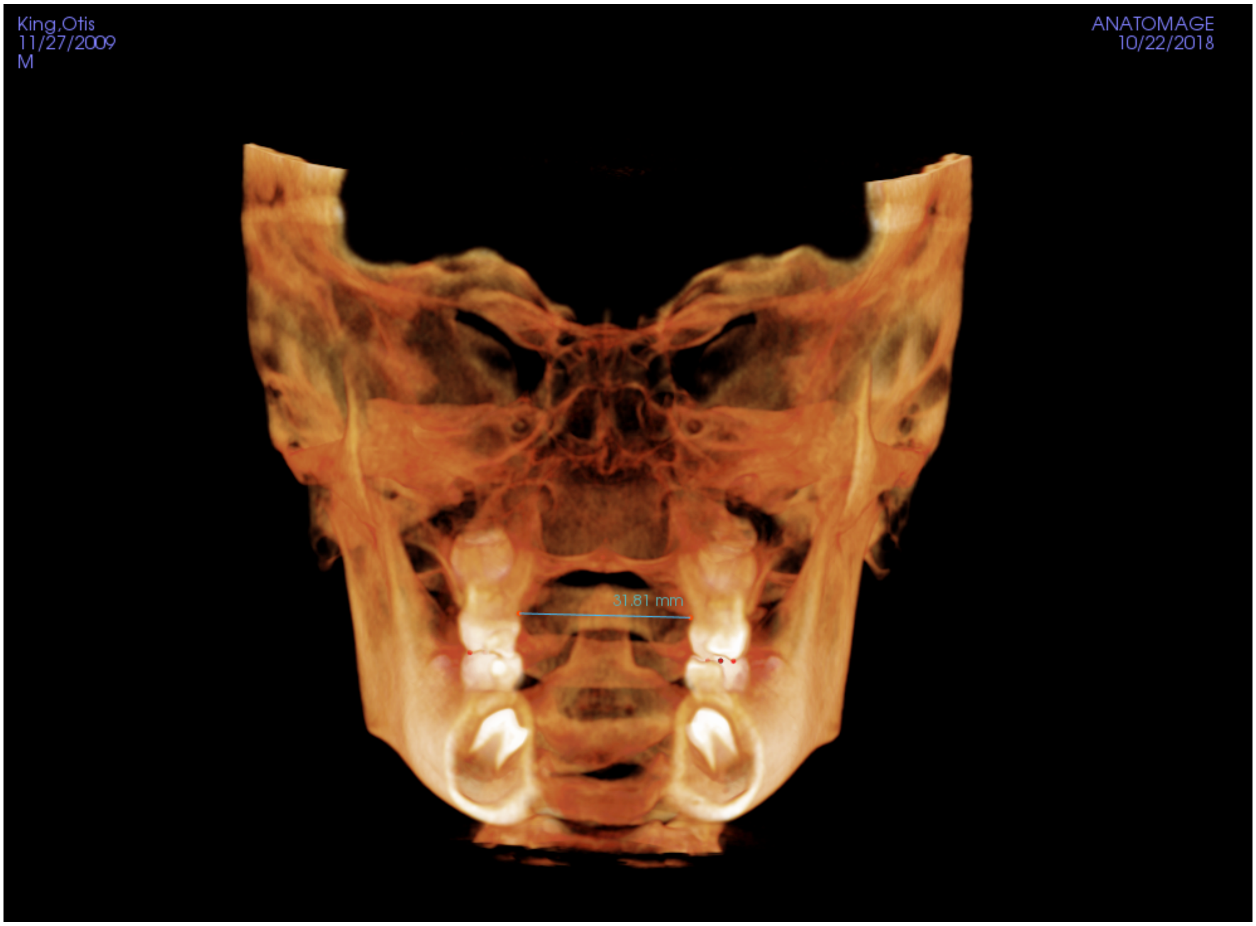

Figure 6 (Intermolar CEJ width)

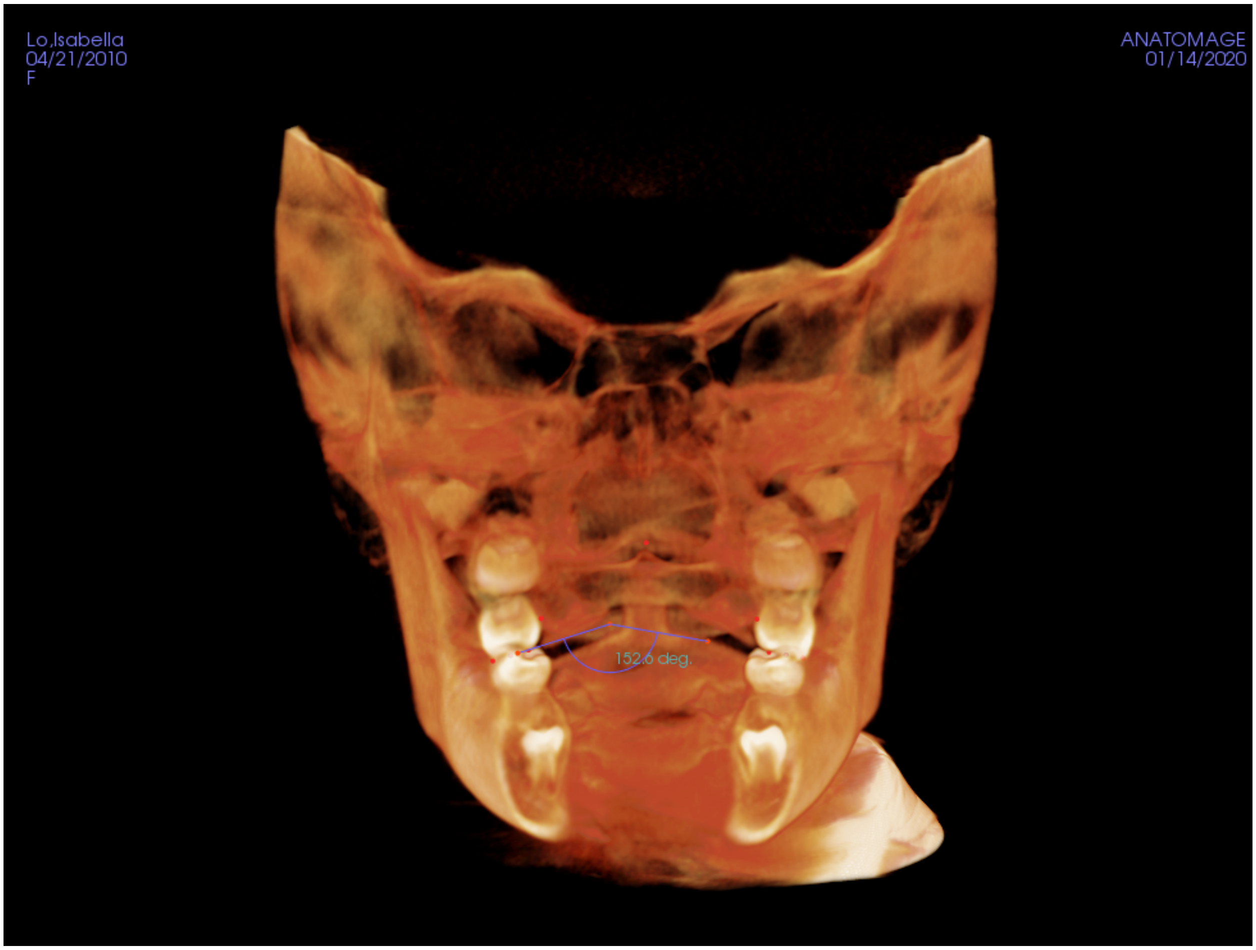

Figure 7 (Molar Angle)

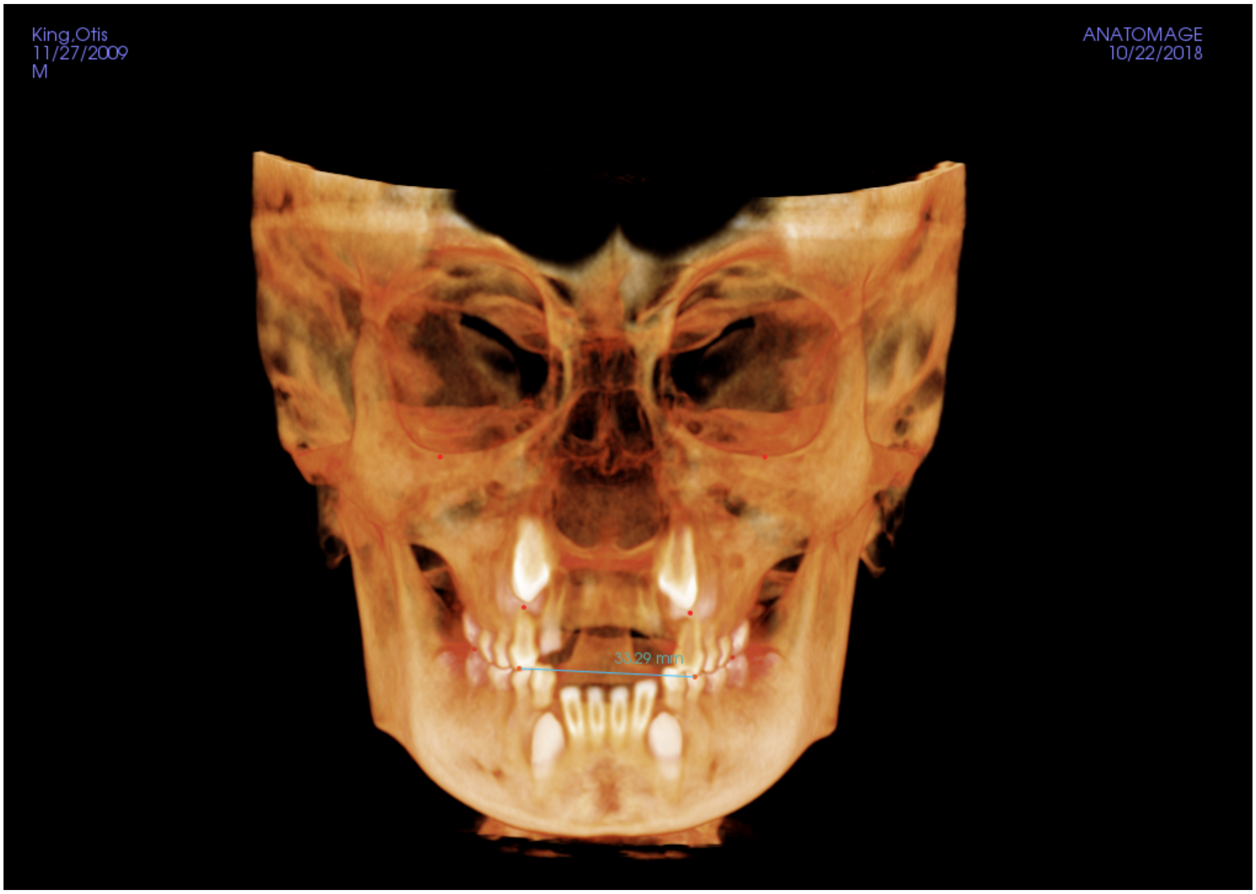

Figure 8 (Intercanine Width)

Figure 9 (Intercanine CEJ Width)

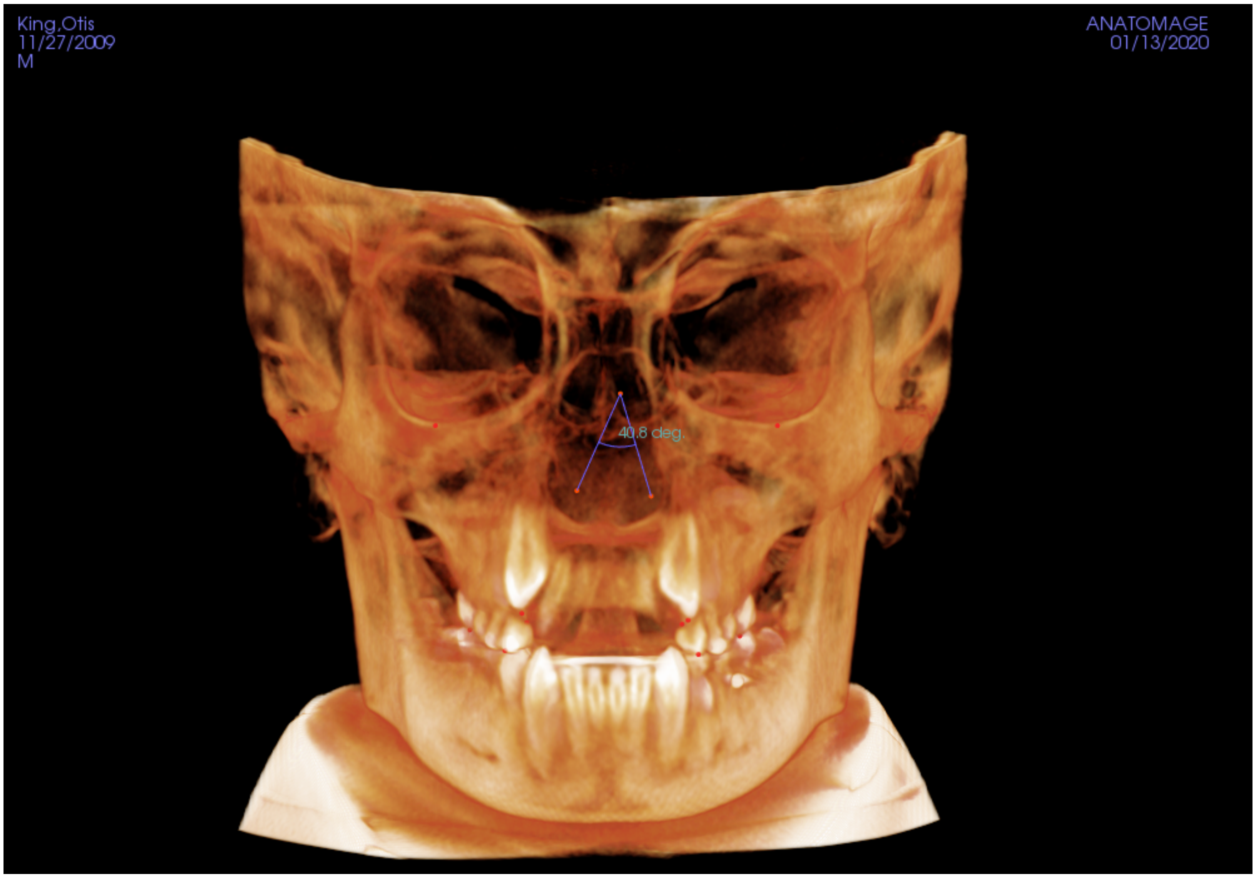

Figure 10 (Canine Angle)

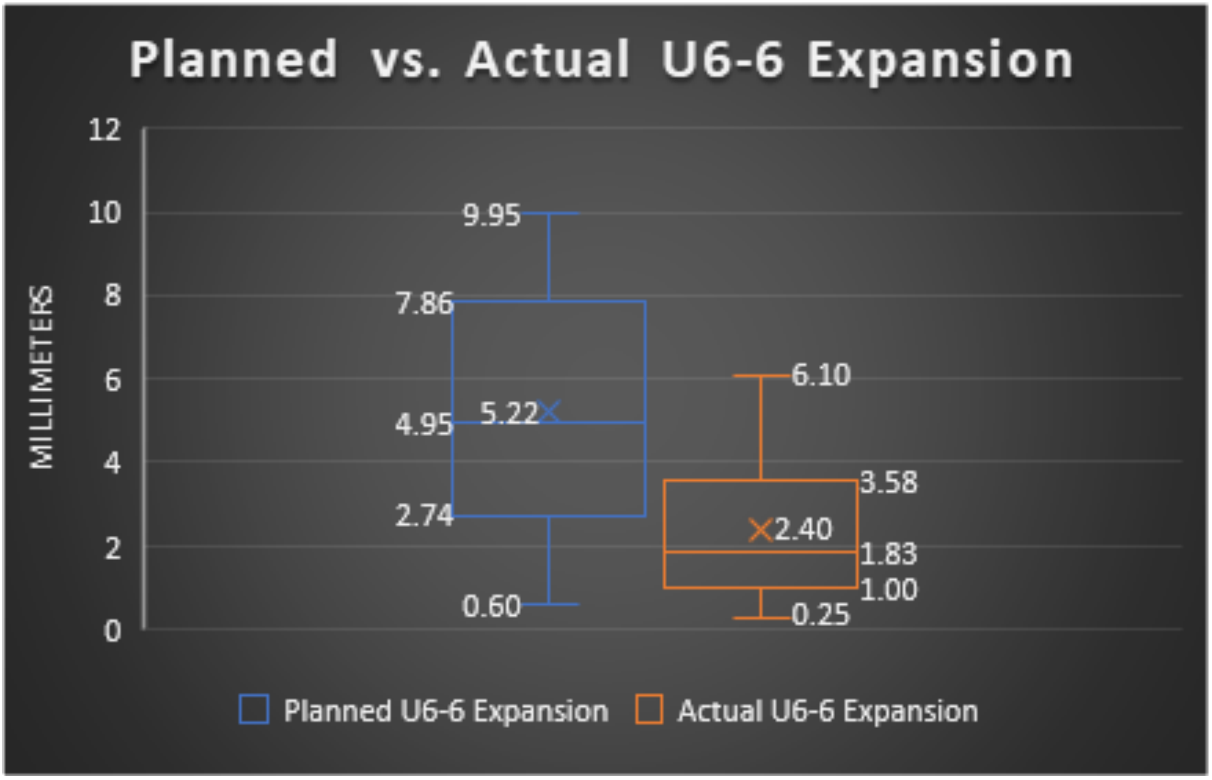

Figure 11 (Planned vs. Actual Maxillary Molar Expansion)

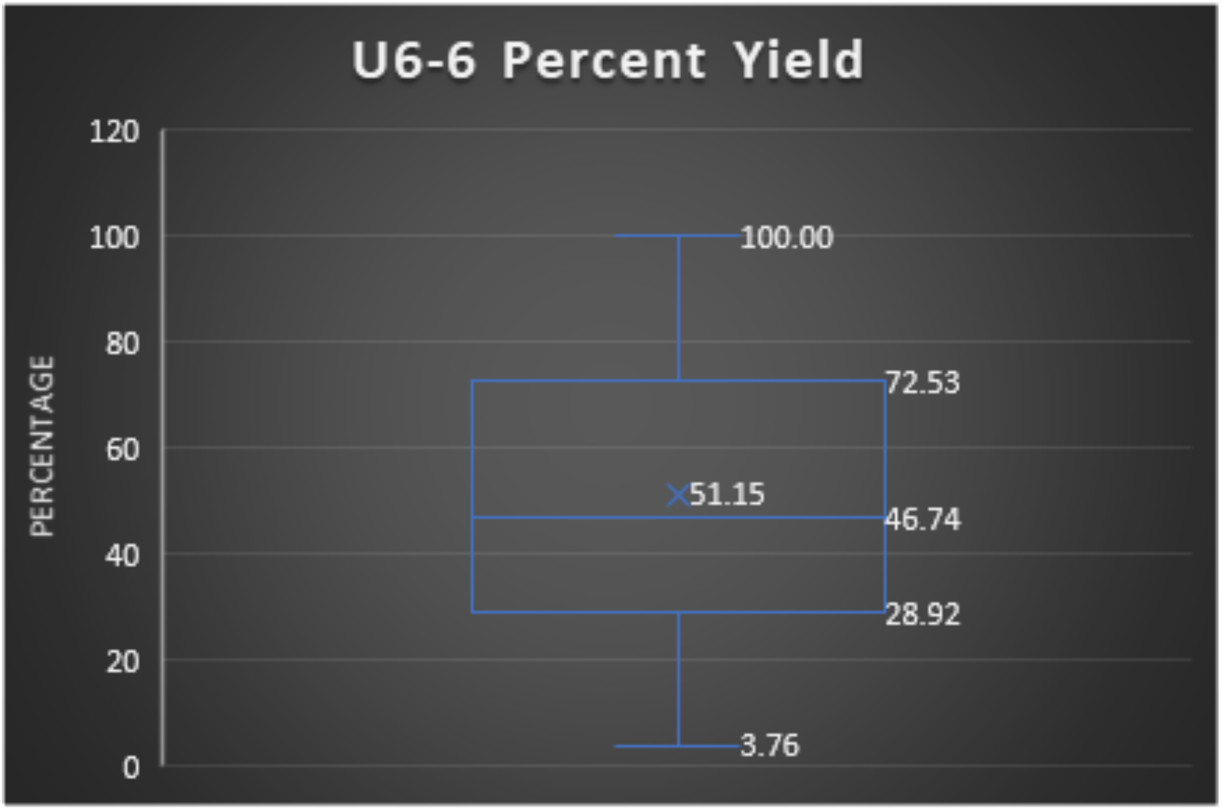

Figure 12 (Percent Yield of Maxillary Molar Expansion)

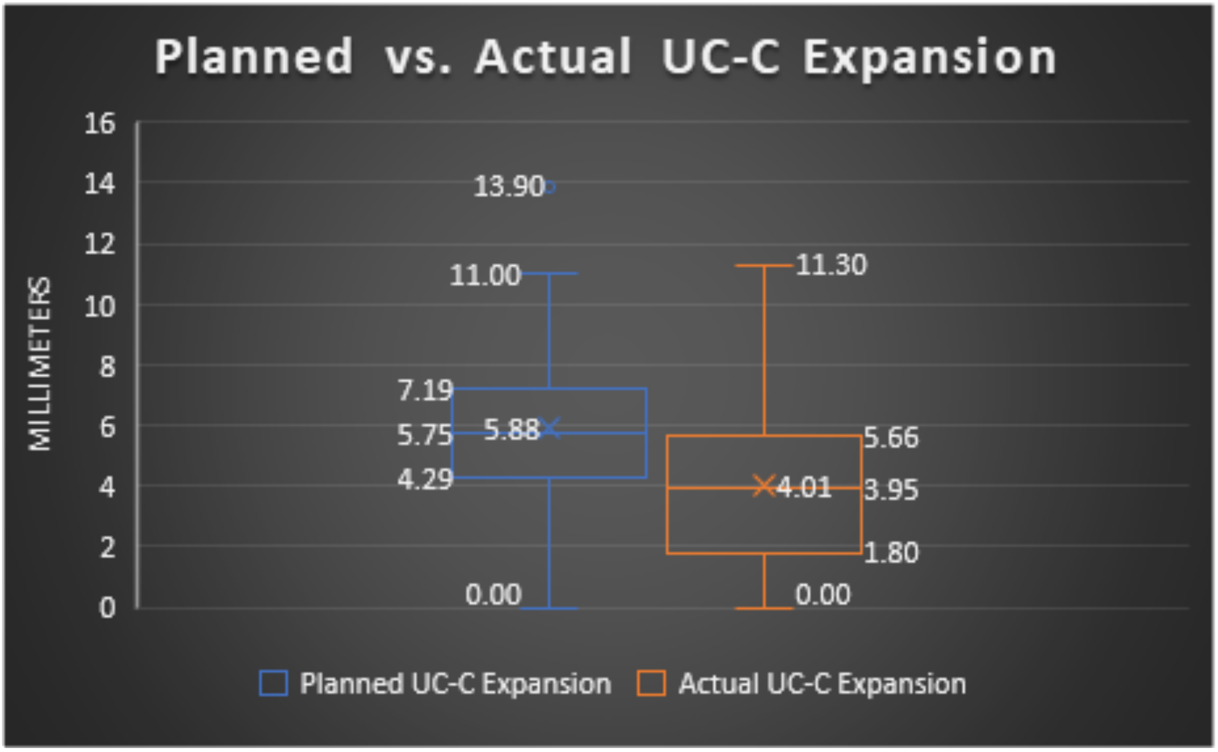

Figure 13 (Planned vs. Actual Maxillary Primary Canine Expansion)

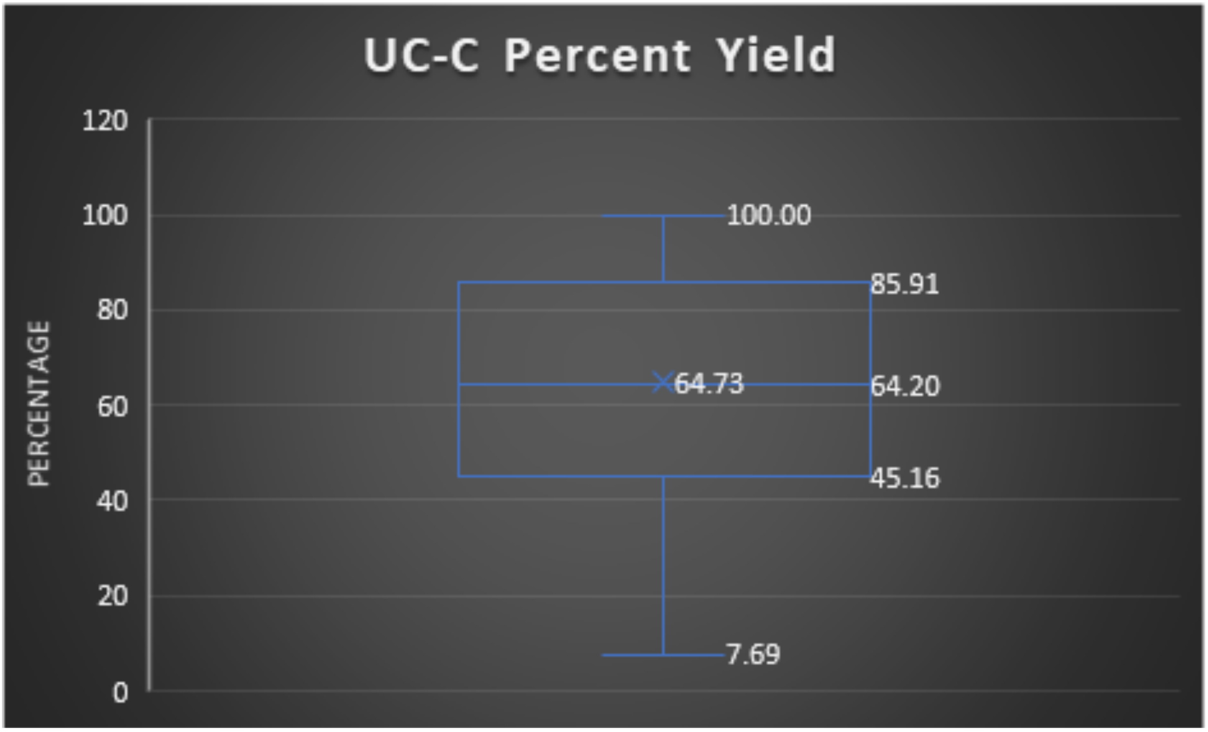

Figure 14 (Percent Yield of Maxillary Primary Canine Expansion)

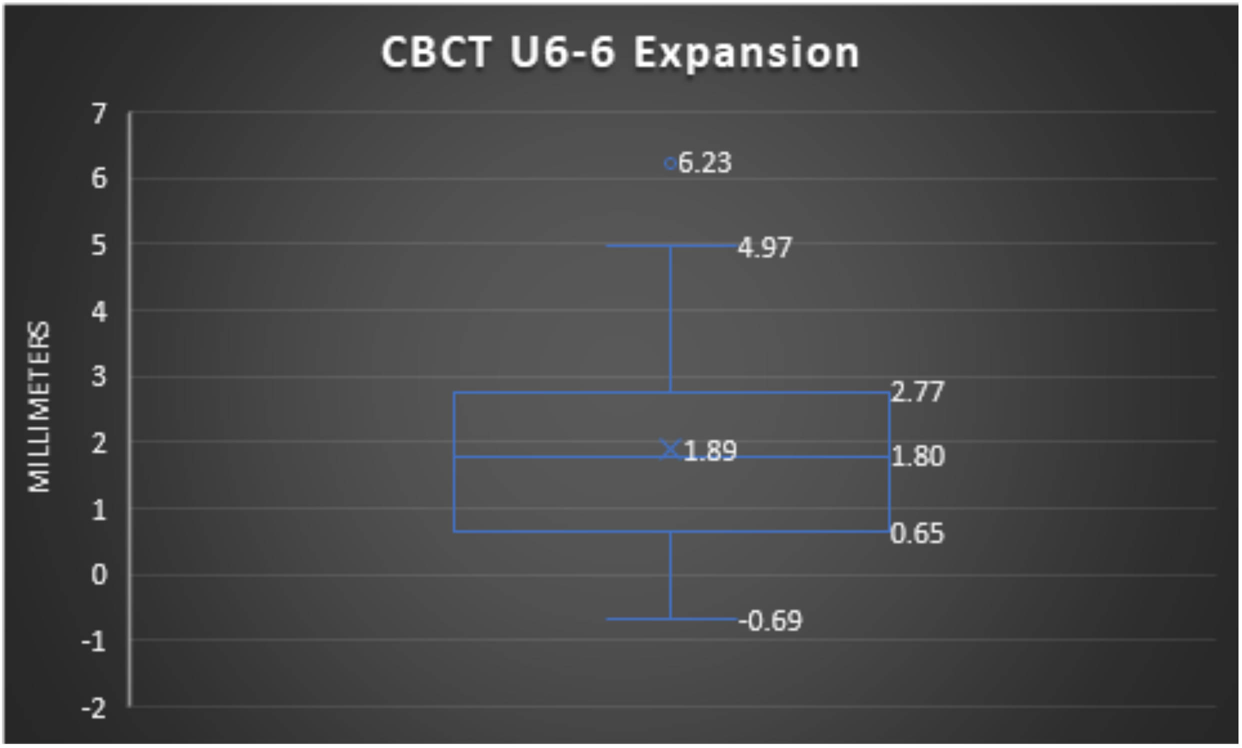

Figure 15 (Maxillary Molar Expansion shown by CBCT)

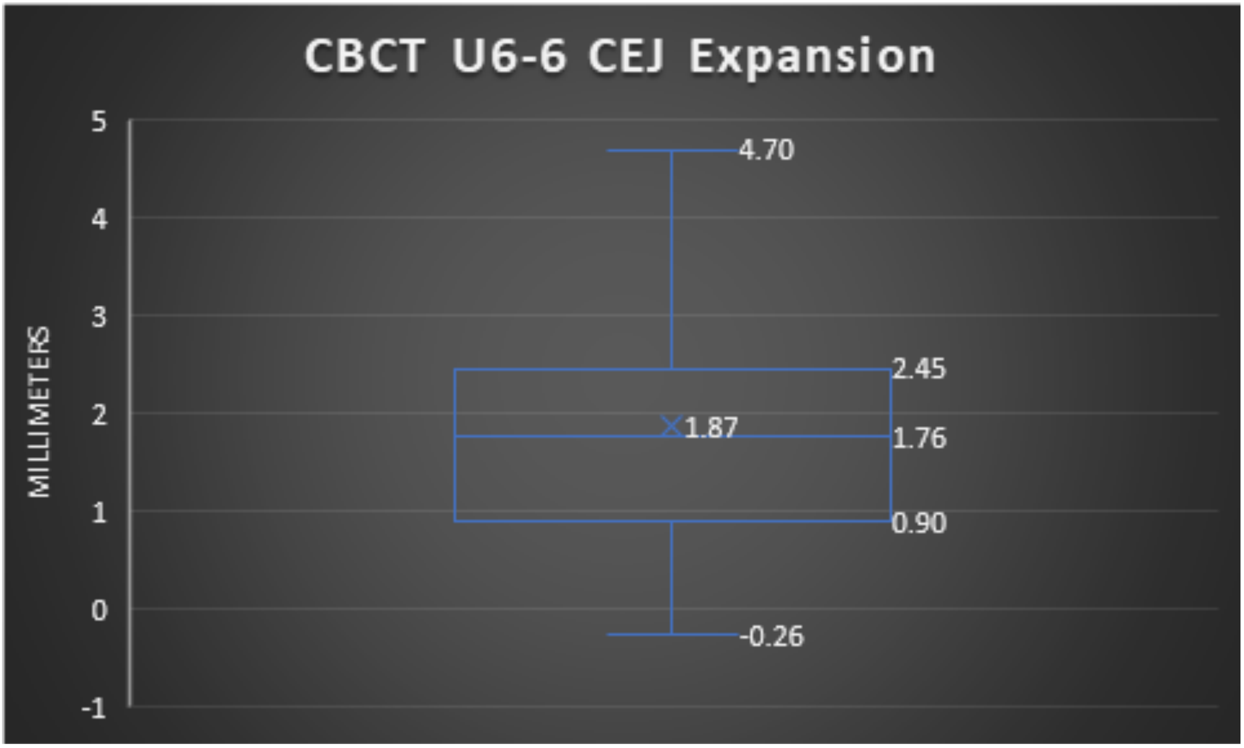

Figure 16 (Maxillary Molar Cementoenamel Junction Expansion shown by CBCT)

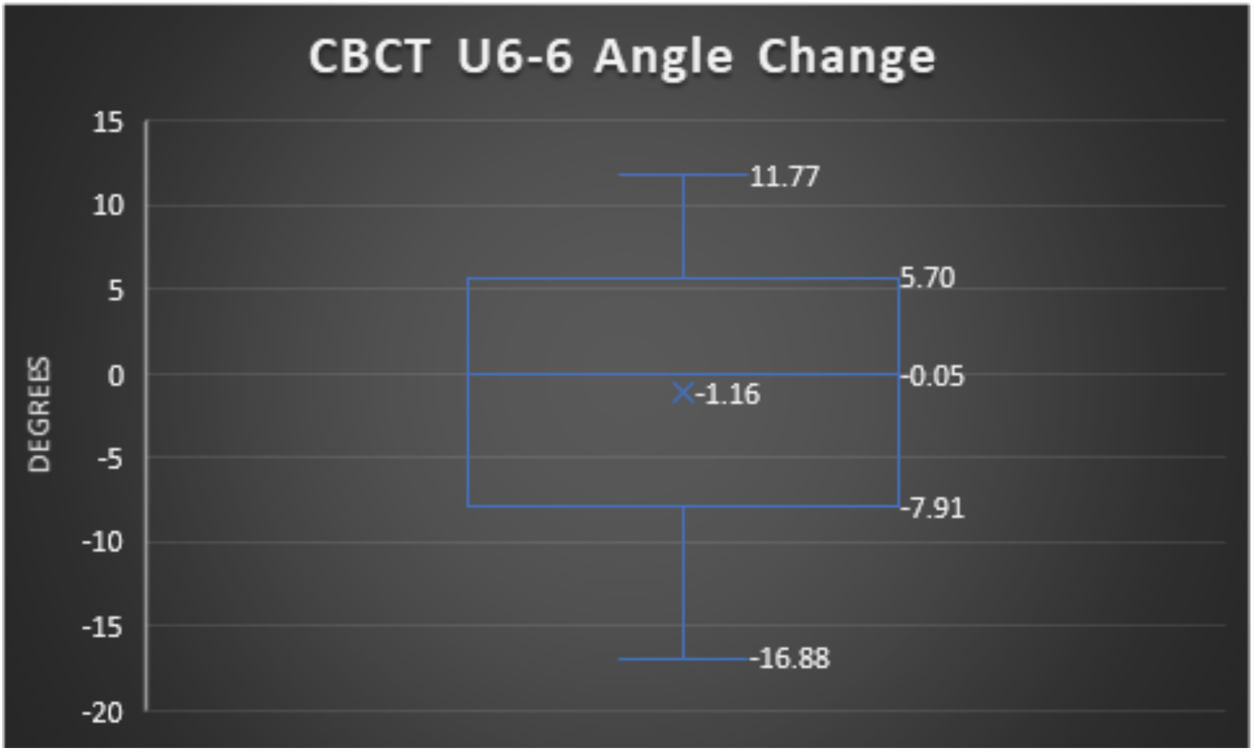

Figure 17 (Maxillary Molar Angle Change shown by CBCT)

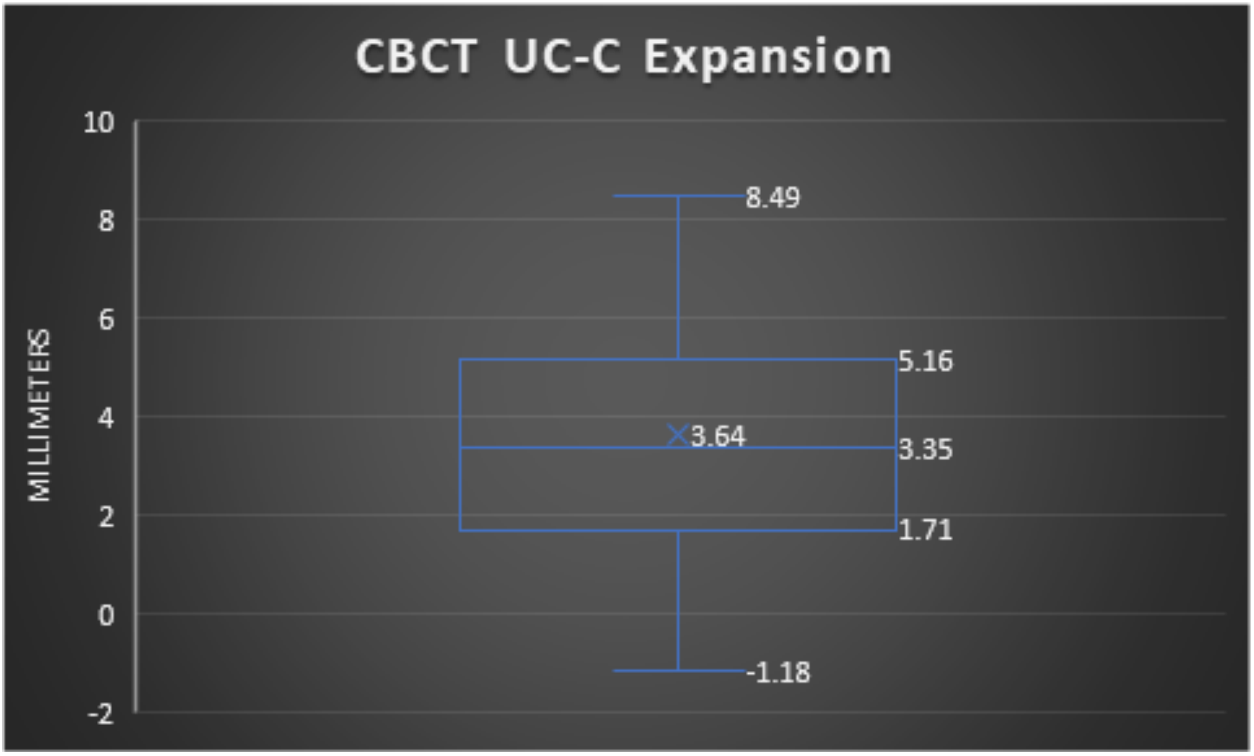

Figure 18 (Maxillary Primary Canine Expansion shown by CBCT)

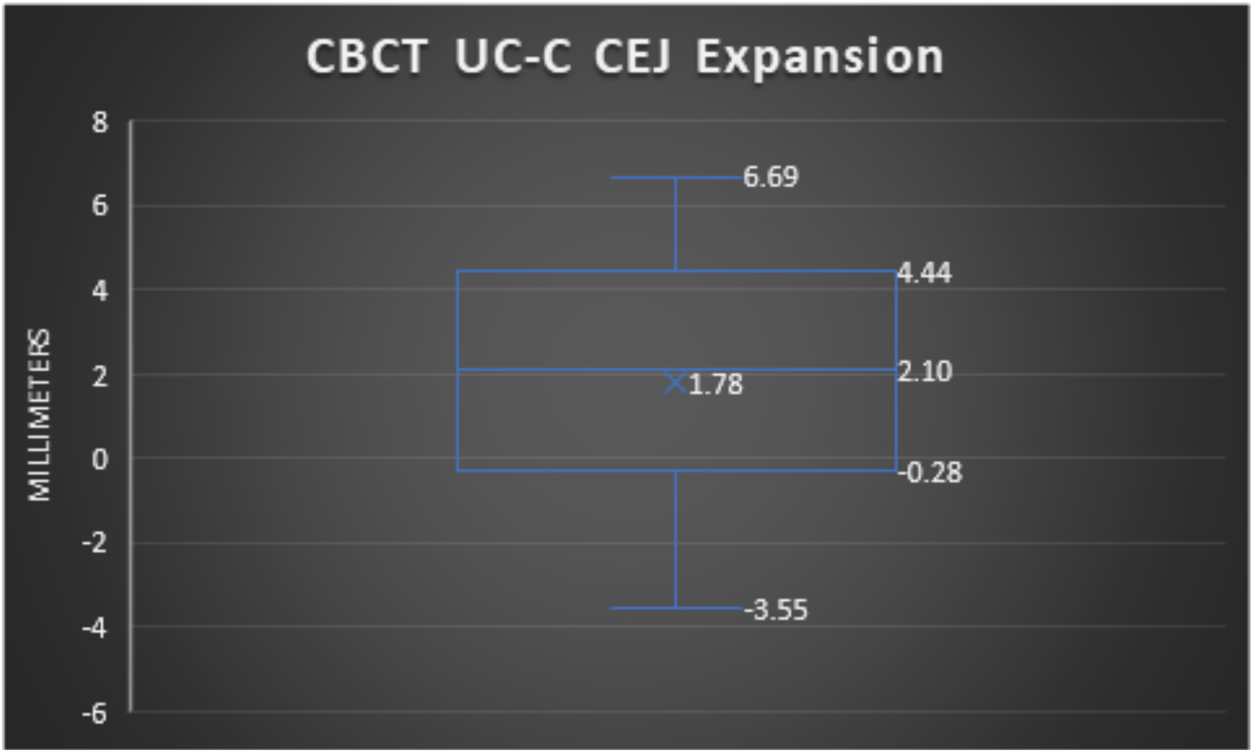

Figure 19 (Maxillary Primary Canine Cementoenamel Junction Expansion shown by CBCT)

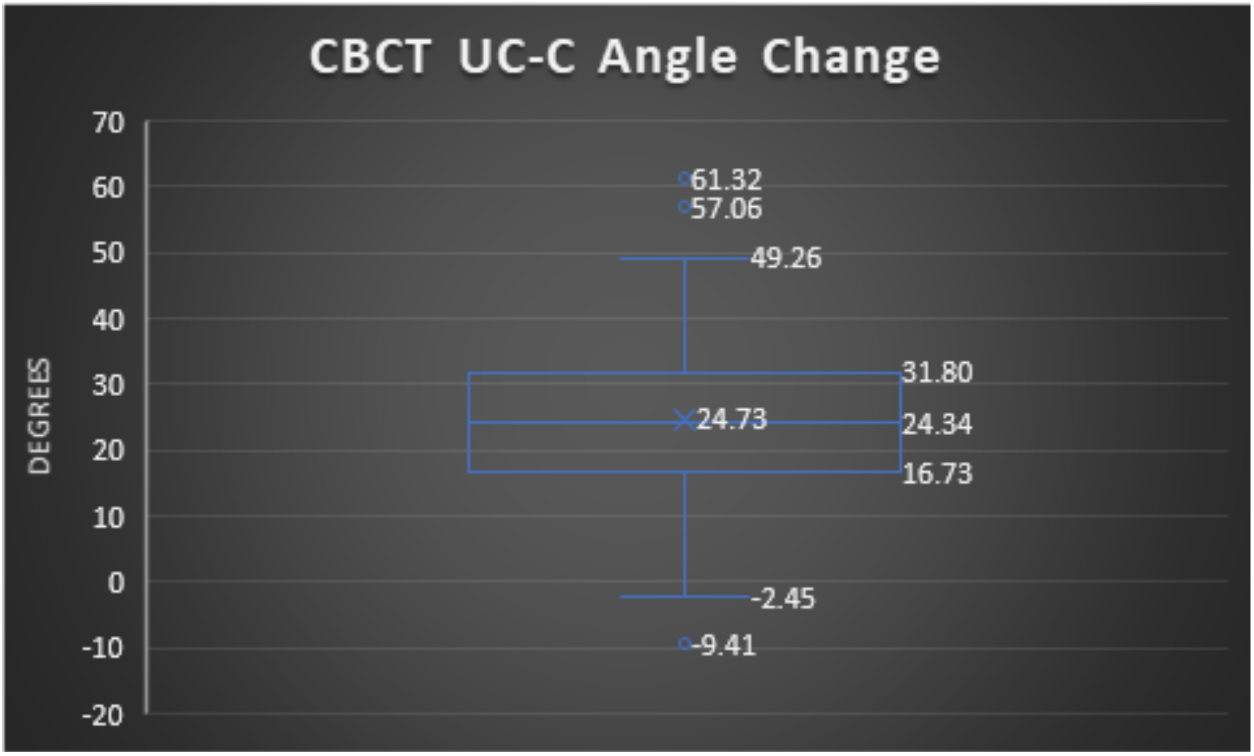

Figure 20 (Maxillary Primary Canine Angle Change shown by CBCT)

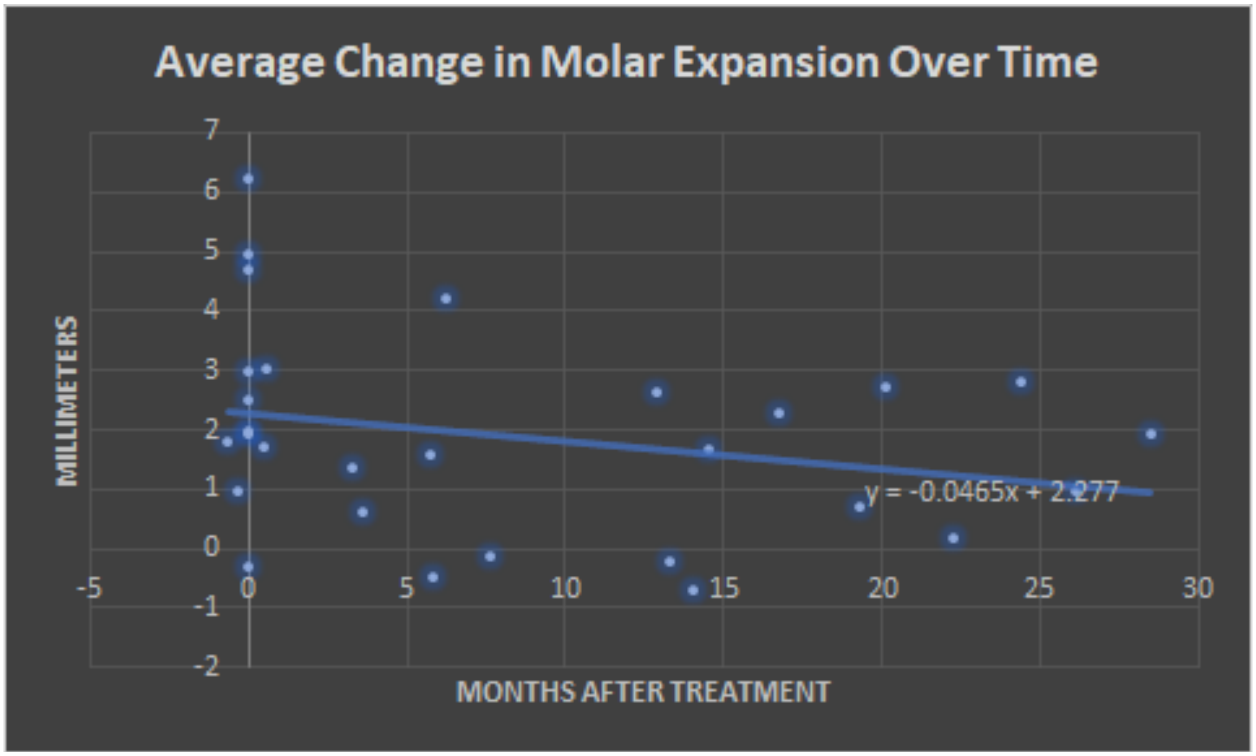

Figure 21 (Maxillary Molar Expansion Change Over Time)

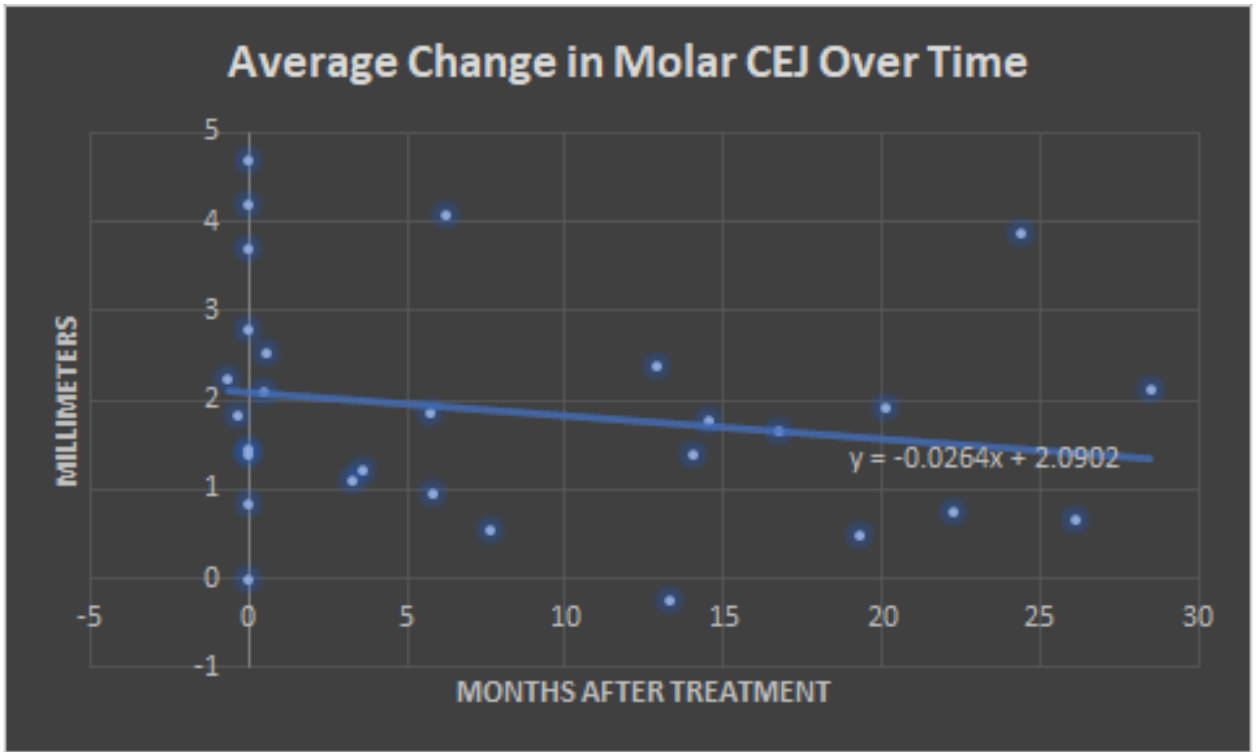

Figure 22 (Change in Maxillary Molar Cementoenamel Junction Over Time)

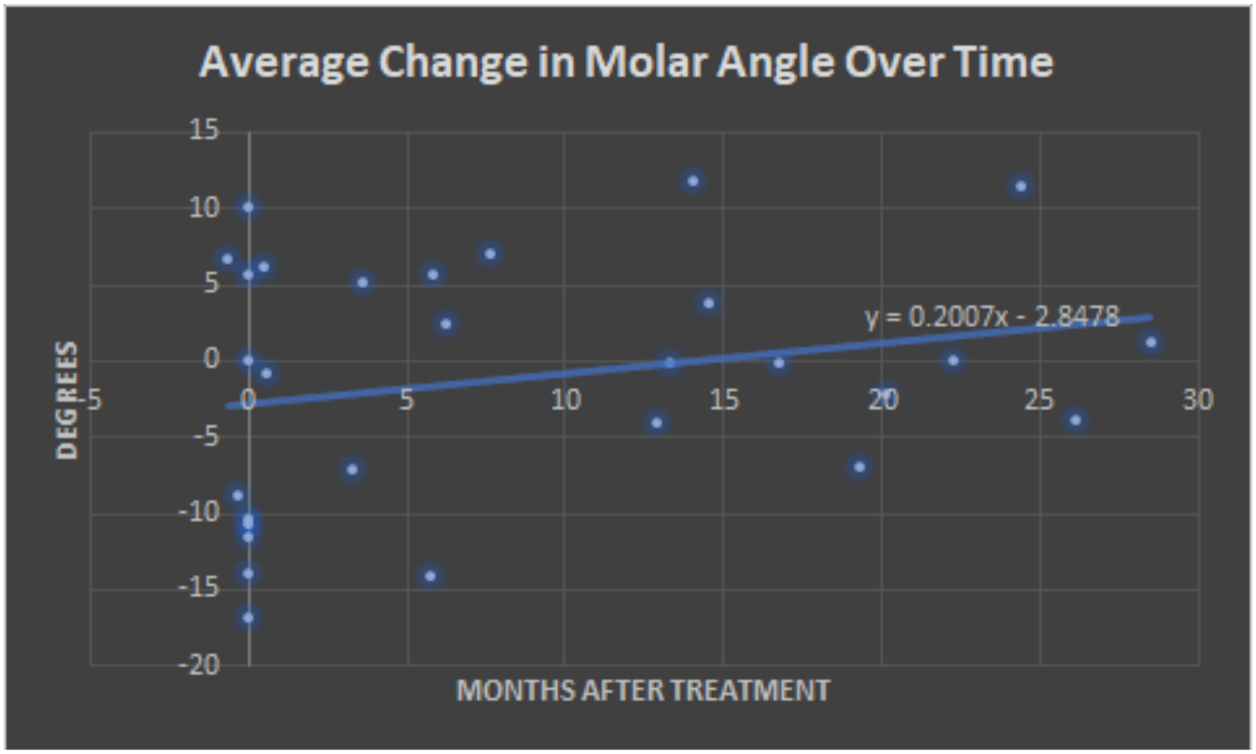

Figure 23 (Change in Molar Angle Over Time)

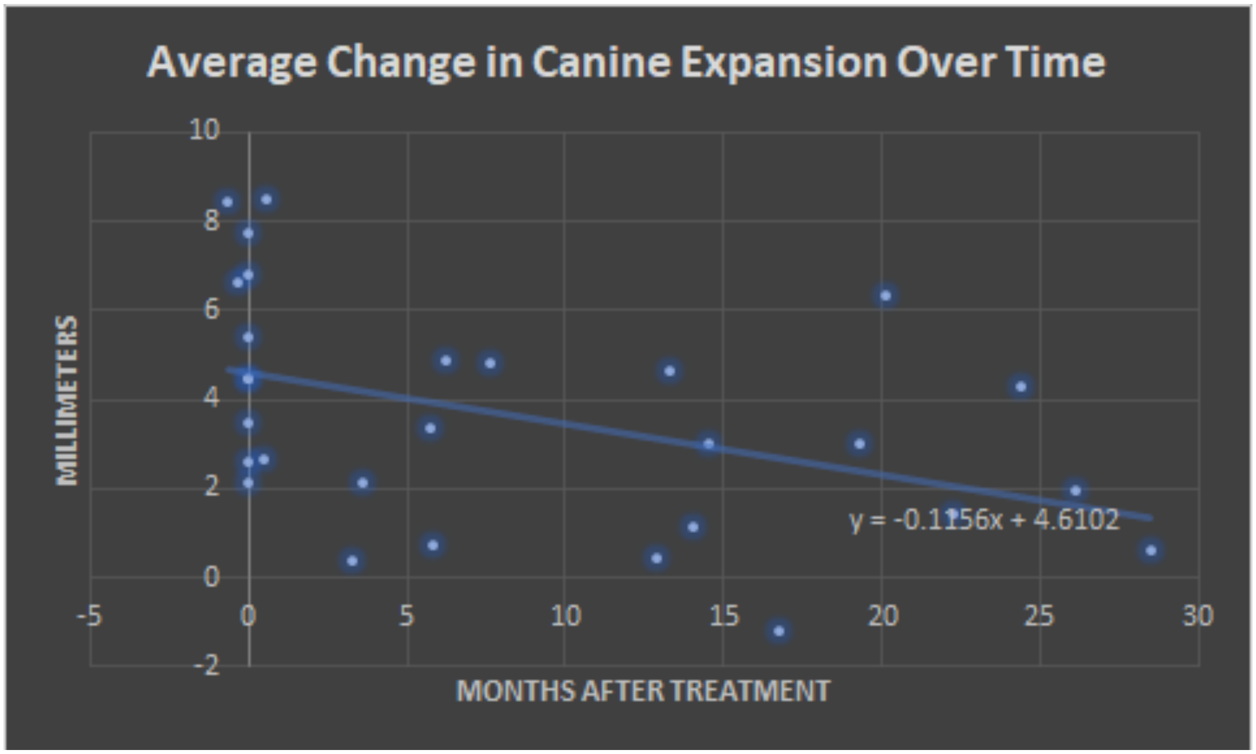

Figure 24 (Maxillary Primary Canine Expansion Change Over Time)

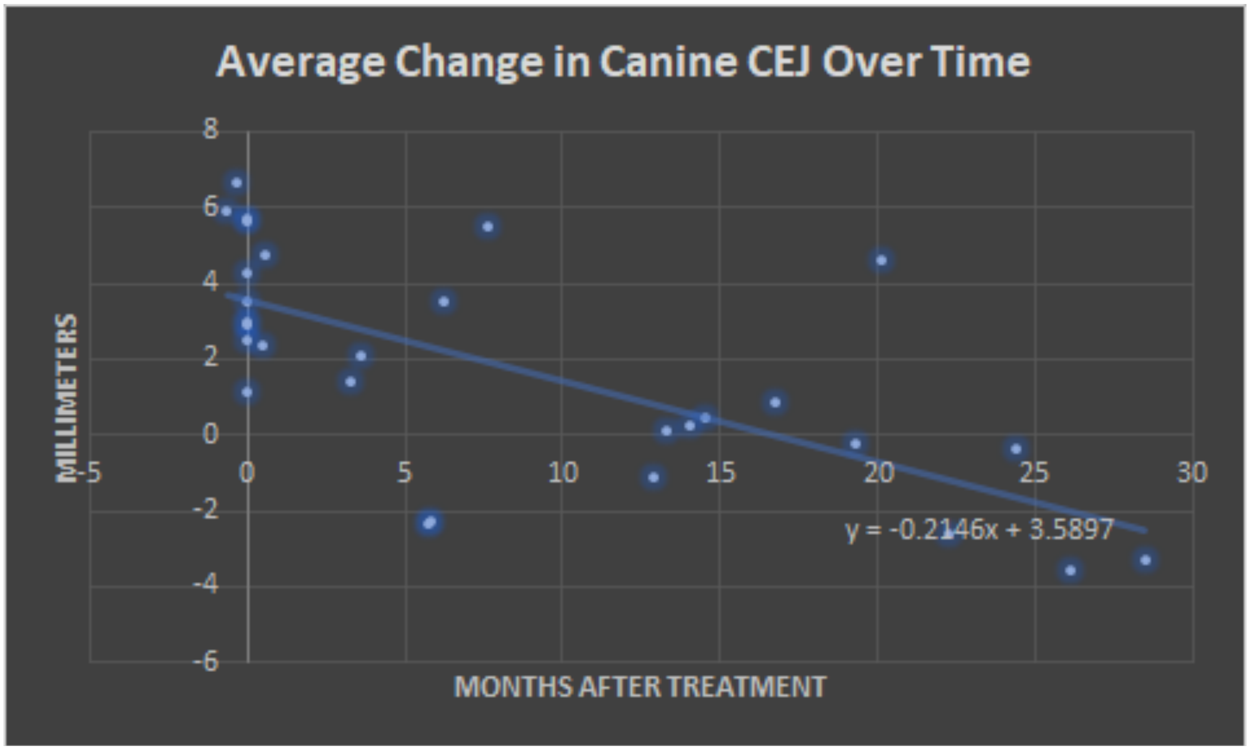

Figure 25 (Change in Maxillary Primary Canine Cementoenamel Junction Over Time)

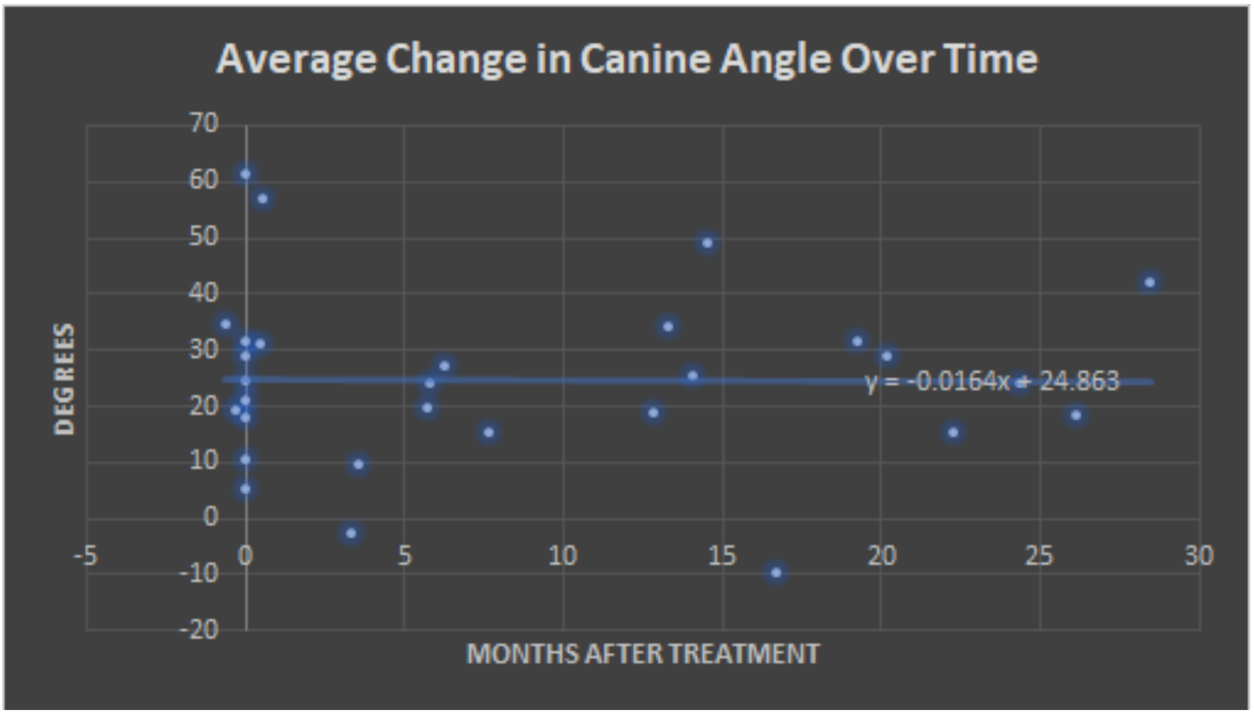

Figure 26 (Change in Canine Angle Over Time)

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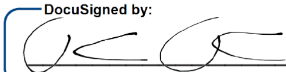

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5/25/2021

Date