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Changes in the Transverse Dimension of the Nasomaxillary Complex Following Rapid Palatal Expansion – a Post-Retention, CBCT Evaluation

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CHANGES IN THE TRANSVERSE DIMENSION OF THE NASOMAXILLARY COMPLEX FOLLOWING RAPID PALATAL EXPANSION – A POST-RETENTION, CBCT EVALUATION

By

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Purpose: The purpose of this investigation was to evaluate the immediate and long-term effects of palatal expansion on the transverse dimension of the nasomaxillary complex.

Materials and Methods: Twenty-eight patients' CBCTs were obtained at four time points: pre-expansion (T_1), post-expansion (T_2), pre-treatment (T_3), and middle or end of orthodontic treatment (T_4). The patients' age, sex, cervical vertebral maturation stage, and the number of instructed expander turns were recorded. Measurements of the nasal floor, nasal passage, maxillary sinus, maxillary first molar mesiolingual cusp, maxillary first molar palatal cusp, maxillary first molar buccal cortical bone, maxillary first molar palatal cortical bone, interorbital, and extraorbital widths were recorded.

Results: During expansion, all parameters except interorbital and extraorbital widths increased significantly. Post-expansion, most parameters continued to increase, with only the cusp tip width decreasing significantly. There were no significant differences between males and females except nasal floor, nasal passage, and interorbital widths during expansion (T_1 to T_2). Pre-expansion growth status did not influence changes except the extraorbital width during orthodontic treatment (T_3 to T_4).

Conclusions: Palatal expansion significantly changed the transverse width of nasomaxillary complex. Long-term retention showed all parameters except maxillary

molar cusp and maxillary molar buccal cortical bone widths continued to increase to the T4 time point, likely due to the patients' growth overcoming any relapse occurring.

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LIST OF ABBREVIATIONS

CBCT	Cone-beam computed tomography
CVM	Cervical vertebral maturation
CVMS	Cervical vertebral maturation stage
ICC	Intraclass correlation coefficient
M1BW	Maxillary first molar buccal cortical bone width
M1CW	Maxillary first molar mesiolingual cusp tip width
M1PW	Maxillary first molar palatal cortical bone width
M1RW	Maxillary first molar palatal root tip width
MSW	Maxillary sinus width
NFW	Nasal floor width
NPW	Nasal passage width
RPE	Rapid palatal expander

CHAPTER 1: INTRODUCTION

When a discrepancy is recognized in a patient's transverse dimension of the nasomaxillary complex, the establishment of the cause and the limits of treatment options need to be recognized and explored (Lux et al., 2004). The transverse discrepancy of the nasomaxillary complex often manifests as a posterior or anterior crossbite in the dentition. A crossbite is "an abnormal buccal, labial, or lingual relationship of a tooth or teeth of the maxilla, the mandible, or both when the teeth of the two arches are in occlusion" (Woods, 1950, Kutin & Hawes, 1969). In Caucasian American children, the incidence of posterior crossbites is about 7% (Infante, 1975, Kutin & Hawes, 1969). In African-American children, the incidence of posterior crossbites is about 2% (Infante, 1975).

The cause of a crossbite could be of skeletal origin, dental origin, or both. A discrepancy of a transverse skeletal relationship may present as a narrow maxilla and palatal vault with posterior maxillary dentition that has excessive lingual root torque, meaning the roots of the posterior dentition are positioned lingually and the crowns are positioned buccally. A discrepancy of dental origin may present as a normal maxilla and palatal vault with posterior maxillary dentition that has excessive buccal root torque, meaning the roots of the posterior dentition are positioned buccally and the crowns are positioned lingually. A combination discrepancy may present as a narrow maxilla with posterior maxillary teeth with excessive buccal root torque. Maxillary constriction, unilateral posterior crossbite, or bilateral posterior crossbite can all be used to describe specific transverse discrepancies.

These transverse discrepancies are best identified intraorally during a clinical examination and with a radiograph that allows for analysis of the widths of the dental arches, like a posteroanterior cephalometric radiograph or a cone-beam computed tomography (CBCT). CBCTs are becoming more popular in dentistry because they provide a three-dimensional image, rather than a two-dimensional image, so that a clinician can have a stronger grasp of the problem in all three planes. The ability to image airways and sinuses is another reason clinicians have begun using three-dimensional imaging modalities. A problem in the transition between two-dimensional and three-dimensional modalities is that measurement points have been standardized to the intersections of anatomical lines on two-dimensional images (Lux et al., 2004). These intersecting anatomical lines on a two-dimensional image do not always intersect in the three-dimensional craniofacial complex, so the landmarks previously used to evaluate the craniofacial complex and dentition do not always translate easily to analyzing the three-dimensional image. Standardized landmarks for measurements and analysis of CBCT images have yet to be established. In the present study, landmarks used in previously published literature were used (Garrett et al., 2008).

A transverse discrepancy can be treated by expansion of the maxillary skeletal and/or dental components depending on the cause of the discrepancy. The goal of the expansion is to create an adequate maxillary width, correcting the posterior crossbite if one exists (Haas, 1965, Haas, 1970, Haas, 1980, Lagravere et al., 2005). The skeletal expansion allows for the coordination of the maxillary skeletal width with that of the mandible. This expansion can be achieved through slow expansion utilizing a w-arch or quad-helix, rapid expansion utilizing a rapid palatal expander, or with surgical expansion depending on the patency of the midpalatal suture and the patients maturity (Haas, 1965).

This retrospective study focuses on rapid palatal expanders (RPEs) used to expand the transverse width of the maxilla and its effects on the nasomaxillary complex. RPEs separate the midpalatal suture with heavy forces, producing orthopedic (skeletal) expansion and orthodontic (dental) tooth movement (Haas, 1961, Haas, 1980, Wertz, 1970, Isaacson et al., 1964, Krebs, 1958). Because the goal is to correct the maxillary skeletal discrepancy, the orthopedic movement is ideally maximized and the dental movement is minimized (Ciambotti et al., 2001). The expander is connected to the maxillary dentition and transmits the forces to the maxillary bones. This force will also act on the maxillary dentition and produce tooth movement. Orthopedic separation is caused by high enough forces that overcome the strength of the suture (Isaacson et al., 1964, Bell, 1982, Storey, 1973). The expansion produces orthopedic changes in the midpalatal suture and new bone forms in the gap created by expansion over time to make permanent changes in the width.

The separation at the midpalatal suture does not only impact the maxillary dentition and oral cavity, but also impacts the nasomaxillary complex, specifically the maxillary bones which form the floor and a portion of the walls of the nasal cavity and contain the maxillary sinuses. Due to this, palatal expansion treatment effects may also include changes in the nasal passage and the maxillary sinuses (Baratieri et al., 2011). The maxillary bones may react to the stresses placed upon them by changing shape or structure or by altering their relationship with adjacent bones (Starnbach et al., 1966).

The stability of changes produced by the rapid palatal expansion is a concern for clinicians regarding long-term stability of their orthodontic treatment and the positive effects it could create it nasal passages. The rapid palatal expansion studies have shown that increases in the maxillary transverse dimension of the nasomaxillary complex are relatively stable (Haas, 1980, Baccetti et al., 2001, Krebs, 1958). However, concerns with the studies that show the stability include that these studies have been short-term (less than 1 year), used posteroanterior cephalometric radiographs for analysis, only evaluated the dentition, and/or evaluated a small number of patients. The research on the stability of the dentition has shown varying rates of relapse from 0% to 55% of the achieved expansion (Vargo et al., 2007, McNamara et al., 2003, Linder-Aronson & Lindgren, 1979).

The present study examined the stability of the changes in the transverse dimension of the nasomaxillary complex following rapid palatal expansion utilizing the benefits of three-dimensional imaging, a larger patient pool, and a longer follow-up time. In addition, the present study investigated the changes in nasal passage and maxillary sinus widths before, during and after expansion of the maxilla and the long-term retention phase including orthodontic treatment.

CHAPTER 2: LITERATURE REVIEW

2.1 Anatomy and Function of the Nasomaxillary Complex

The bony nasomaxillary complex is formed by the ethmoid bone, maxilla, vomer, nasal bone, frontal bone, sphenoid bone, lacrimal bone, palatine bone and inferior nasal concha (Schuenke et al., 2010). The maxillary bones form about 50% of the anatomic structure of the nasal cavity (Oliveira De Felippe et al., 2008).

The nasomaxillary complex terminates superiorly at the frontonasal suture. The maxilla is constrained anteriorly and laterally by the muscles of facial expression and the soft tissue of the face. The zygomatic bones also articulate with the maxillary bones on the lateral aspect at the zygomaticomaxillary suture. Many of the muscles of facial expression originate from the bony nasomaxillary complex. The superior portion of the nasomaxillary complex, including the lacrimal and ethmoid bones, is constrained laterally by the orbit. The nasomaxillary complex terminates inferiorly with the crowns of the maxillary dentition. The maxillary dentition is housed in the alveolar process of the maxilla. The nasomaxillary complex terminates posteriorly at the sphenoid bone, the posterior portion of the palatine bones, and the nasopharynx. Internally, the nasomaxillary complex contains the maxillary sinuses, the inferior nasal concha and the vomer. (Figures 2.1-2.5)

Sutures allow bones to interdigitate, act as joints that permit relative movement, and serve as growth sites. Changes that affect the maxilla take effect through the sutural articulations, called the circummaxillary sutures. The circummaxillary sutures include the intermaxillary, internasal, maxillonasal, frontomaxillary, frontonasal, frontozygomatic, zygomaticomaxillary, zygomaticotemporal, and pterygomaxillary sutures (Figure 2.6) (Ghoneima et al., 2011).

The primary biological function of the nasomaxillary complex is to provide a passage for air from the nasal passage to the rest of the pharynx, ending in the lungs (Handelman & Osborne, 1976). The nasal cavity is designed to prepare the air by humidification, temperature control, and removal of particles (Oliveira De Felippe et al., 2008).

2.2 Growth of the Cranium and Nasomaxillary Complex

The nasomaxillary complex grows passively due to active growth of the cranial base. In addition to the passive growth from the cranium, the nasomaxillary complex grows actively at growth sites. The growth sites are the circummaxillary sutures, and the growth is in addition to growth by surface modeling. After bone is formed, it can also remodel, which results in a net zero sum due to the resorption and apposition occurring at the same location. The growth of the nasomaxillary complex needs to be well coordinated to achieve normal anatomy. A discrepancy of growth in any dimension results in an imbalance which may lead to a clinically noticeable discrepancy.

2.2.1 Cranial Growth

As measured by Scammon, neural growth exhibited a minimal change in growth beyond six years of age, with 94% to 95% of the growth completed by age six (Scammon, 1923). When analyzing the cranial width on posteroanterior cephalograms, 94% to 95% of the width had been achieved at age six in comparison to the width at age eighteen, following the neural growth pattern (Snodell et al., 1993). Growth in the cranial width from ages ten to fourteen was minimal (Yavuz et al., 2004). The bihamular width plateaus at the end of the second year of life, which implies that the cranial width near the nasomaxillary complex is established early in life (Subtelny, 1955).

2.2.2 Midpalatal Suture

After analyzing autopsy material histologically, Melsen found that the midpalatal suture has four developmental stages: infantile (up to ten years of age), juvenile (ten to thirteen years of age), adolescent (thirteen to fourteen years of age), and adult (over fourteen years of age) (Melsen, 1975, Melsen & Melsen, 1982). Adult midpalatal sutures have synostoses and bony bridge formations across the suture (Melsen & Melsen, 1982).

The fusion process in the midpalatal suture begins with bone spicules along the suture margins with islands of inconsistently calcified tissue and acellular tissue in the middle (Angelieri et al., 2013). The bone spicules form in many locations (Persson & Thilander, 1977). The number of spicules also increased as people matured (Wehrbein & Yildizhan, 2001). This leads to many scalloped areas separated by connective tissue (Wehrbein & Yildizhan, 2001). During this time, interdigitation increased (Melsen, 1975). Fusion occurred earlier in the posterior area and progressed anteriorly with resorption of the cortical bone and formation of cancellous bone (Persson & Thilander, 1977). This process varied with age and sex (Persson & Thilander, 1977).

Although Persson and Thilander observed fusion in fifteen to nineteen year olds, Korbmacher observed a seventy-one year old patient with no sign of fusion of the midpalatal suture (Korbmacher et al., 2007). Therefore, there was variability in the age of fusion, but it has usually begun by the third decade of life (Persson & Thilander, 1977)

2.2.3 Nasal Passage - Transverse Dimension

Nasal passage width had the greatest remaining growth of the width measurements analyzed on posteroanterior cephalograms, with 80% growth attained at seven years old for males and 86% growth attained at seven years old for females (Lux et al., 2004). Similarly, after analyzing 25 male and 25 female patients, Snodell et al. discovered that at six years of age the nasal passage width was 75% of the adult width for males and 80% of the adult width for females (Snodell et al., 1993). For females, the nasal width growth was completed between fifteen years and eighteen years of age (Snodell et al., 1993). For males, nasal width growth continued after eighteen years of age (Snodell et al., 1993). Melsen found that, after fifteen years of age in females and seventeen years of age in males, the midpalatal sutures contained a narrow sheet of connective tissue with inactive osteoblasts, implying no additional bone could be formed (Melsen, 1975). Melsen and Snodell's data agreed for females and disagreed for males.

Following an analysis of frontal head films (posteroanterior cephalograms), the mean width of the nasal cavity at three years old was 22.0mm with an increase of 0.5mm each year until 30.0mm at nineteen years old (Ricketts, 1982). In a cross-sectional study of 588 Australian children, the average nasal width was 25.91mm at seven years of age and 30.19mm at fourteen years of age (Athanasiou et al., 1992). In a different study on subjects who were exposed at ten, eleven, twelve, and fourteen years of age, statistically significant growth changes were found between each age period for both nasal width and maxillary width (Yavuz et al., 2004). The study by Yavuz et al. observed that the growth changes from ten to twelve years of age were greater than the changes from twelve to fourteen years of age in females, and, in males, the growth changes from twelve to fourteen years of age were greater than the growth changes from ten to twelve years of age. In the present study, both the male and female results contradicted Ricketts' analysis from 1981. Sex significantly affected the cranial, facial, nasal, and maxillary widths, specifically the transverse widths which were significantly greater in males than females (Yavuz et al., 2004).

When analyzing the patients of the longitudinal Belfast Growth Study, Lux found that the differences were minimal for seven-year-old males and females in the transverse dimension of all measurements, including the nasal widths and maxillary skeletal base widths (Lux et al., 2004). However, at fifteen years of age, the measurements were all larger in males than females. This analysis of the Belfast Growth Study showed significantly different nasal widths between the sexes at ages eleven, thirteen, and fifteen. It also showed that the maxillary skeletal base width was significantly different at ages seven, nine, eleven, thirteen, and fifteen. Males also had significantly more growth of the nasal width than females from eleven to thirteen years old, from thirteen to fifteen years old, and when looking at the entire study. For the nasal width, males had 6.89mm of growth from seven to fifteen years of age where females had 4.21mm of growth (Lux et al., 2004).

In regards to the transverse growth of the maxilla, Athanasiou et al. measured the width of the maxilla annually on posteroanterior cephalograms for untreated Austrian school children (Athanasiou et al., 1992). Athanasiou et al. found that at six years of age, the width was 60.99mm. The width increased to 67.37mm at fifteen years of age, with the largest annual increase of 1.45mm occurring from thirteen to fourteen years of age (Athanasiou et al., 1992). Cortella et al. analyzed 36 patients from the Bolton-Brush records and found that the maxillary width was 53.0mm at six years of age and 59.1mm at fifteen years of age, when the radiographic enlargement was corrected (Cortella et al., 1997). In the present study, there were two points which had the largest annual increase, both ages five to six and eight to nine had increases of 1.5mm (Cortella et al., 1997). This does not match the result found by Athanasiou et al. When analyzing the Belfast Growth study, Lux et al. measured the greatest change in width over two year increments and found that it occurred from seven to nine years of age for both males and females (Lux et al., 2004). The largest changes in growth of the maxilla were 2.41mm and 1.74mm, respectively (Lux et al., 2004). This agreed with the one-year interval of eight to nine by Cortella but disagreed with Athanasiou. Yavuz examined patients at ten, eleven, twelve, and fourteen years of age. Females had maxillary widths of 58.0mm, 58.9mm, 60.2mm and 61.8mm, and males had maxillary widths of 60.1mm, 61.6mm, 62.3mm, and 64.7mm, respectively (Yavuz et al., 2004).

2.2.4 Nasal Passage – Anteroposterior and Vertical Dimensions

The total depth of the nasopharynx was established in the first or second year of life (Brodie, 1940, King, 1952). However, the nasopharyngeal height increased by 38 percent from six years to maturity (Bergland, 1963). A study on patients who had serial posteroanterior cephalograms taken showed that the vertical heights of the patients' nasomaxillary complex progressively increased from ten to fourteen years old for both sexes, completing growth around seventeen to eighteen years of age (Subtelny, 1954, Yavuz et al., 2004).

2.2.5 Maxillary Sinuses

Contained within the maxilla, the maxillary sinuses are present at birth (Scuderi et al., 1993). The maxillary sinuses reached their maximum width at sixteen in females and fifteen in males as measured as “the longest distance perpendicular from the most prominent point of the medial wall to the most prominent point of the lateral wall as presented on the axial image” (Lorkiewicz-Muszynska et al., 2015). Although the maxillary sinus width tended to be larger in males than in females, this difference was not statistically significant at any individual year of life (Lorkiewicz-Muszynska et al., 2015).

2.3 Prevalence and Correction of Posterior Crossbites

Insufficient growth, or restricted growth, of the maxilla in the transverse dimension can cause a width discrepancy between the maxilla and mandible. Several studies found that one in every thirteen children has a unilateral or bilateral posterior crossbite (Infante, 1975, Kutin & Hawes, 1969). Posterior crossbites in the primary dentition did not self-correct when the permanent first molar erupted in most children (da Silva Filho et al., 1991, Kutin & Hawes, 1969). In a study on preschoolers and second graders, only two of twenty-six children observed had a correction of their posterior crossbite through the eruption of the permanent dentition alone, without expansion intervention (Kutin & Hawes, 1969). Because the transverse discrepancy does not usually self-correct for a majority of patients, Kutin recommended beginning expansion treatment as early as possible (Kutin & Hawes, 1969). Filho and Garrett et al. found that rapid palatal expanders corrected the maxillary width discrepancy (Filho, 1995, Garrett et al., 2008).

2.4 Mechanism of Expansion

Rapid expansion creates heavy forces which overwhelm the midpalatal suture before physiologic sutural adjustment can occur (Haas, 1970, Wertz, 1970, Ciambotti et al., 2001). Persson and Thilander hypothesized that midpalatal sutures with less than 5% fusion could be expanded with a rapid palatal expander. Rapid palatal expansion delivered 15 to 50N of force (Lagravere et al., 2005). The maximum force of a single activation of an expander occurred immediately after activation (Zimring & Isaacson, 1965). Over the twelve-hour period immediately following expander activation, the load dissipated (Zimring & Isaacson, 1965). If the activation was frequent enough that the load did not completely dissipate, a progressive build-up of load caused a residual load (Zimring & Isaacson, 1965). However, the increment of force produced by a single activation of the expander remained consistent throughout treatment (Figures 2.6a) (Zimring & Isaacson, 1965). Six weeks after the last activation, the residual load had completely dissipated (Figure 2.6b) (Zimring & Isaacson, 1965).

Within a week of application of force from the rapid palatal expander, lateral tipping of the posterior maxillary teeth occurred with compressed periodontal soft tissues (Starnbach & Cleall, 1964, Bell, 1982, Storey, 1973). After the first week, tooth movement was bodily in nature (Storey, 1973).

2.4.1. Histological Analysis of Expansion

Immediately after expansion, a blood clot formed in the area of the suture separation. Fibroblasts produced collagen fibers and chondroblasts began to produce fibrocartilage, creating a callus. This callus bridged the space between the two maxillary bones. Osteoblasts and osteoclasts then moved in, replacing the cartilage with bone.

Histologically, the tissue in the suture appeared as free-floating bone fragments, microfractures, cyst-like formations, disorganized vascular connective tissue, and dystrophic ossification with immature bone tissue (Melsen, 1975, Starnbach & Cleall, 1964, Storey, 1973, Bell, 1982). Also noted histologically, expansion caused remodeling of the frontonasal, zygomaticomaxillary, and zygomaticotemporal sutures (Starnbach et al., 1966).

In a study of sacrificed Macaca rhesus monkeys, the periodontal ligament was stretched on the palatal aspect after two weeks of orthodontic expansion (Starnbach et al., 1966). The stretched periodontal ligament was disorganized and contained cell-free zones on the buccal aspect (Starnbach et al., 1966). The alveolar bone showed areas of resorption along the length of the roots (Starnbach et al., 1966). After three months of expansion, the buccal plate had almost completely remodeled, and there was new bone deposition on the palatal side of the tooth (Starnbach et al., 1966). After three months of expansion, the bone and periodontal ligament both showed improvement in organization and cell population (Starnbach et al., 1966).

2.5 Changes to the Nasomaxillary Complex during Expansion

The maxillary bones form the outer walls of the nasal cavity (Haas, 1965). Haas noted that as the maxillary bones moved laterally, the concha moved away from the nasal septum (Haas, 1965). The maxillary bones separated approximately around the frontonasal suture in a triangular fashion with the base located at the level of the maxillary dentition (Haas, 1961, Wertz, 1970, Garrett et al., 2008, Storey, 1973). In a CBCT study of 25 rapid expansion patients, the frontonasal, intermaxillary, zygomaticomaxillary, and midpalatal sutures separated significantly during expansion

(Woller et al., 2014). The study by Woller et al. did not find a significant separation of the palatomaxillary suture (Woller et al., 2014).

2.5.1 Transverse Dimension

Separation of the maxillary bones during rapid palatal expansion caused an increase in width of the nasal cavity (Haas, 1961, Babacan et al., 2006, Oliveira De Felippe et al., 2008, Garrett et al., 2008, Chung & Font, 2004). The first study that analyzed this nasal width increase was a case study that noted “the increase in width of the dental arch during active treatment was about twice that of the basal maxillary segments, while the increase of the alveolar arch lingually to the canines was almost midway between these two” (Krebs, 1958). As noted in the case study and in another study, the separation of the maxillary bones was less than or equal to 50% of the total expansion accomplished (Garrett et al., 2008, Krebs, 1958). The case study also pointed out that the increase in the nasal cavity width was less than the increase between the maxillary segments (Krebs, 1958). In a long-term study of ten subjects, an average increase of 9mm in apical base width and an average increase of 4.5mm in nasal width were observed six to fourteen years after treatment completion (Haas, 1980).

Prior to rapid palatal expansion, patients who need expansion differed significantly from a control group in almost all transverse parameters (Kartalian et al., 2010). Although expansion changed these widths, the measurements of the treated patients were still smaller after expansion than the control patients, though not significantly (Kartalian et al., 2010). Similar to Kartalian, Cross also found that the post-treatment widths were still slightly lower than the untreated controls, though the difference was not significant (Cross, 2000). In another study that compared 42 patients who received expansion with Haas-type rapid maxillary expander to twenty non-treated controls from the University of Michigan Elementary and Secondary School Growth Study, the treated group exceeded the expected growth of the non-treated controls by 2.3mm (Cameron et al., 2002). This excess change almost made up for the initial deficiency of 2.7mm seen in the treated group. In the study by Cameron et al., the initial deficiency in nasal passage width of the treated group (0.6mm deficiency) was overcorrected 2.0mm after treatment in comparison to the untreated group. This excess in nasal passage width of 2.0mm was the only significant difference at the end of treatment between the 42 treated patients and the 20 untreated controls (Cameron et al., 2002). Various studies observed that the nasal width increased by 1.06mm to 2.08mm with rapid palatal expansion treatment (Wertz, 1970, Cross, 2000, Filho, 1995, Krebs, 1958).

A nasal width increase of one-third of the expander's opening was found on computed tomography images (Garib et al., 2007). Similarly, on CBCT images, the nasal width increased by 37.2% and 33.23% in two different studies (Garrett et al., 2008, Christie et al., 2010). A 2D cephalometric analysis reported a nasal width increase of 23.1% of the appliance expansion (Chung & Font, 2004). The increase in nasal width occurred with a decrease in maxillary sinus width in a study by Garrett et al. (Garrett et al., 2008). In a study of the volumetric change in maxillary sinuses, Darsey found that the right and left sinuses individually, as well as the sum of the two sinuses, changed negligibly during rapid maxillary expansion (Darsey et al., 2012). After analyzing the decrease in width observed by Garrett et al. with the negligible change in volume, Darsey theorized that the sinuses are possibly being reshaped (Darsey et al., 2012).

When comparing patients who were treated before the peak pubertal growth spurt and after the peak, the nasal passage width increased significantly more in the group treated before the peak pubertal growth spurt (Baccetti et al., 2001, Lagravere et al., 2005). Baratieri et al. indicated that this significant change in width in the pre-pubertal group may be due to the decreased amount of calcification of the midpalatal suture. Results have also shown that patients under the age of twelve have greater and more stable orthopedic changes (Wertz, 1977).

2.5.2 Anteroposterior and Vertical Dimensions

Rapid palatal expansion caused inferior displacement of the maxilla and the maxillary molars, which in turn rotated the mandible downward and backward (Krebs, 1958, Haas, 1961, Haas, 1965, Haas, 1970, Wertz, 1970, da Silva Filho et al., 1991). Due to the location of the expander and the articulations of the nasomaxillary complex with the cranial base, the nasomaxillary complex opened more at the level of the dentition than the palate and more at the palate than the superior portion of the nasal cavity in a triangular fashion (Haas, 1961, Haas, 1965, Haas, 1970, Wertz, 1970, Oliveira De Felippe et al., 2008, da Silva Filho et al., 1991, Krebs, 1958). However, after five years of follow-up in a study that evaluated expansion and orthodontic treatment, the sagittal and vertical dimensions of the jaws were unchanged from the pre-orthodontic dimensions (Garib et al., 2007). Another study found that the differences noted on lateral cephalometric x-rays were of normal growth alone, not due to treatment (Velazquez et al., 1996).

2.5.3 Relapse of the Nasomaxillary Complex

In a study that followed adult patients for four years after surgically-assisted rapid palatal expansion, the post-expansion changes in the nasal cavity and skeletal maxillary width were negligible and the skeletal changes were stable (Chamberland & Proffit, 2011). Similarly, the increase in nasal cavity width found by Cameron was maintained 5 years post-expansion (Cameron et al., 2002). The stability of the expansion may be attributed to the midpalatal repair and new bone formation (Gurel et al., 2010).

2.6 Changes to the Maxillary Dentition during Expansion

In a study by Garrett that evaluated the effects of expansion three months or less after the expansion was completed, the greatest amount of expansion occurred between the incisors and the least between the molars (Garrett et al., 2008). This triangular shape, with more expansion in the anterior and less in the posterior, matched other studies (Wertz, 1970, Sandikcioglu & Hazar, 1997, Krebs, 1958). In contrast, Christie found that the midpalatal suture opened in a parallel fashion (Christie et al., 2010).

The orthopedic expansion occurred by bodily movement, as well as by buccal rotation of the alveolar processes (Isaacson et al., 1964, Garrett et al., 2008, Krebs, 1958). In a study by Garrett et al., the orthopedic, alveolar bending, and orthodontic contributions (buccal tipping of the teeth) to expansion respectively were as follows: 55%, 6%, and 39% for the first premolars; 45%, 9%, and 46% for the second premolar; and 38%, 13%, and 49% for the first molar (Garrett et al., 2008). Moving posterior in the dentition, the orthopedic contribution decreased while the alveolar bending and orthodontic contributions increased (Garrett et al., 2008). These results agreed with other reports from Krebs and Ciambotti (Ciambotti et al., 2001, Krebs, 1958). A potential reason for the decreased orthopedic contribution in the molar region was the interlocking pyramidal processes of the palatine bone with the immovable pterygoid plates of the sphenoid bones (Garrett et al., 2008, Wertz, 1970).

The buccal crown tipping of the first molars that occurred from rapid palatal expansion was approximately six degrees (Christie et al., 2010). This result agreed with a study done by Ciambotti, but the amount of tipping was slightly less than a study done by Kilic that found seven degrees of buccal crown tipping (Ciambotti et al., 2001, Kilic et al., 2008). The expansion increased dehiscences on the buccal aspect of the anchorage teeth (Garib, 2006). It also reduced the buccal alveolar bone crest level (Garib, 2006).

There were no statistically significant differences in dental widths between males and females as measured on dental casts (Gurel et al., 2010).

2.6.1 Relapse of the Dentition

One year after expansion treatment, the maxillary first molar tip had decreased significantly, but the molar width was still significantly greater than the control (Baratieri et al., 2014). Orthodontic treatment caused a relapse of 34% of the intermolar width (Gurel et al., 2010).

Eleven months after the expansion completed, the models of 54 patients who received no retention showed the maintenance of 70% of the expansion width (Vargo et al., 2007). Another study found that the intermolar width correction maintained was two-thirds of the initial discrepancy (McNamara et al., 2003). After a five-year follow-up period, one study found that the intermolar width was close to the post-treatment width (Gurel et al., 2010). In contradiction to those studies, another study found that only 45% of the initial expansion remained (Linder-Aronson & Lindgren, 1979).

2.7 Validity of CBCT in Volumetric Measurements

Historically, analysis of the development of the nasomaxillary complex in the transverse dimension occurred on posteroanterior cephalometric radiographs (Yavuz et al., 2004). Before cone-beam computed tomography (CBCT) allowed practitioners to view the skull in three dimensions, orthodontists would make width measurements on a posteroanterior cephalogram. CBCT scans allowed practitioners to view multiplanar images and provided three-dimensional information with uniform magnification (Scarfe et al., 2006, Kobayashi et al., 2004). Landmarks that exist on two-dimensional cephalometric images do not always exist on three-dimensional images. This is because anatomic structures do not overlap on three-dimensional images like they do when they are captured on a two-dimensional image (de Oliveira et al., 2008). The images produced by CBCT machines are comprised of voxels, small cuboid structures that are equal in all dimensions (Scarfe et al., 2006). The size of the voxel determines the resolution of the image, ranging from 0.4mm to as low as 0.125mm (Scarfe et al., 2006).

CBCT images allow for accurate distance measurements (Kobayashi et al., 2004). Reproducible data is possible from CBCT images with proper calibration of the operator (de Oliveira et al., 2008). The reliability of CBCT measurements was high ($r>0.90$) (Baumgaertel et al., 2009).

In regards to the software utilized for the analysis of the CBCT images, InVivoDental5.0 (Anatomage Inc.) measurements are more reproducible and user-friendly than 3DCeph™ (University of Illinois at Chicago, Chicago, IL, USA) (Sawchuk et al., 2014). Because there is no superimposition of structures or distortion in CBCT images, the images allow for accurate visualization and measurements of the nasomaxillary complex (Baratieri et al., 2014).

2.7.1 CBCT and Radiation Exposure

Radiation dose may differ significantly based on the field of view, voxel size, exposure time, and other radiation exposure parameters. The effective dose of radiation for a medium or large field of view CBCT of a child (ranging from 13-769 microsieverts) was significantly higher than that of a single panoramic radiograph (2.9-11 microsieverts) and that of a single lateral cephalometric radiograph (1.1-5.6 microsieverts) (Scarfe et al., 2006, Ludlow et al., 2015, Li, 2013). However, depending on the parameters used, the effective dose can be approximately equal to a film-based full mouth series of periapical images (13-100 microsieverts) (Scarfe et al., 2006). The added benefit of a CBCT image is that the panoramic and cephalometric images can be rendered from the CBCT image (Scarfe et al., 2006).

For CBCTs from a Kodak 9500 (Carestream Dental), the effective dose for a large field of view (20cm x 18cm) was 136μSv (Li, 2013, Pauwels et al., 2012). This 136μSv was 12-45 times that of a single panoramic radiograph and 24-124 times that of a single lateral cephalometric radiograph. Because of the generally higher effective dose of CBCTs as compared to panoramic and lateral cephalometric radiographs, Li recommended choosing a CBCT scanning protocol that is most appropriate while reducing the patient dose as much as possible.

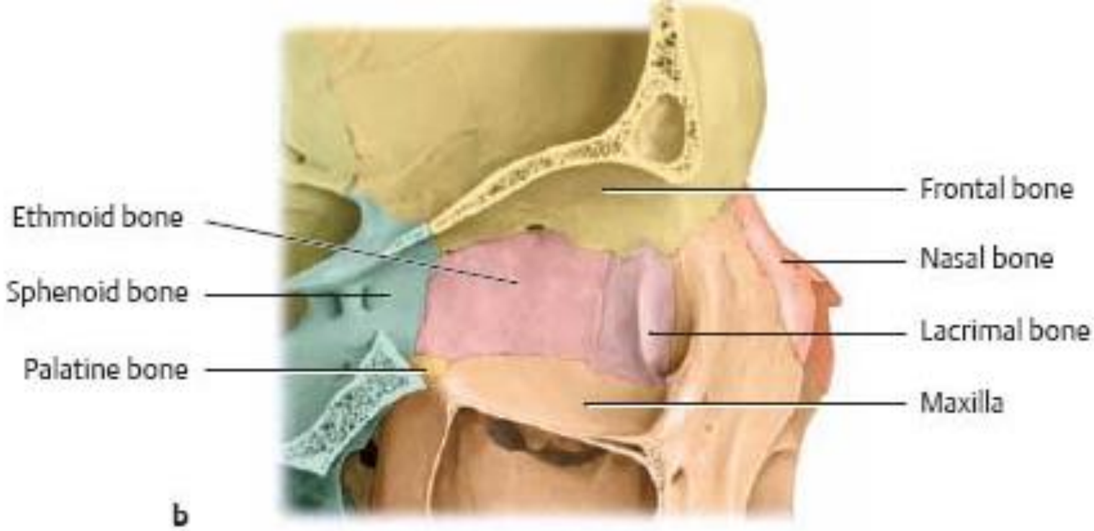

Figure 2.1: Sagittal View of the Superior Part of the Nasomaxillary Complex and Orbit

The above drawing displays the connections of the maxilla to the frontal, nasal, lacrimal, ethmoid, sphenoid, and palatine bones (Schuenke et al., 2010).

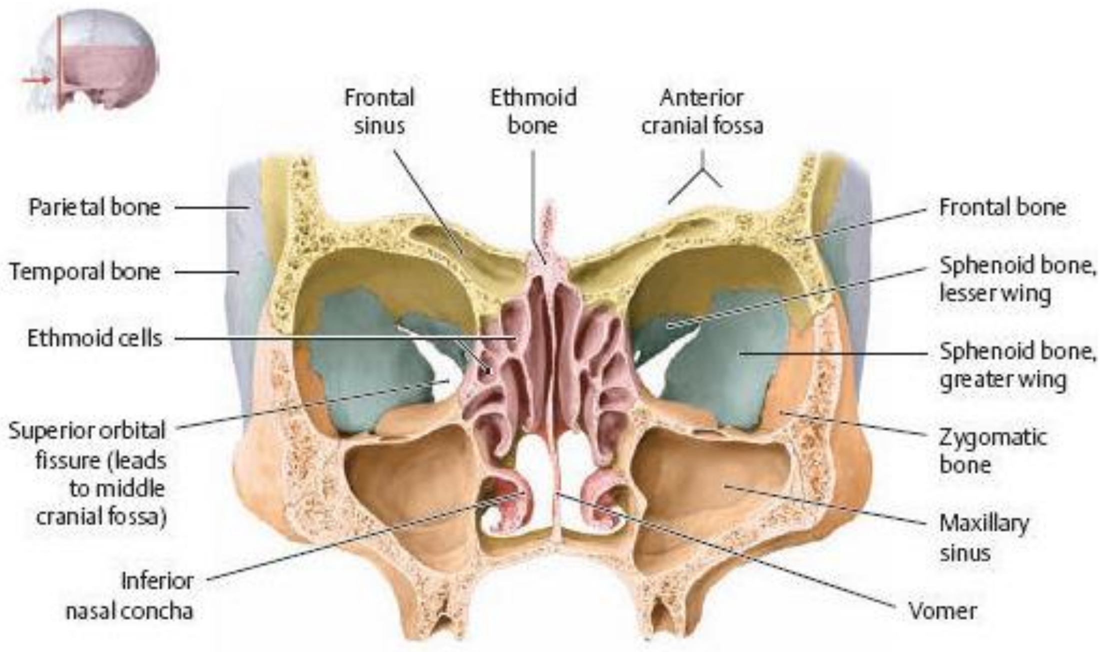

Figure 2.2: Frontal View of the Nasomaxillary Complex and Orbit

The above drawing displays the connections of the maxilla to the frontal bone, vomer, zygomatic bone, and sphenoid bone. The above drawing also displays the maxillary sinus location within the maxilla and the concha location within the nasal passage (Schuenke et al., 2010).

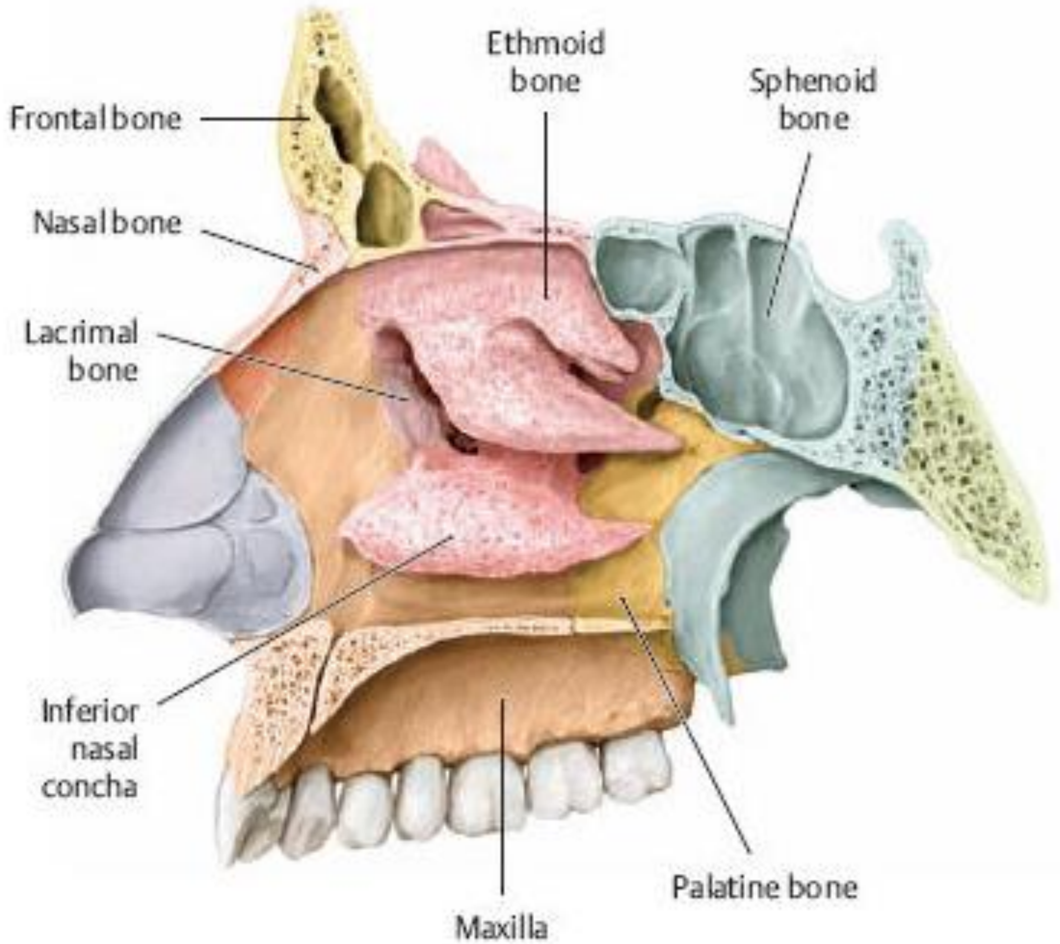

Figure 2.3: Sagittal View of the Nasomaxillary Complex

This drawing is a sagittal view of the nasomaxillary complex from within the nasomaxillary complex. It shows the maxillary dentition and maxilla in relation to the palatine bone in the posterior, the concha and ethmoid bone in the superior and the nasal bone in the anterior (Schuenke et al., 2010).

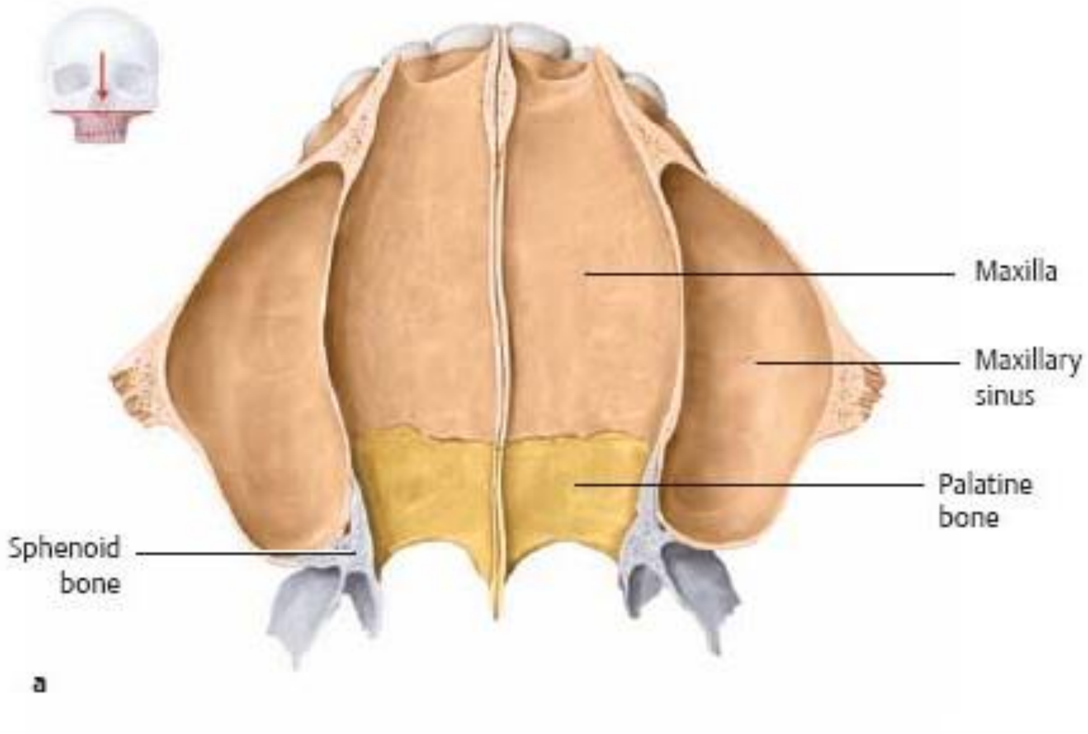

Figure 2.4: Axial View of the Nasomaxillary Complex

The above drawing shows the nasomaxillary complex, looking down from the superior. It shows the inferior part of the nasal cavity and maxillary sinuses. It also shows the palatine bone at the posterior of the nasal cavity (Schuenke et al., 2010).

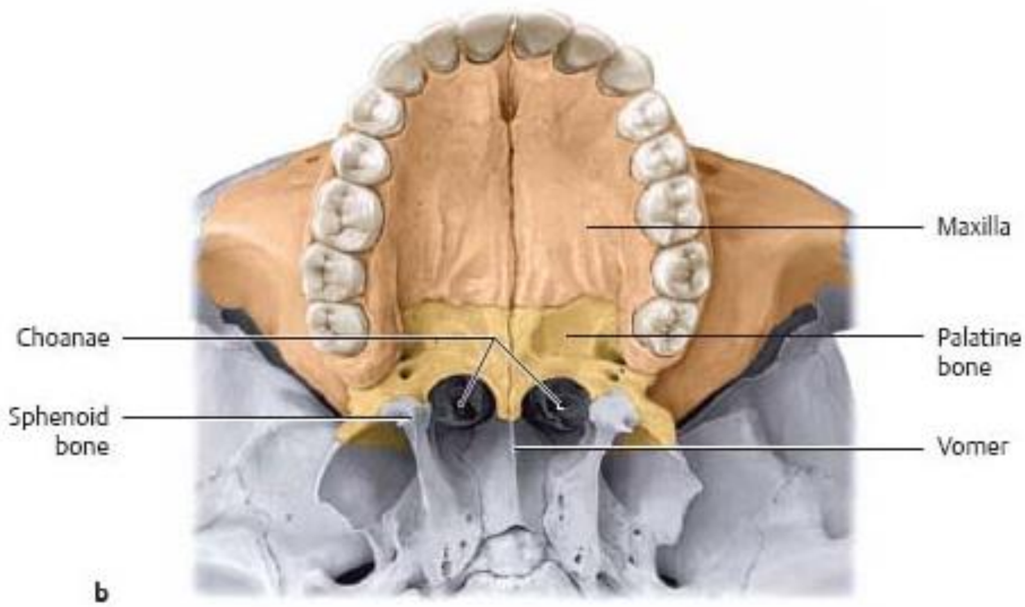

Figure 2.5: Axial View of the Nasomaxillary Complex

The above drawing shows the nasomaxillary complex, looking up from the inferior. It shows the hard palate from the oral cavity. It also shows the palatine bone at the posterior of the hard palate from the oral cavity (Schuenke et al., 2010).

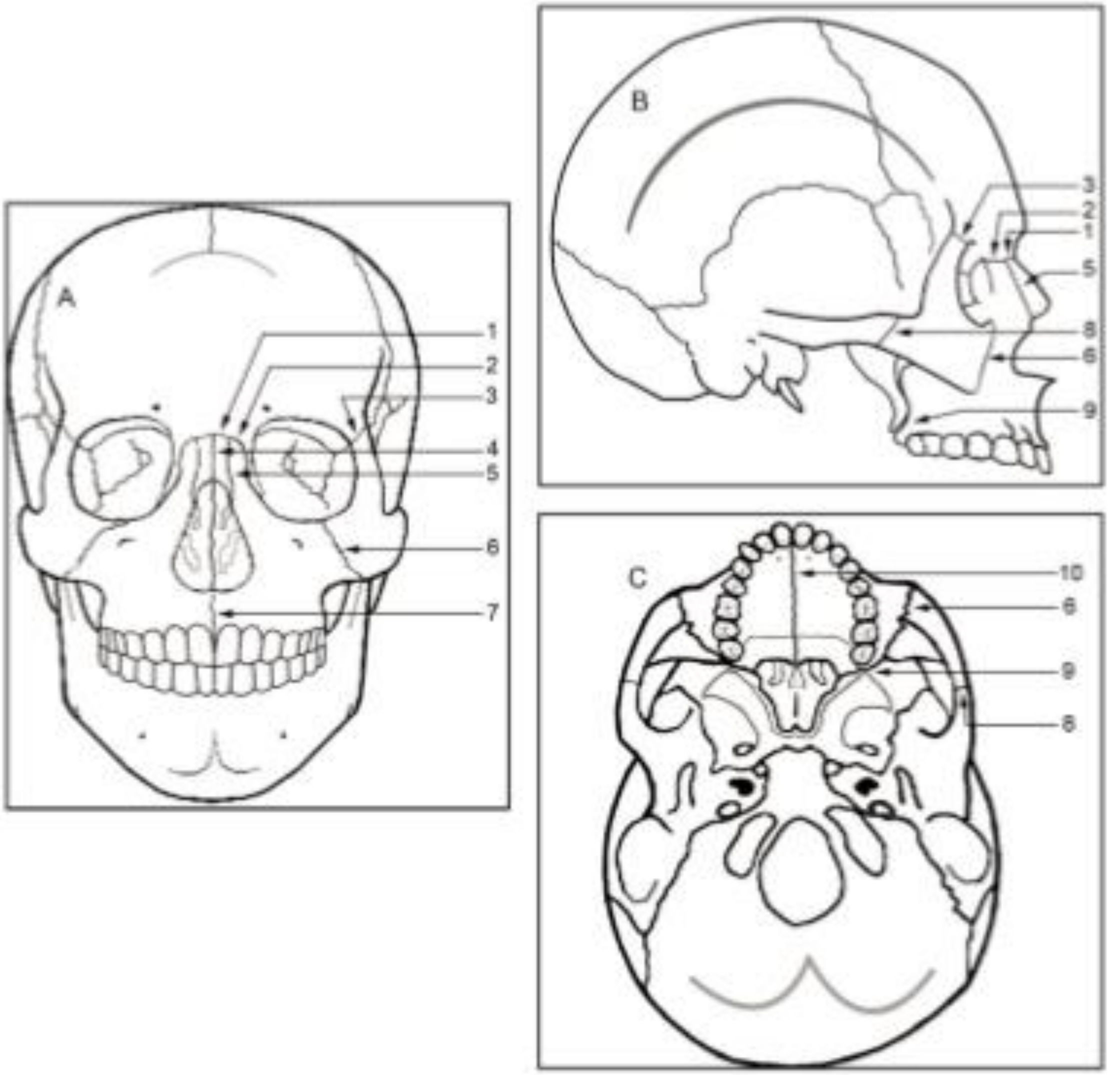

Figure 2.6 Circummaxillary Sutures

The above images shows the circummaxillary sutures. The figures are labeled with numbers that correspond to a circummaxillary suture. 1. Frontonasal. 2. Frontomaxillary. 3. Frontozygomatic. 4. Internasal. 5. Nasomaxillary. 6. Zygomaticomaxillary. 7. Intermaxillary. 8. Temporozygomatic. 9. Pterygomaxillary. 10. Midpalatal (Ghoneima et al., 2011)

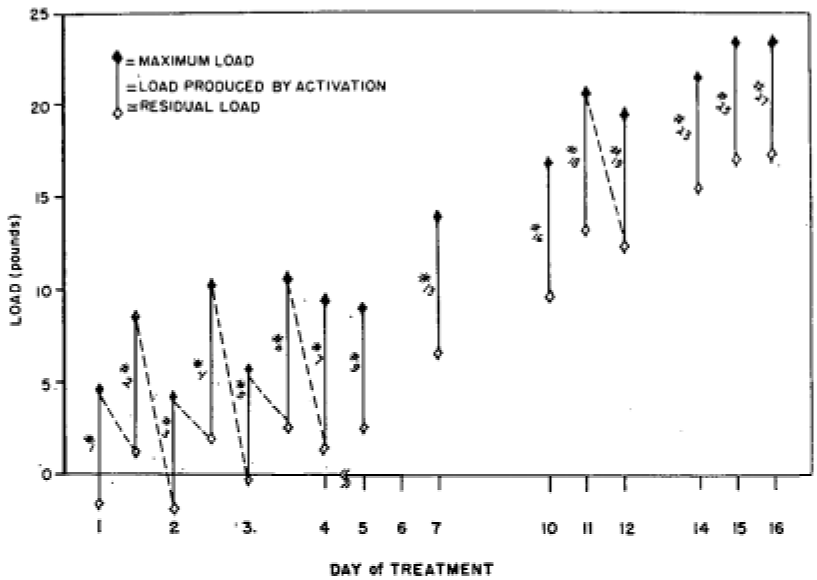

Figure 2.6a Load after Expander Activation

The graph above represented forces produced in a single patient during activation. The consistency of the load produced by activation was observed. This also demonstrated the residual load found after activation (Zimring & Isaacson, 1965).

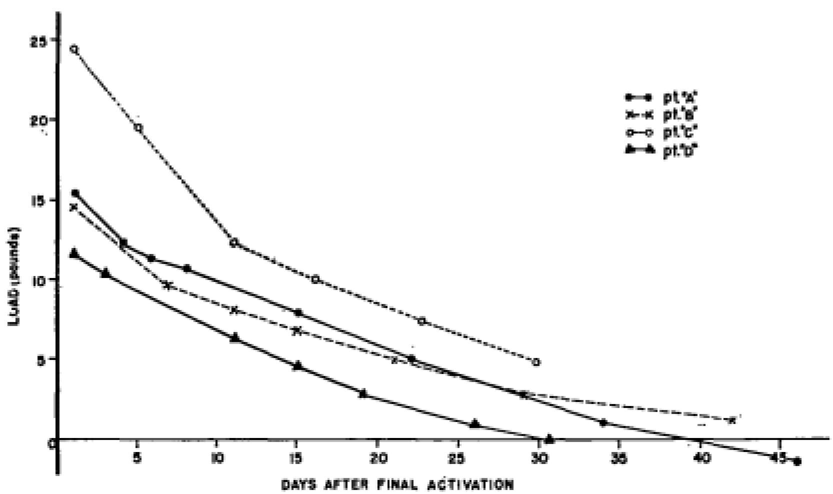

Figure 2.6b Residual Load Dissipation

The graph above represented the loads after the final activation. The load dissipation was about the same rate in all patients and steadily approached zero (Zimring & Isaacson, 1965).

CHAPTER 3: SPECIFIC AIMS & RESEARCH HYPOTHESES

3.1 Statement of the Problem

Currently, much of the research in the changes of the nasomaxillary complex width following rapid palatal expansion is limited to surgically-assisted rapid palatal expansion in adults or utilized a low number of patients. These studies often utilized two-dimensional images and/or the observations made on the changes that were less than a year in duration. There is limited research characterizing the long-term changes in the width of the nasomaxillary complex that occur after rapid palatal expansion in adolescents utilizing three-dimensional images. The stability of the orthopedic changes of the transverse width of the maxilla and its effects on the nasopharyngeal airway and maxillary sinus has not yet been fully examined. In addition, effects on the nasomaxillary complex and the long-term stability of the changes associated with this expansion may be of importance with the growing research interest in airway anatomy and air flow dynamics with computational fluid dynamics.

3.2 Central Research Null Hypothesis

There is no difference in the nasomaxillary complex width measurements taken before and after rapid palatal expansion. In addition, there is no difference between the nasomaxillary complex width measurements taken after rapid palatal expansion and during or at the end of orthodontic treatment.

3.3 Specific Aims

- Determine the immediate changes in dimensions of the nasomaxillary complex in patients who have undergone rapid palatal expansion and comprehensive orthodontic treatment from CBCT radiographs.

- Determine the stability of the RPE-induced changes in the transverse dimensions of the nasomaxillary complex.
- Determine the relationship between the patients' age, sex, growth status, amount of expansion performed, and the changes in dimensions of the nasomaxillary complex in patients who have undergone rapid palatal expansion and comprehensive orthodontic treatment.

CHAPTER 4: MATERIALS AND METHODS

4.1 IRB Approval

An application for research was submitted and approved by the UNMC Institutional Review Board (IRB). The IRB protocol number for the study was 518-17-EX.

4.2 Study Design and Patient Pool

This investigation was a retrospective clinical study completed on patients who had rapid palatal expansion and orthodontic treatment that was previously planned and completed by a private practice orthodontist (MB). A power analysis was performed to obtain the number of patients needed to reach statistical significance. Accordingly, thirty patients were recruited for the present study. One hundred twenty-four patients were initially screened, and a total of twenty-eight patients were identified to be included in the retrospective study. The patients consisted of 18 females and 10 males, with an average age of 9.08 years old, with a range of 7.14 years to 11.54 years. A patient demographic summary is displayed in Table 4.1. Full patient demographics are shown in Table A. Inclusion criteria included that the patient had a rapid palatal expander, the patient had a post-expansion (T_2) CBCT radiograph that was taken within one year of the conclusion of the rapid palatal expansion, and the patient had a follow-up CBCT radiograph at least 6 months after the post-expansion CBCT radiograph (T_3). Exclusion criteria included any patients with the previous diagnosis of any craniofacial anomaly or syndrome. Patients were also excluded if one of their radiographs was not measurable due to scatter or motion artifact on the image. A description of the time points observed was given in Table 4.2.

The number of rapid palatal expander turns that the patient was instructed to complete were obtained from the patient's chart or dental record. The practitioner had not recorded the amount of expansion obtained on the expander itself so that data was not available. If the instructions were followed, 1 turn resulted in 0.2mm of expansion in the RPE based on the expander the practitioner used.

After adequate expansion was completed as determined by the practitioner, a vacuum-formed or Hawley retainer was given to the patient for retention. When appropriate based on the patients' dental development and malocclusion, comprehensive orthodontics was initiated. The practitioner treated each patient as was determined appropriate for alignment, anteroposterior correction and vertical correction as needed. The comprehensive orthodontic treatment effects were localized to the dentition and the dental alveolar housing.

4.3 Cone-Beam Computed Tomography (CBCT) Imaging

All CBCT images included in the study were taken using the same Kodak 9500 machine (Carestream, Rochester, New York). The patients were placed in a standing position in their natural head position. All patients were positioned by the same practitioner (MB), and the image was taken under the following settings: tube voltage – 90kVp, tube current – 10mA, and exposure time – 10800ms. The field of view for the produced image was 18 cm in diameter and 20 cm in height and a voxel size of 0.3mm was used. Files produced by the CBCT scan were imported into Invivo5 Anatomage software version 2.1 (San Jose, California) licensed to the University of Nebraska Medical Center. All CBCT images were analyzed by a single practitioner (AS).

4.4 CBCT Analysis

All measurements were performed using InVivo5 Anatomage software.

4.4.1 CBCT Orientation

In the present study, the CBCT radiographs were oriented prior to recording any measurements. The CBCT radiographs were oriented so that the axial and coronal views were aligned along the most cervical point of the maxillary first molar furcations. (Figure 4.1 and 4.2) Because the images were all taken in the patient's natural head position with the Frankfort horizontal line parallel to the floor, the sagittal orientation of the CBCT image was not adjusted.

All nasal passage and maxillary sinus measurements were obtained from the coronal image in the anteroposterior plane that intersected the cervical most point of both maxillary first molar furcations. (Figure 4.2) The coronal slice of the image was then moved anteriorly as necessary to measure the mesiolingual cusp tips of the maxillary first molar from cusp tip to cusp tip. The coronal slice of the image was then moved anteriorly or posteriorly as necessary to measure the palatal root tips of the maxillary first molar from root tip to root tip.

4.4.2 Nasal Floor Width (NFW) Measurements

The nasal floor width was measured at the intersection of the palatine process of the maxilla and the medial wall of the maxillary sinus to the same intersection on the contralateral side. (Figure 4.3) Because this measurement was bony landmark to bony landmark, it was not made parallel to the line connecting the maxillary first molar furcations.

4.4.3 Nasal Passage Width (NPW) and Maxillary Sinus Width (MSW) Measurements

The nasal passage measurement was defined as the largest width of the nasal passage from the medial surface of the right maxillary sinus to the medial surface of the left maxillary sinus in a line parallel to the axial line through the most cervical point of the maxillary first molar furcations. (Figure 4.4) The maxillary sinus measurement was defined as the width from the medial surface of the lateral wall of the maxillary sinus to the medial surface of the opposite lateral wall of the maxillary sinus in a line that overlapped the nasal passage measurement for the entire length of the nasal passage measurement. (Figure 4.5)

4.4.4 Palatal Cortical Bone Width (M1PW) and Buccal Cortical Bone Width (M1BW) Measurements

The palatal cortical bone width was measured from the medial surface of the palatal cortical plate of the alveolar process to the contralateral medial surface of the palatal cortical plate of the alveolar process in a line that overlaps the line in the coronal slice of the CBCT that connects the cervical most point of the maxillary first molar furcations. The buccal cortical bone width was measured from the lateral surface of the buccal cortical plate of the alveolar process to the contralateral lateral surface of the buccal cortical plate of the alveolar process in a line that overlaps the line in the coronal slice of the CBCT that connects the cervical most point of the maxillary first molar furcations. (Figure 4.6 and 4.7)

4.4.5 Maxillary First Molar Mesiolingual Cusp Tip Width (M1CW) and Palatal Root Tip Width (M1RW) Measurements

The coronal plane was readjusted in order to capture the mesiolingual cusp tips and palatal root tips for these measurements. The maxillary first molar mesiolingual cusp width was measured from the most inferior part of the cusp tip to the contralateral cusp tip. (Figure 4.8) The maxillary first molar palatal root width was measured from the most superior part of the palatal root to the contralateral palatal root. (Figure 4.9)

4.4.6 Interorbital Width Measurements

The interorbital width was measured at the intersection of the cribriform plate and the orbital surface of the frontal bone to the same intersection on the contralateral side. (Figure 4.10)

4.4.7 Extraorbital Width Measurements

The extraorbital width was measured from the medial surface of the frontal process of the zygomatic bone to the contralateral medial surface of the frontal process of the zygomatic bone in a line that overlaps the interorbital width measurement. (Figure 4.11)

4.4.8 Cervical Vertebral Maturation Stage (CVMS)

The maturation stage of each patient was determined on the midsagittal slice of each CBCT image based on the five maturational stages outlined in “An improved version of the cervical vertebral maturation (CVM) method for the assessment of mandibular growth” (Baccetti et al., 2002). (Figure 4.12 and Figure 4.13) The CVM method utilized the morphology of the bodies of the second, third and fourth cervical vertebrae as measured on a cephalogram to stage patients. CVMS I was defined as having lower borders of C2, C3, and C4 that are flat or potentially a slight concavity on the lower border of C2. CVMS II was defined as having concavities on both the lower border of C2 and C3 with vertebral bodies that are trapezoid or horizontal rectangular. Baccetti et al. found that peak in mandibular growth will occur within a year of this stage. CVMS III was defined as having concavities on the lower borders of C2, C3, and C4 with C3 and C4 having horizontal rectangular shapes. Baccetti et al. also found that the peak in mandibular growth occurred one to two years prior to this stage. CVMS IV was defined as maintaining the concavities on the lower borders of C2, C3, and C4 with the bodies of C3 and C4 becoming more square in shape. CVMS V was again defined as maintaining the concavities on the lower borders of C2, C3, and C4 with C3 and C4 approaching a vertical rectangular shape. CVMS V was at least two years after the peak mandibular growth spurt. Figure 4.13 showed an outline of the vertebral bodies in the shapes appropriate to each CVMS.

According to Baccetti et al., the peak in pubertal growth of the mandible occurs between CVMS II and III (Baccetti et al., 2002). Based on the growth curves for the maxilla and the mandible overlaid on the Scammon Growth Curve, the maxilla peaks before the mandible; therefore, the peak growth of the maxilla would also occur before CVMS III (Figure 4.14) (Proffit et al., 2013). Table 4.2 shows a summary of the patients' CVM stages at each time point. Table G shows the raw data of CVM stages.

4.5 Reliability

All CBCT scans in the study were analyzed by a single examiner (AS). Two weeks after all scans had been analyzed, the 28 pre-expansion (T_1) scans were analyzed again by the same examiner to measure the reliability of the analysis. In each T_1 CBCT, all measurements were calculated again.

4.6 Statistical Analysis

Descriptive statistics such as mean and standard deviation were calculated for all applicable variables. Student t-tests were used to compare the means of each measurement to the same parameter means at the other time points. Pearson correlation coefficients were calculated to compare changes between time points. One-way random-effects models for absolute agreement were performed to determine the repeatability of each measure.

	N	Age of Patients at T_1 (years)	Turns prescribed
Boys	10	9.30	40.4
Girls	18	9.03	54.3
Total	28	9.13	48.8

Table 4.1: Patient Demographics

There were 8 more females (n=18) than males (n=10) in the present study. The average patient age was 9.13 years old. The average patient was instructed to turn their expander 49 times, with girls being instructed to turn 14 more turns than boys on average.

Time Point	Description
T_1	Prior to Rapid Palatal Expansion
T_2	After Rapid Palatal Expansion
T_3	Prior to Comprehensive Orthodontic Treatment
T_4	During or After Comprehensive Orthodontic Treatment

Table 4.2: Time Points

The table above gives a description of each time point analyzed.

	T_1		T_2		T_3		T_4	
CVMS	Number	% Total	Number	% Total	Number	% Total	Number	% Total
I	22	78.57	12	42.86	2	7.14	0	0
II	6	21.43	15	53.57	12	42.86	0	0
III	0	0	1	3.57	13	46.43	5	29.41
IV	0	0	0	0	1	3.57	12	70.59
V	0	0	0	0	0	0	0	0.00
Total	28	100	28	100	28	100	17	100

Table 4.3: Total for CVM Stage at Each Time Point

There were twenty-two patients who were CVMS I and six patients who were CVMS II at T_1. As time progressed, patients matured. At T_3, two patients were CVMS I, twelve patients were CMVS II, thirteen patients were CVMS III, and one patient was CMVS IV. Of the seventeen patients who had T_4 CBCTs, five patients were CVMS III and 12 patients were CVMS IV. The percent of the total number of patients who were each CMVS are shown in separate columns.

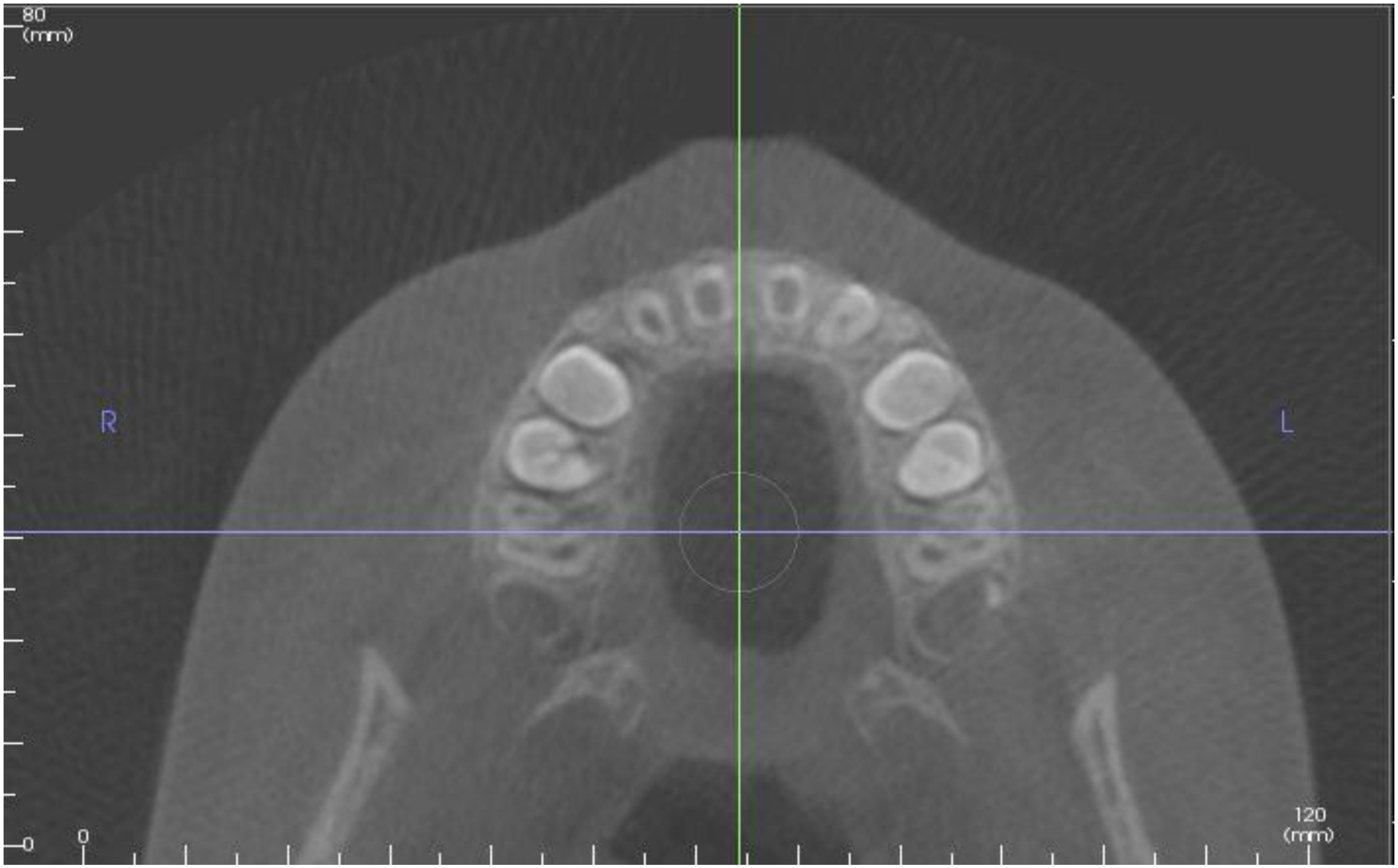

Figure 4.1: Axial View through the Cervical Point of the Maxillary First Molar Furcations

The most cervical point of the maxillary first molar furcations was aligned in the axial view.

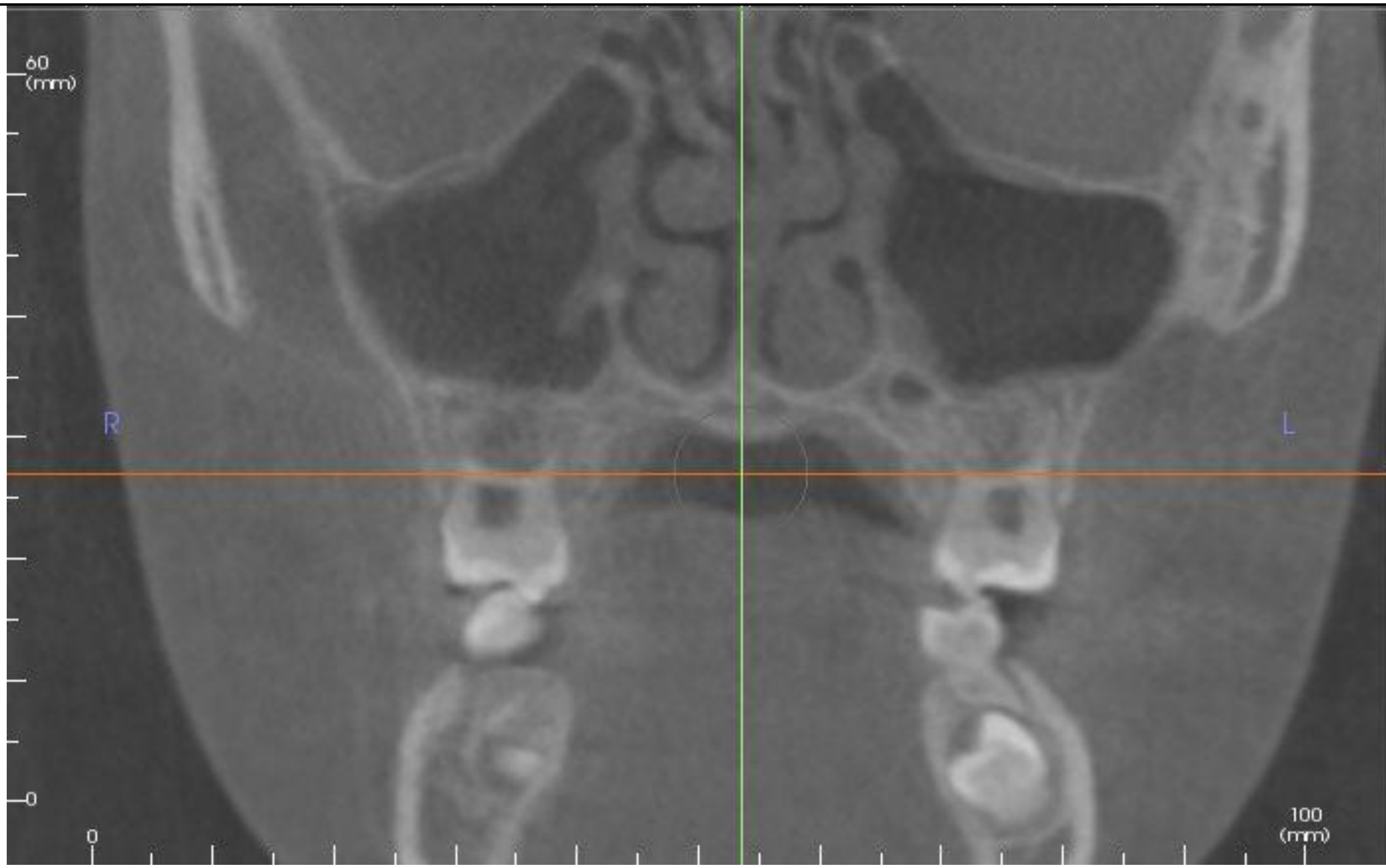

Figure 4.2: Coronal View through the Cervical Point of the Maxillary First Molar Furcations

The most cervical point of the maxillary first molar furcations was aligned in the coronal view.

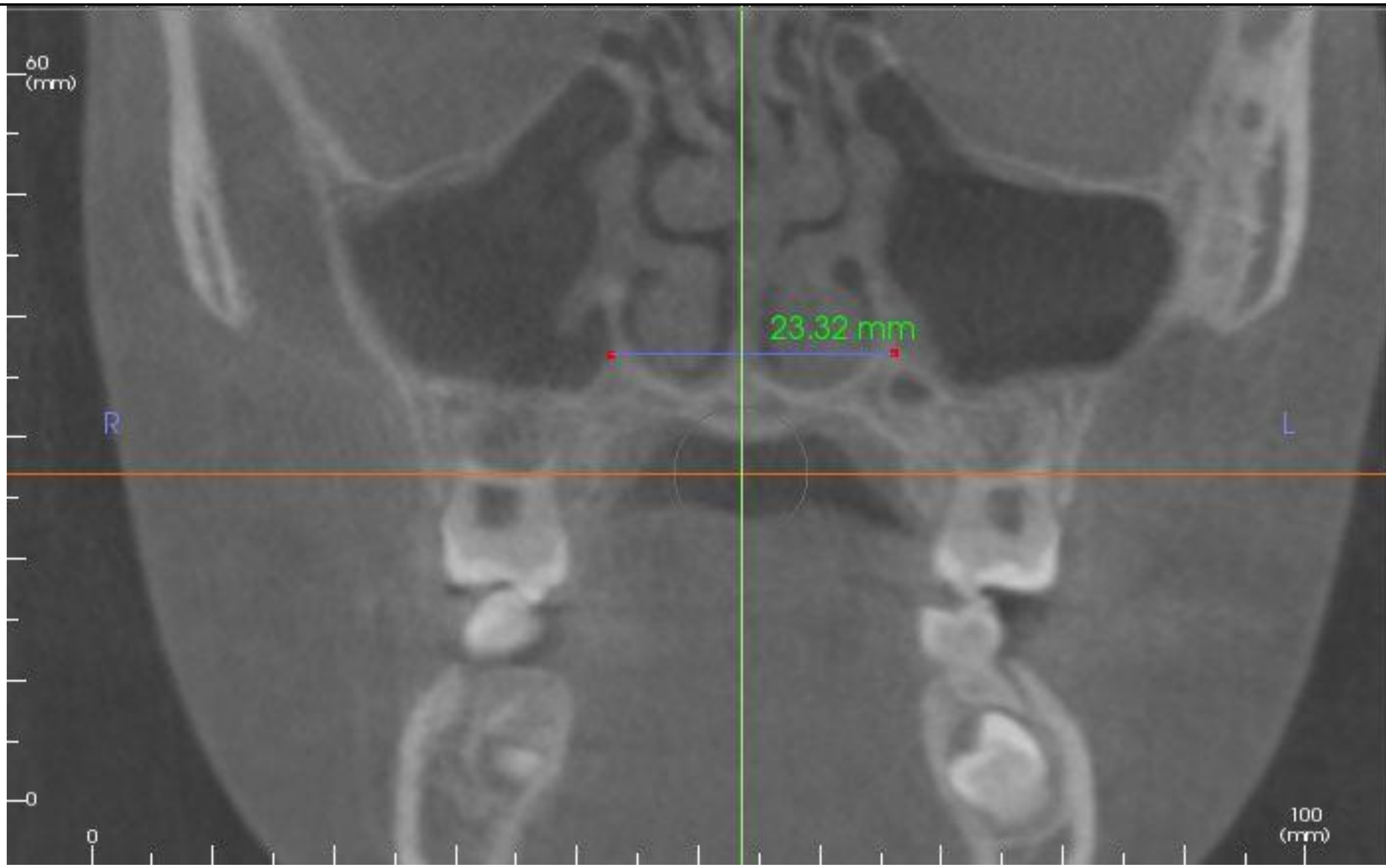

Figure 4.3: Nasal Floor Width Measurement

The nasal floor width was measured at the intersection of the palatine process of the maxilla and the medial wall of the maxillary sinus to the same intersection on the contralateral side.

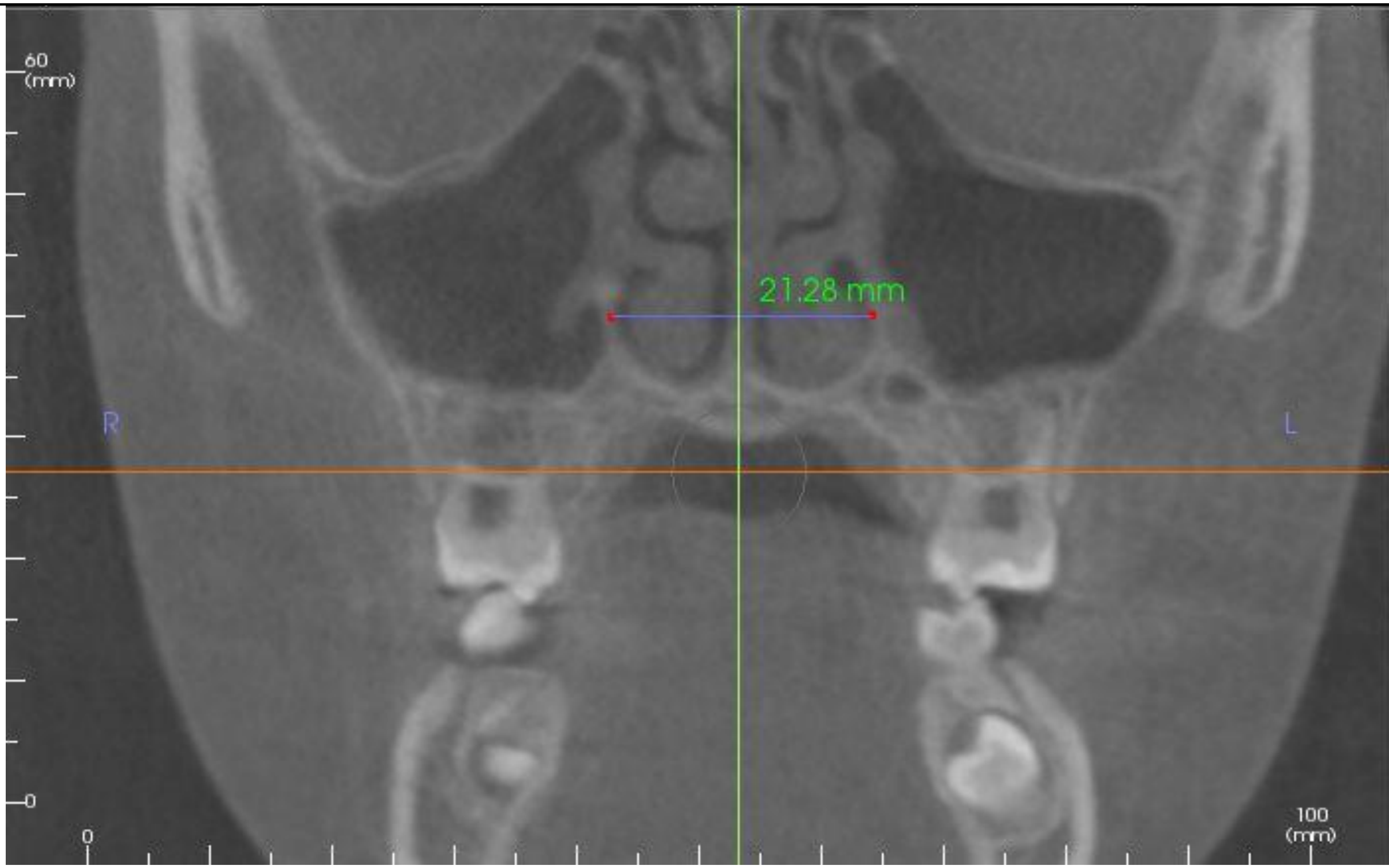

Figure 4.4: Nasal Passage Width Measurement

The nasal passage width was measured at the widest part of the nasal cavity in a line parallel to the line connecting the maxillary first molar furcations.

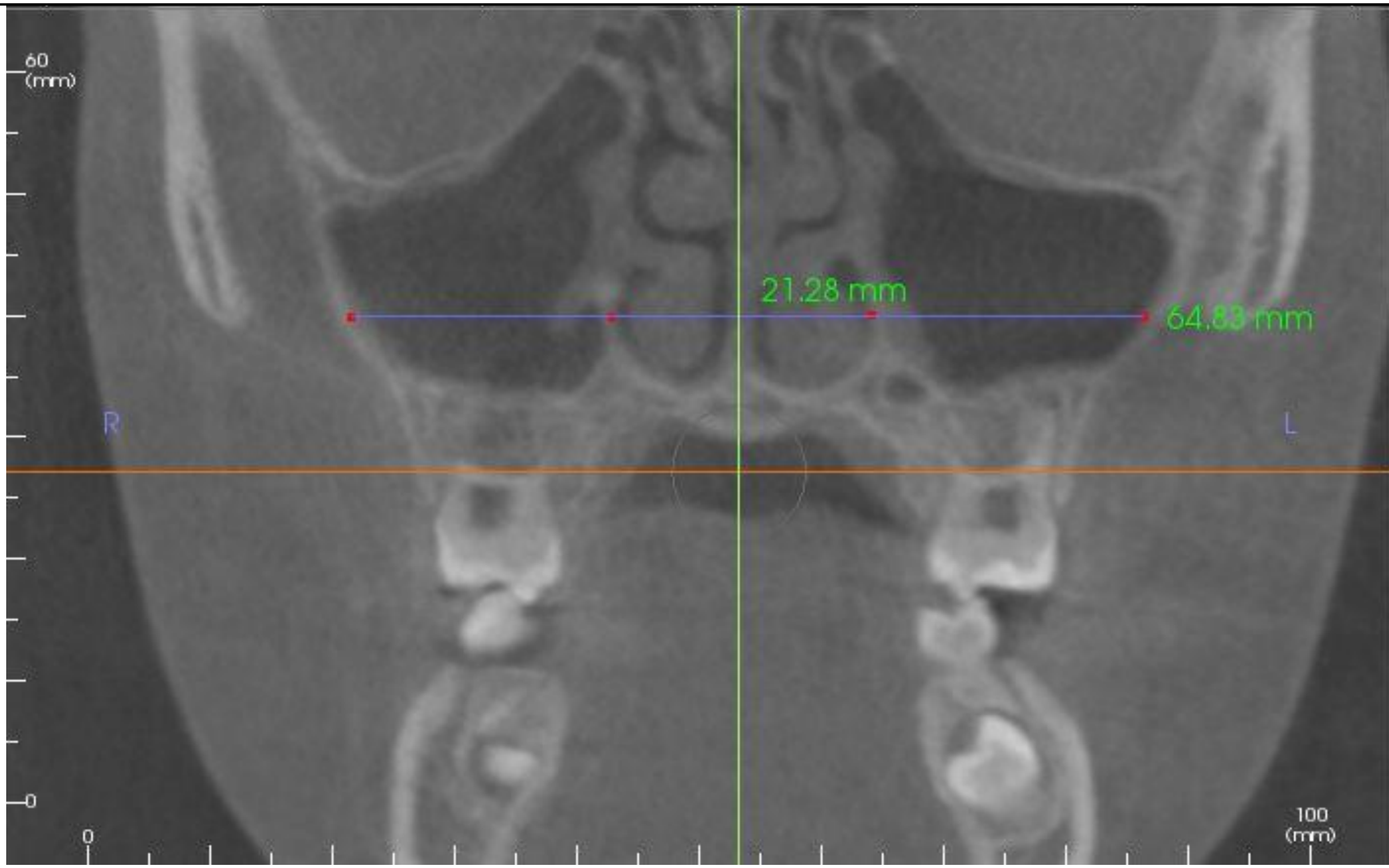

Figure 4.5: Maxillary Sinus Width Measurement

The maxillary sinus width was measured in a line parallel to and on top of the nasal passage width measurement, meaning it was also parallel to the line connecting the maxillary first molar furcations.

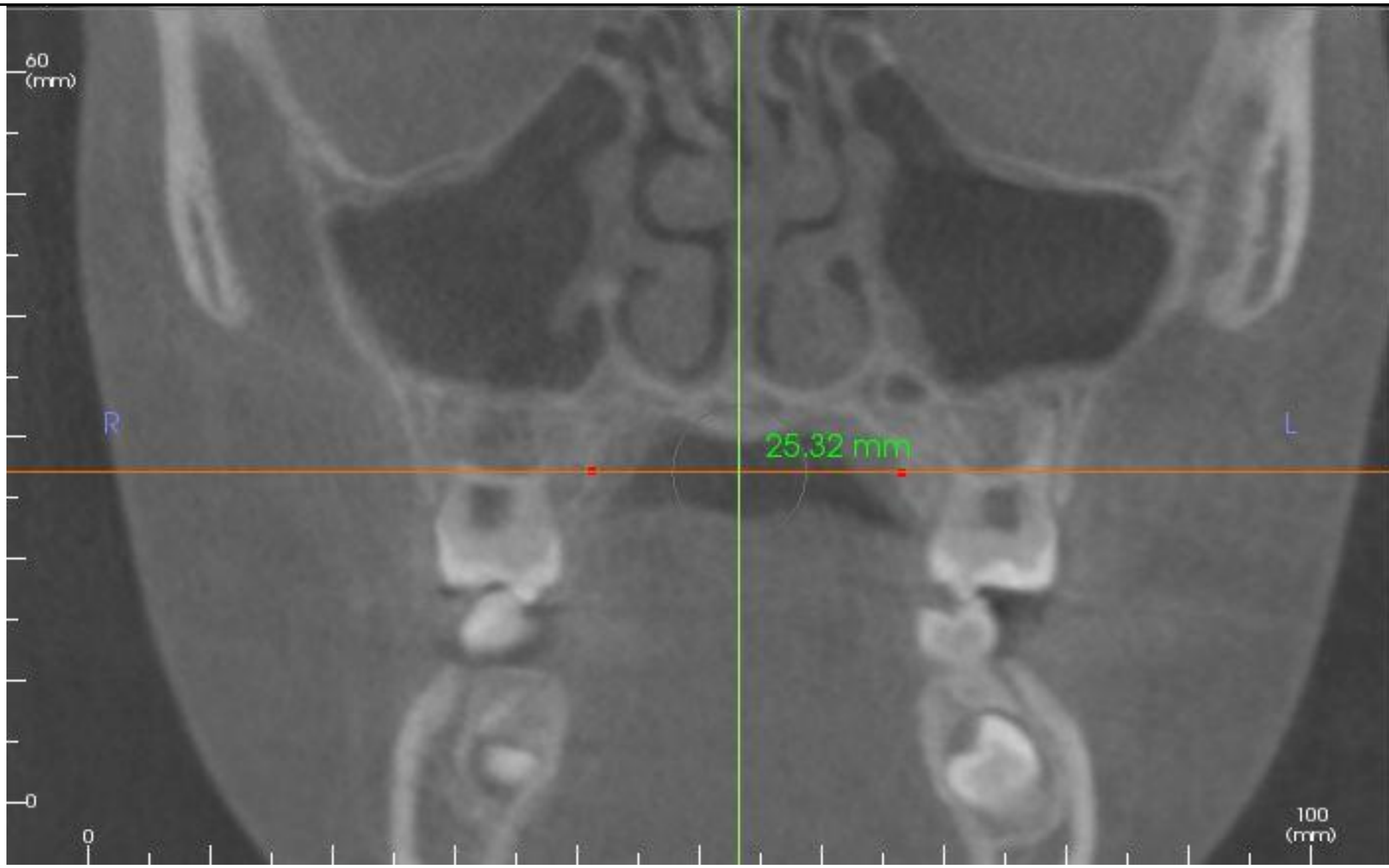

Figure 4.6: Maxillary First Molar Palatal Cortical Bone Width Measurement

The palatal cortical bone width was measured from the medial surface of the palatal cortical plate of the alveolar process to the contralateral medial surface of the palatal cortical plate of the alveolar process in a line that overlaps the line in the coronal slice of the CBCT that intersects the cervical most point of the maxillary first molar furcations.

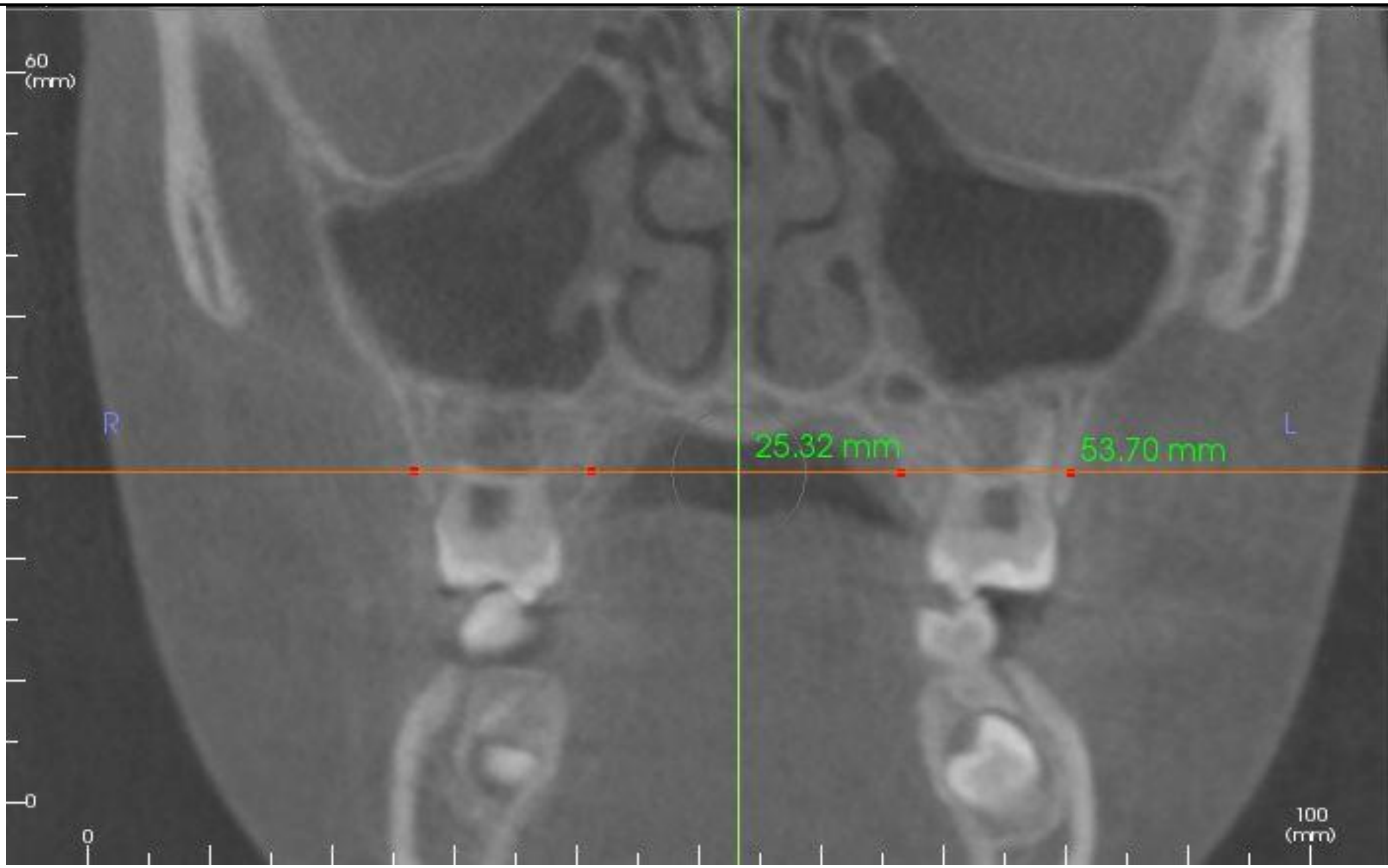

Figure 4.7: Maxillary First Molar Buccal Cortical Bone Width Measurement

The buccal cortical bone width was measured from the lateral surface of the buccal cortical plate of the alveolar process to the contralateral lateral surface of the buccal cortical plate of the alveolar process in a line that overlaps the line in the coronal slice of the CBCT that intersects the cervical most point of the maxillary first molar furcations.

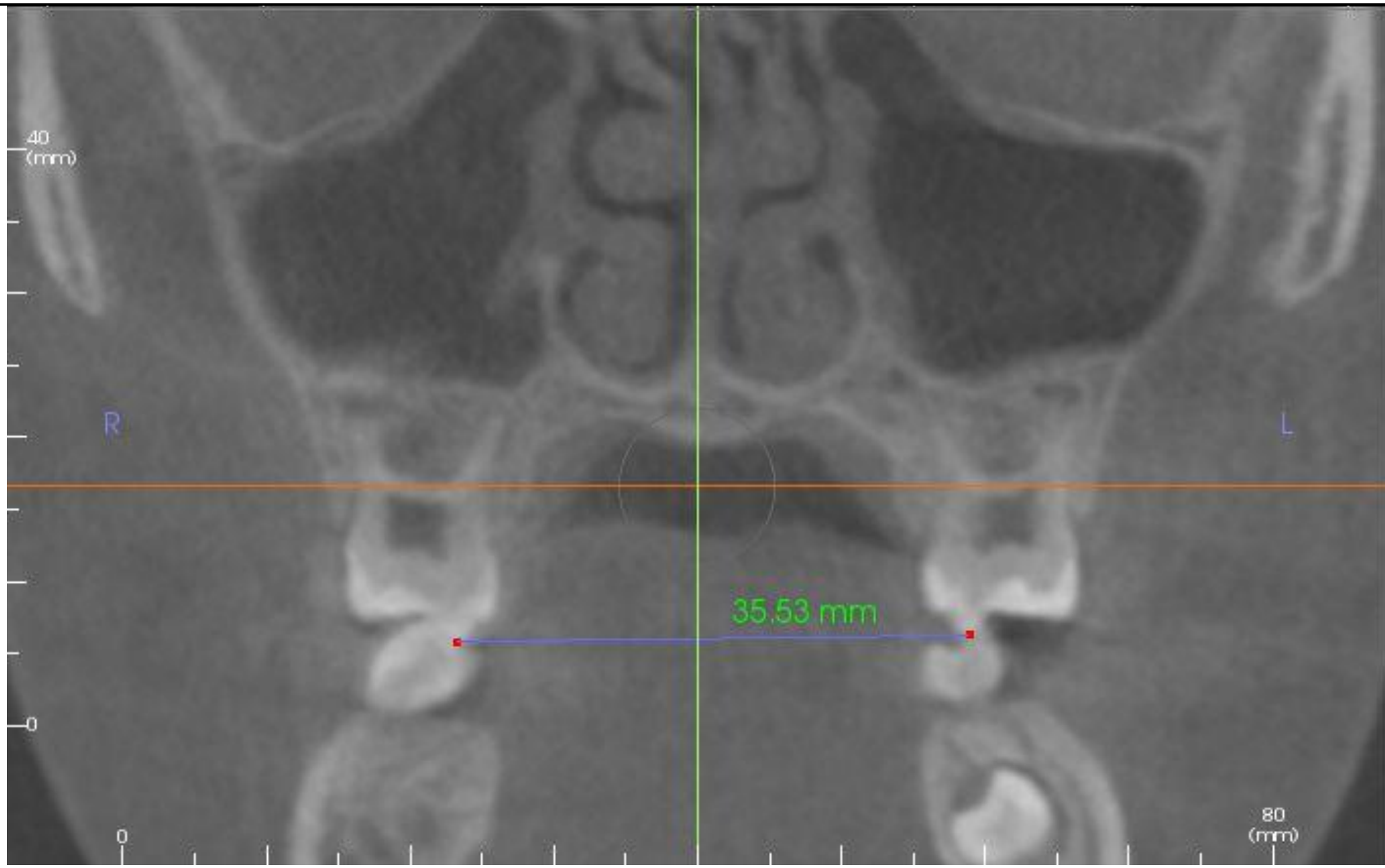

Figure 4.8: Maxillary First Molar Mesiolingual Cusp Tip Width Measurement

The maxillary first molar mesiolingual cusp width was measured from the most inferior part of the cusp tip to the contralateral cusp tip.

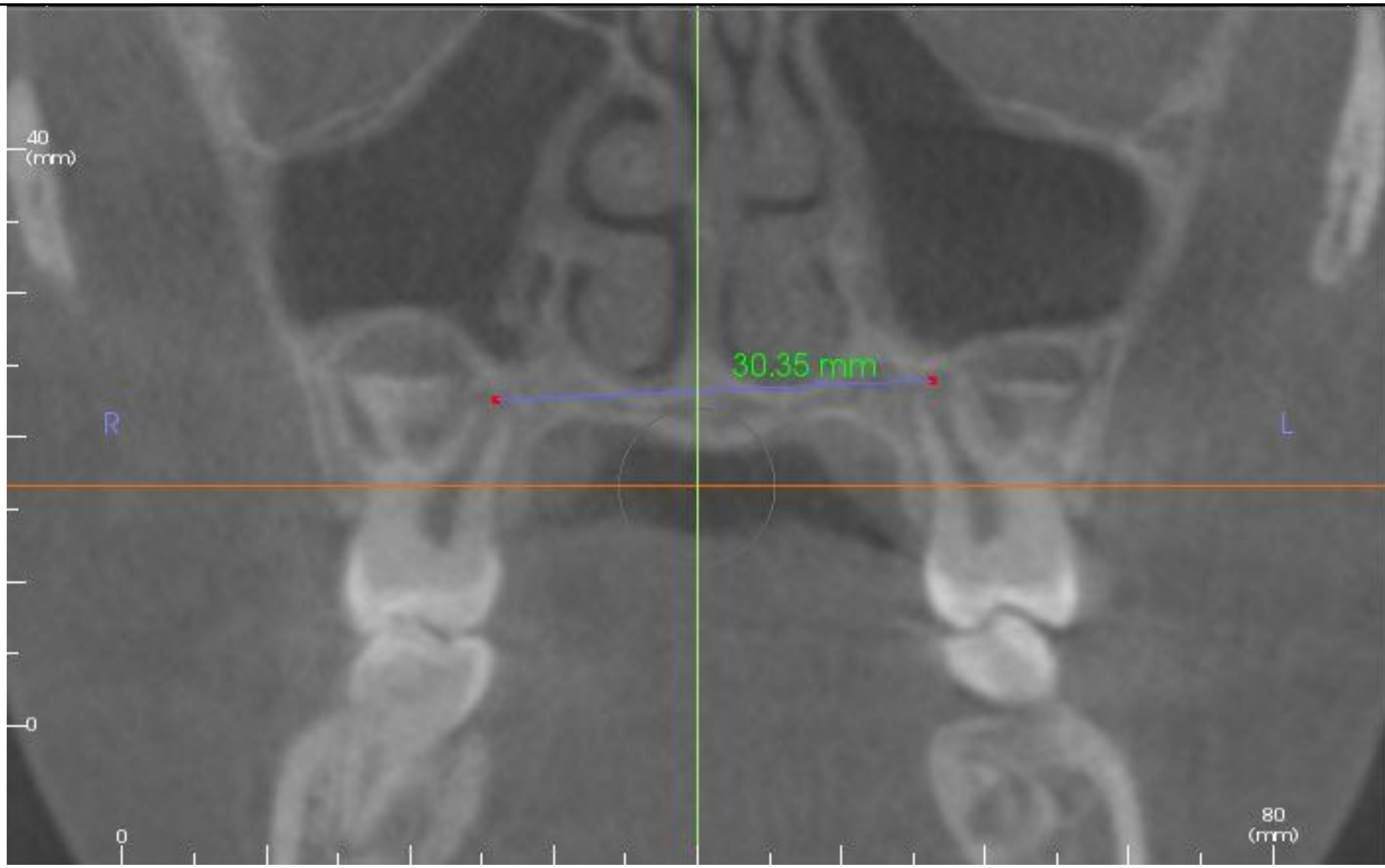

Figure 4.9: Maxillary First Molar Palatal Root Tip Width Measurement

The maxillary first molar palatal root width was measured from the most superior part of the palatal root to the contralateral palatal root.

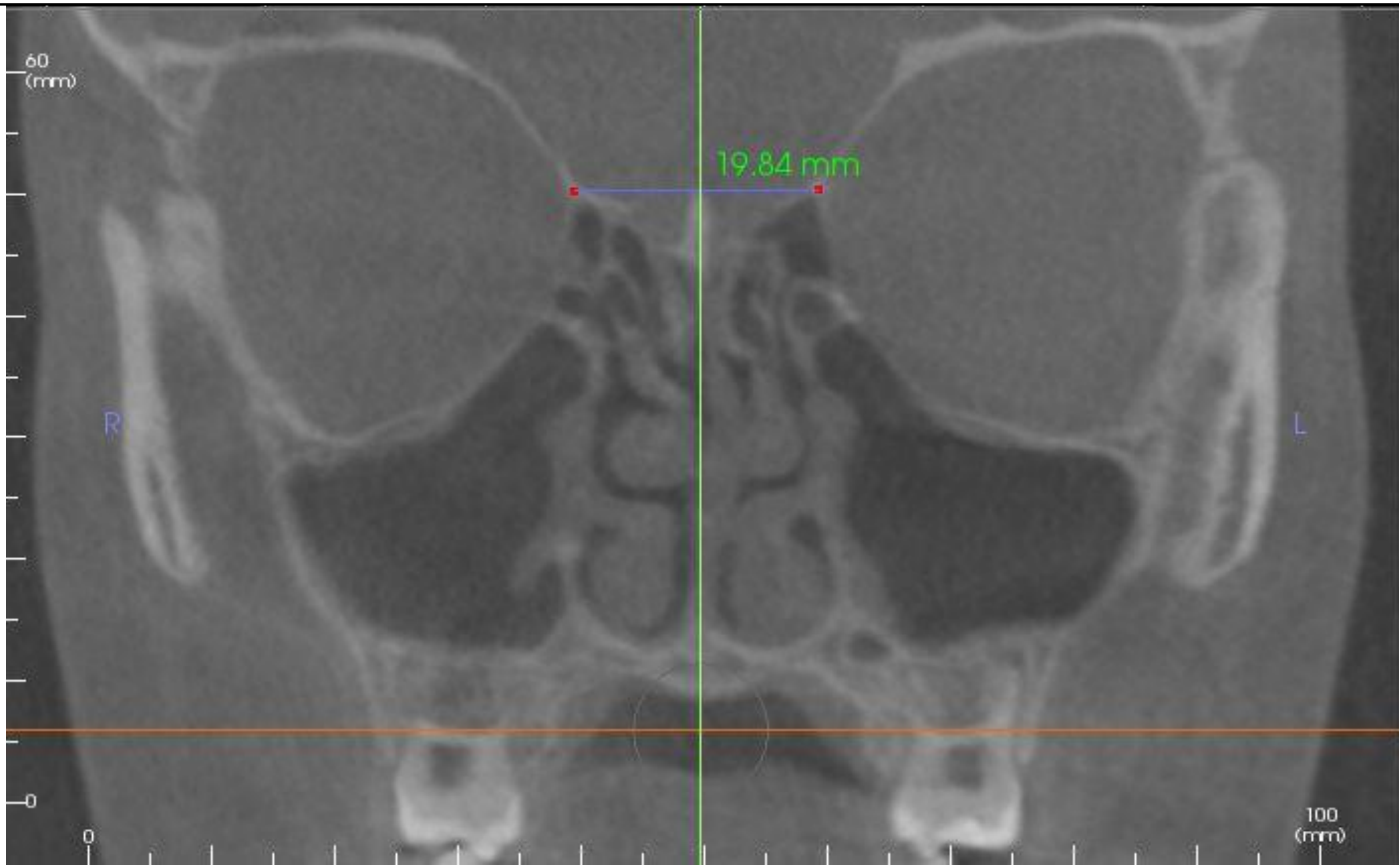

Figure 4.10: Interorbital Width Measurement

The interorbital width was measured at the intersection of the cribriform plate and the orbital surface of the frontal bone to the same intersection on the contralateral side.

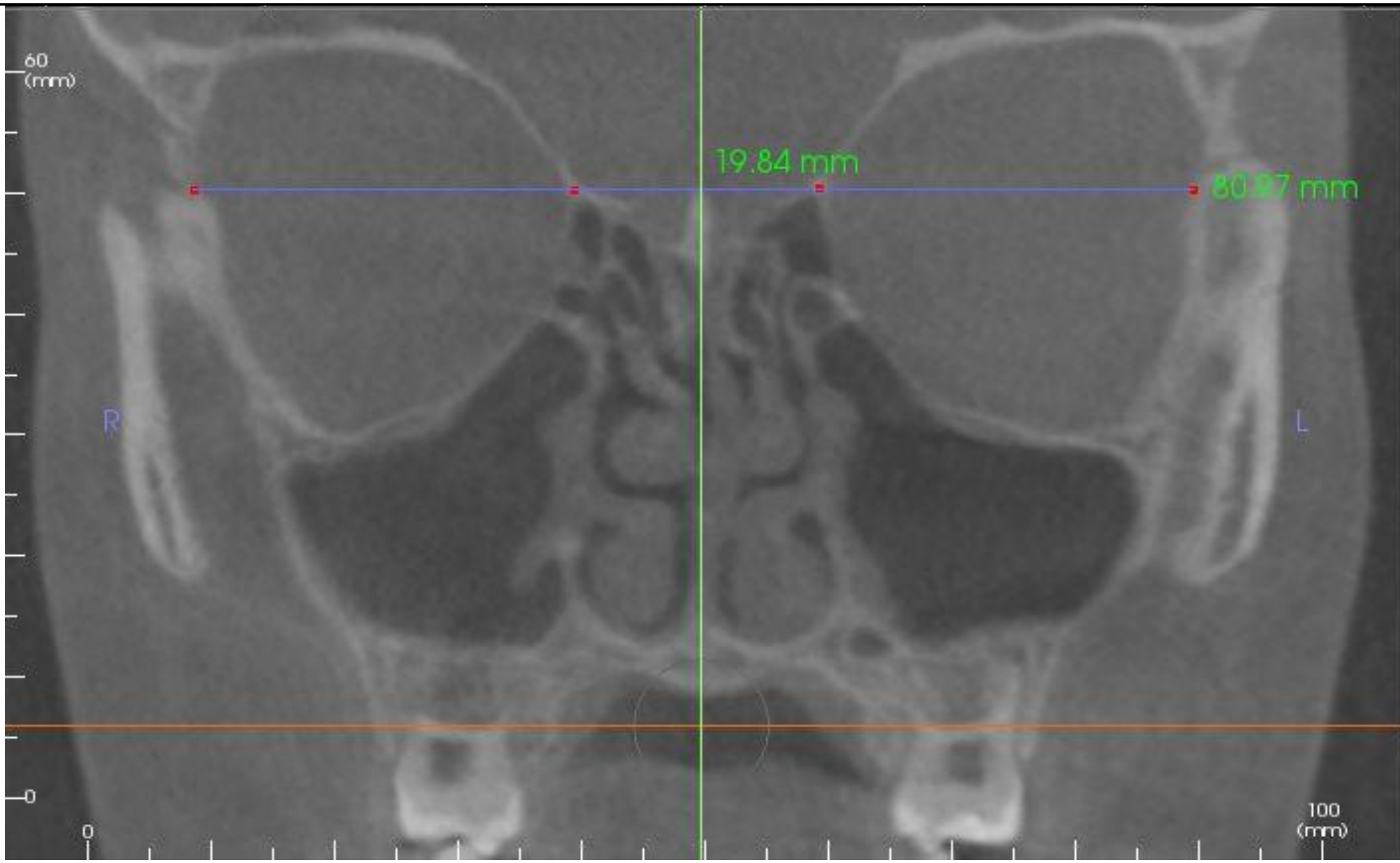

Figure 4.11: Extraorbital Width Measurement

The extraorbital width was measured from the medial surface of the frontal process of the zygomatic bone to the contralateral medial surface of the frontal process of the zygomatic bone in a line that overlaps the interorbital width measurement.

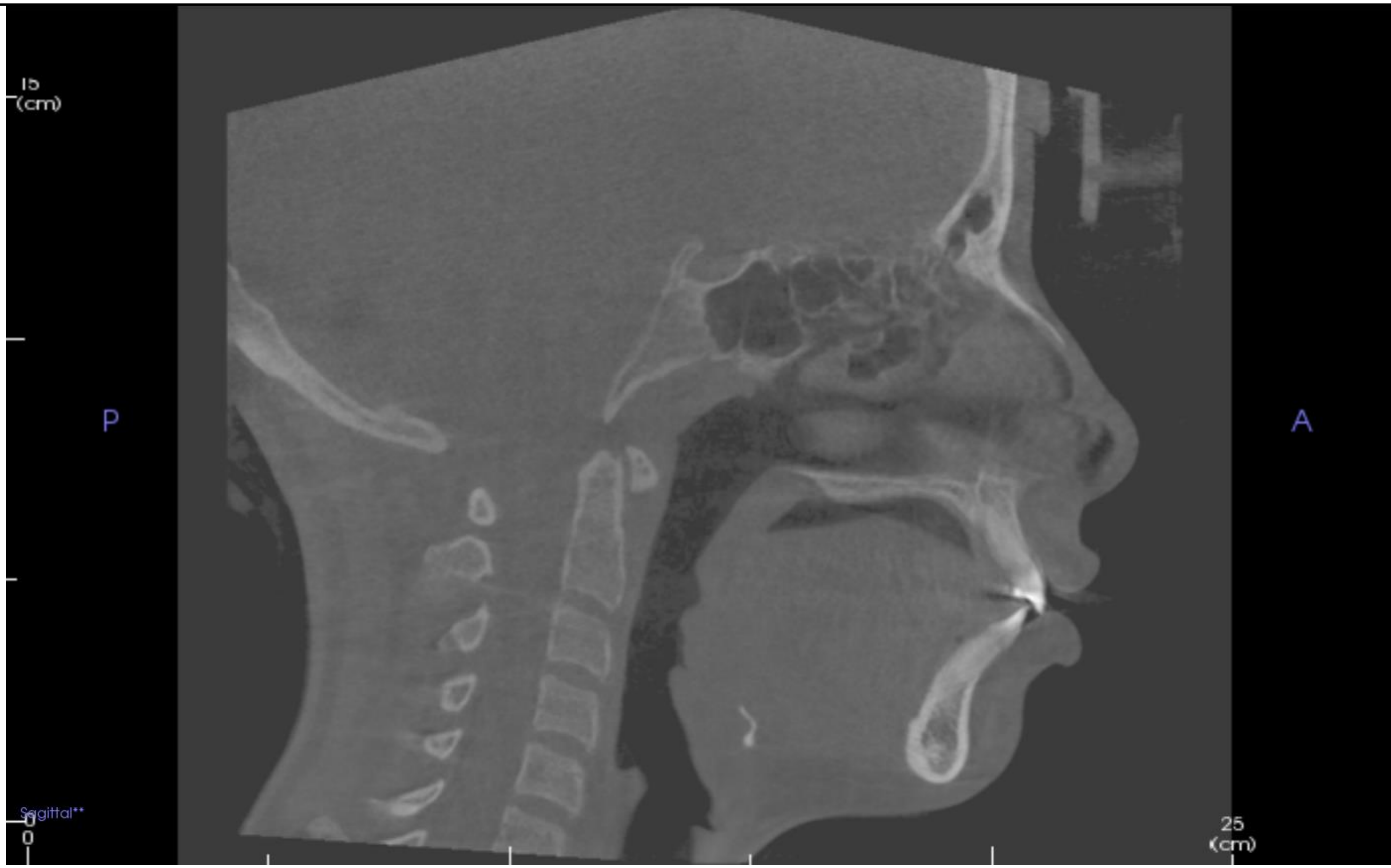

Figure 4.12: Cervical Vertebral Maturation Stage Measured on the Midsagittal View

The maturation stage was determined on the midsagittal slice of the CBCT image based on the five maturational stages outlined in “An improved version of the cervical vertebral maturation (CVM) method for the assessment of mandibular growth” (Baccetti et al., 2002). See Figure 4.13.

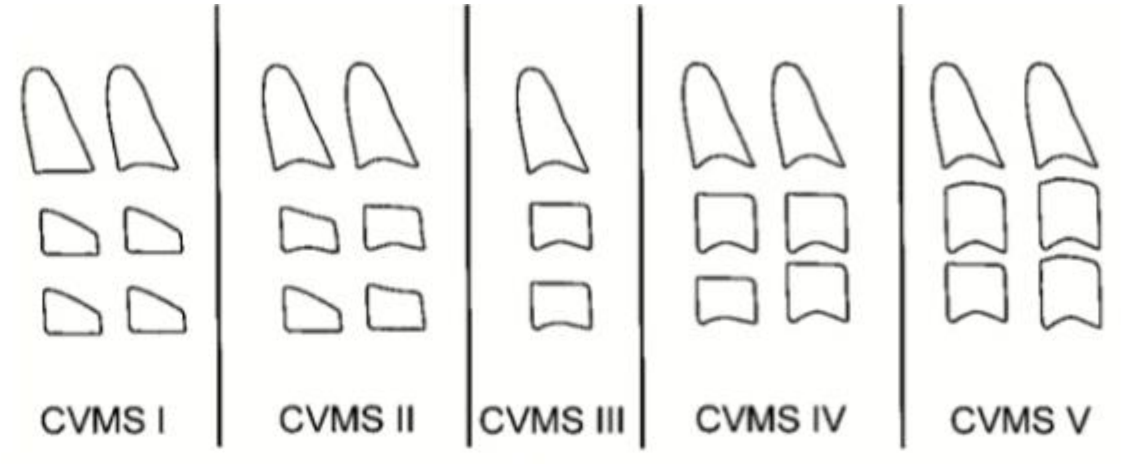

Figure 4.13: Cervical Vertebral Maturation Stages

The five developmental stages of the cervical vertebral maturation method are shown above. The lower borders of the C2, C3, and C4 vertebrae change morphology from stage I to stage III. In stages IV and V, the vertebrae elongate (Baccetti et al., 2002)

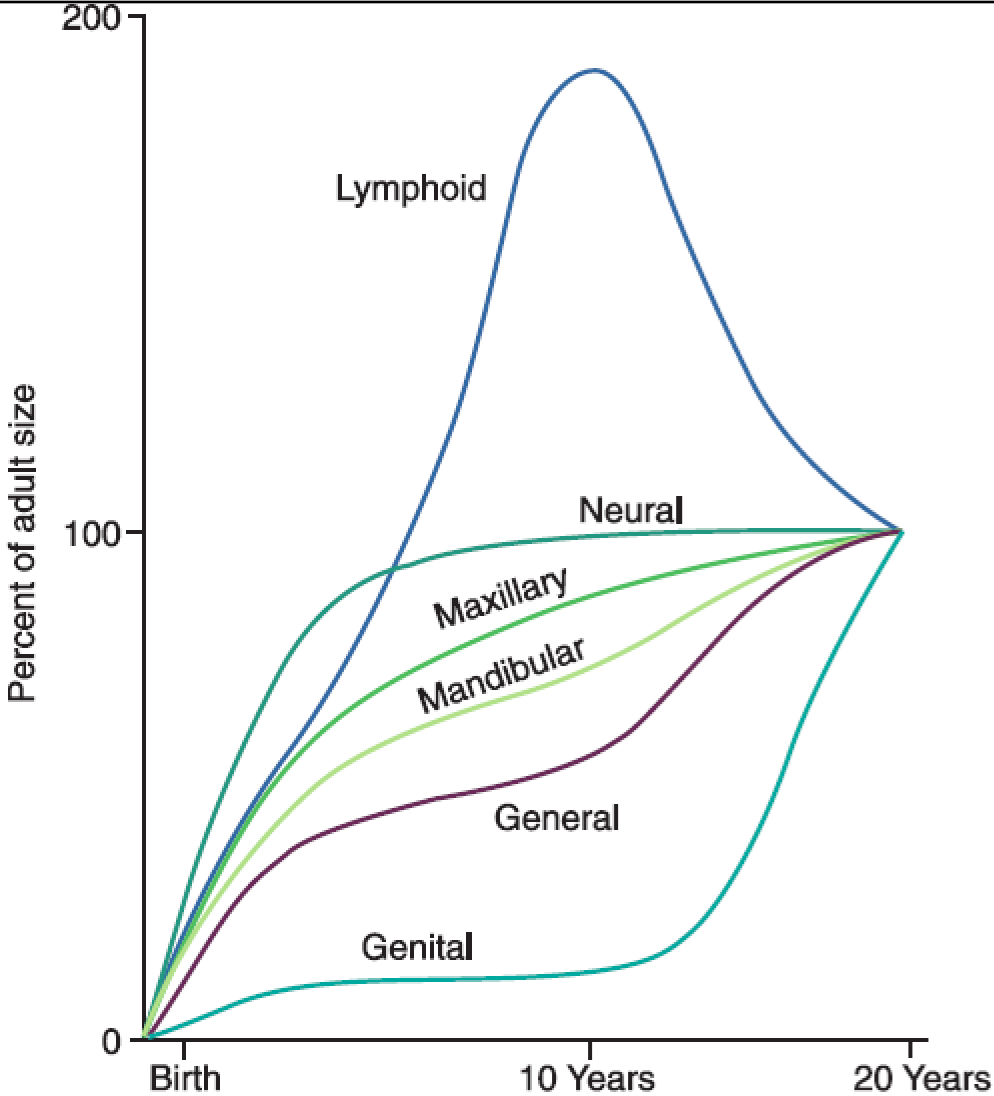

Figure 4.14: Growth Curves for the Maxilla and Mandible with Scammon's Growth Curves

The figure above shows the peak in size of the lymphatic tissue and the decrease to adult size. It also shows the early peak of neural tissue in growth and the delayed peak of genital growth. Maxillary and mandibular growth peak around relatively the same time with the maxilla peaking slightly earlier than the mandible. (Proffit et al., 2013)

CHAPTER 5: RESULTS

All the parameters were measured in the CBCT images obtained at the following time points: pre-expansion (T_1), post-expansion (T_2), pre-orthodontic treatment (T_3), and middle or end of orthodontic treatment (T_4). The parameters measured include nasal floor width (NFW), nasal passage width (NPW), maxillary sinus width (MSW), maxillary first molar palatal root tip width (M1RW), maxillary first molar mesiolingual cusp tip width (M1CW), mean maxillary first molar palatal cortical bone width (M1PW), maxillary first molar buccal cortical bone width (M1BW), interorbital width, and extraorbital width. Parameters were compared based on sex, the number of RPE turns the patient was instructed, cervical vertebral maturation stage at the start of treatment, and age at the start of treatment for all of the time points.

5.1 Pre-Expansion Measurements of the Nasomaxillary Complex on CBCTs (T_1)

All twenty-eight patients had pre-expansion CBCTs on which measurements were made. The average age of patients at T_1 was 9.13 years old. The mean nasal floor width was 28.54mm (SD ± 3.20mm), the mean nasal passage width was 26.31mm (SD ± 2.59mm), the mean maxillary sinus width was 64.39mm (SD ± 6.85mm), the mean maxillary first molar palatal root width was 31.29mm (SD ± 4.06mm), the mean maxillary first molar mesiolingual cusp tip width was 39.17mm (SD ± 3.14mm), the mean maxillary first molar palatal cortical bone width was 27.22mm (SD ± 2.14mm), the mean maxillary first molar buccal cortical bone width was 57.35mm (SD ± 3.65), the mean interorbital width was 21.41mm (SD ± 3.69mm), and the mean extraorbital width was 76.66mm (SD ± 6.86mm). These mean pre-expansion measurements are shown in Figure 5.1. Error bars represent the standard deviation of each measurement group.

Means and standard deviations for each parameter evaluated are shown in Table 5.1 and Figure 5.9. All raw data from each patient are shown in Table B.

5.2 Post-Expansion Measurements of the Nasomaxillary Complex on CBCTs (T_2)

All twenty-eight patients had post-expansion CBCTs on which measurements were made. The average age of patients at T_2 was 10.08 years old. The mean nasal floor width was 29.75mm (SD ± 3.62mm), the mean nasal passage width was 28.02mm (SD ± 2.52mm), the mean maxillary sinus width was 67.31mm (SD ± 6.77mm), the mean maxillary first molar palatal root width was 33.71mm (SD ± 3.07mm), the mean maxillary first molar mesiolingual cusp tip width was 43.76mm (SD ± 3.21mm), the mean maxillary first molar palatal cortical bone width was 30.17mm (SD ± 3.14mm), the mean maxillary first molar buccal cortical bone width was 60.36mm (SD ± 3.36mm), the mean interorbital width was 22.41mm (SD ± 4.74mm), and the mean extraorbital width was 77.65mm (SD ± 6.82mm). These mean post-expansion measurements are shown in Figure 5.1. Error bars represent the standard deviation of each measurement group. Means and standard deviations for each parameter evaluated are shown in Table 5.1 and Figure 5.9. All raw data from each patient are shown in Table C.

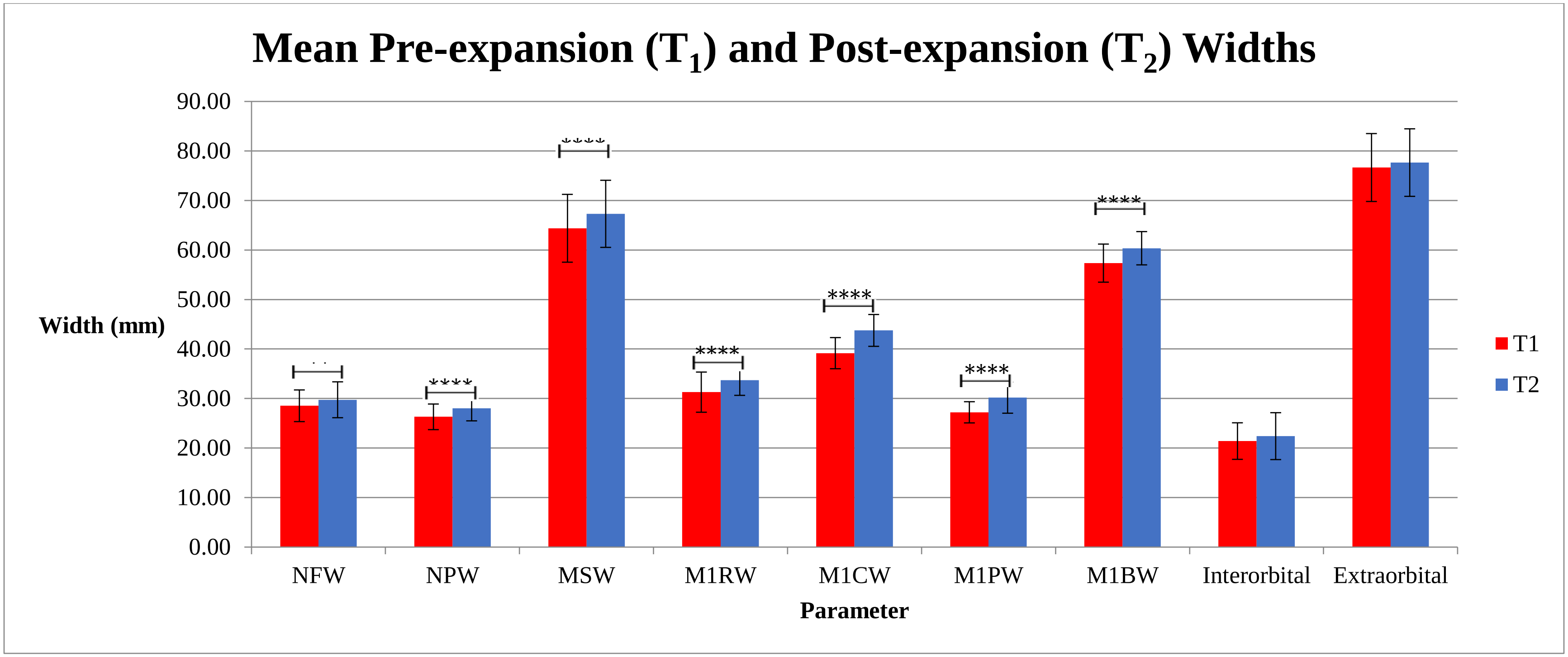

Figure 5.1: Mean Widths of the Nasomaxillary Complex Prior to and After Expansion

(Statistical Significance: * - p ≤0.05; ** - p ≤0.01; *** - p ≤0.001; **** - p ≤0.0001)

Mean widths of the nasomaxillary complex prior to and after expansion are shown above. Nasal floor width (NFW), nasal passage width (NPW), maxillary sinus width (MSW), maxillary first molar palatal root width (M1RW), maxillary first molar mesiolingual cusp width (M1CW), maxillary first molar palatal cortical bone width (M1PW), maxillary first molar buccal cortical bone width (M1BW), interorbital width, and extraorbital width are shown with error bars representing standard deviations. Statistical significance is shown above the bar for each parameter. All parameters increased, but the interorbital and extraorbital increases were not significant.

5.3 Changes between Pre-Expansion and Post-Expansion Measurements (T_1 vs. T_2)

The mean amount of time between the pre-expansion and post-expansion CBCTs was 11.47 months (SD ± 5.01). The average age for patients at T_1 was 9.13 years old versus 10.08 years old at T_2. From the pre-expansion CBCT to the post-expansion CBCT, the mean change in nasal floor width was 1.21mm, the mean change in nasal passage width was 1.71mm, the mean change in maxillary sinus width was 2.92mm, the mean change maxillary first molar palatal root width was 2.42mm, the mean change in maxillary first molar mesiolingual cusp tip width was 4.59mm, the mean change in maxillary first molar palatal cortical bone width was 2.95mm, the mean change in maxillary first molar buccal cortical bone width was 3.01mm, the mean change in interorbital width was 1.00mm, and the mean change in extraorbital width was 1.00mm. Mean changes comparing T_1 and T_2 measurements are shown in Figure 5.2. Error bars represent the standard deviation of each measurement group. The mean number of RPE turns prescribed for each patient was 48.8 turns. For every outcome measured, the width increased from pre-expansion to post-expansion. Standard t-test statistics were used to test for significant differences in the measurements following expansion. The nasal floor width ($p=0.01$), nasal passage width ($p<0.0001$), maxillary sinus width ($p<0.0001$), maxillary first molar palatal root width ($p<0.0001$), maxillary first molar mesiolingual cusp width ($p<0.0001$), maxillary first molar palatal cortical bone width ($p=0.0001$), and maxillary first molar buccal cortical bone width ($p<0.0001$) all significantly increased during rapid palatal expansion. Statistically significant differences were not found for the interorbital and extraorbital widths.

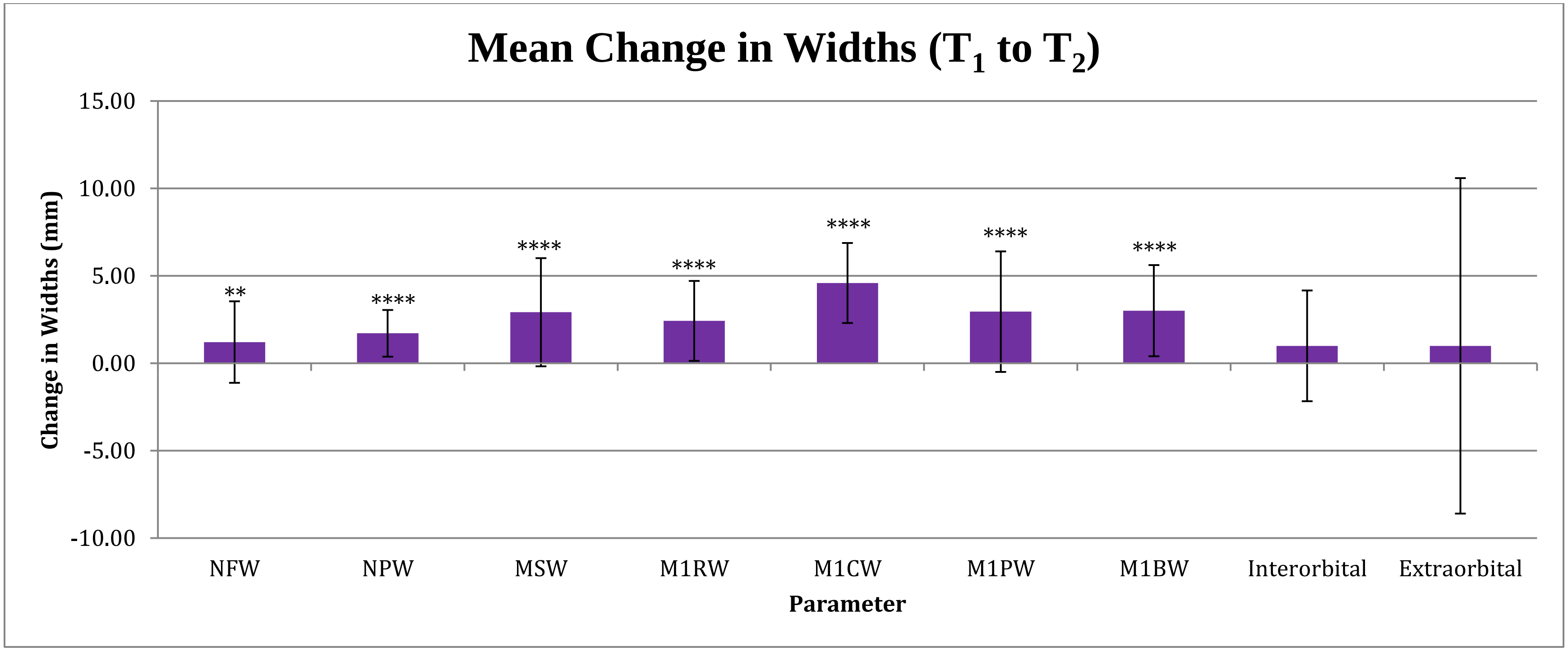

Figure 5.2: Mean Change in the Nasomaxillary Complex Widths from Pre-expansion to Post-expansion

(Statistical Significance: * - p ≤0.05; ** - p ≤0.01; *** - p ≤0.001; **** - p ≤0.0001)

Mean width changes of the nasomaxillary complex from before to after expansion are shown above. Nasal floor width (NFW), nasal passage width (NPW), maxillary sinus width (MSW), maxillary first molar palatal root width (M1RW), maxillary first molar mesiolingual cusp width (M1CW), maxillary first molar palatal cortical bone width (M1PW), maxillary first molar buccal cortical bone width (M1BW), interorbital width, and extraorbital width are shown with error bars representing standard deviations. Statistical significance is shown above the bar for each parameter. All parameters increased, but the interorbital and extraorbital increases were not significant.

5.4 Pre-Orthodontic Measurements of the Nasomaxillary Complex on CBCTs (T_3)

All twenty-eight patients had pre-orthodontic CBCTs on which measurements were made. The average age of patients at T_3 was 11.66 years old. The mean nasal floor width was 30.04mm (SD ± 3.62mm), the mean nasal passage width was 28.45mm (SD ± 2.31mm), the mean maxillary sinus width was 70.01mm (SD ± 6.22mm), the mean maxillary first molar palatal root width was 33.63mm (SD ± 3.57mm), the mean maxillary first molar mesiolingual cusp tip width was 42.61mm (SD ± 6.06mm), the mean maxillary first molar palatal cortical bone width was 30.66mm (SD ± 2.48mm), the mean maxillary first molar buccal cortical bone width was 59.74mm (SD ± 3.31mm), the mean interorbital width was 22.31mm (SD ± 3.97mm), and the mean extraorbital width was 79.83mm (SD ± 6.17mm). These mean pre-orthodontic treatment measurements are shown in Figure 5.3. Error bars represent the standard deviation of each measurement group. Means and standard deviations for each parameter evaluated are shown in Table 5.1 and Figure 5.9. All raw data from each patient are shown in Table D.

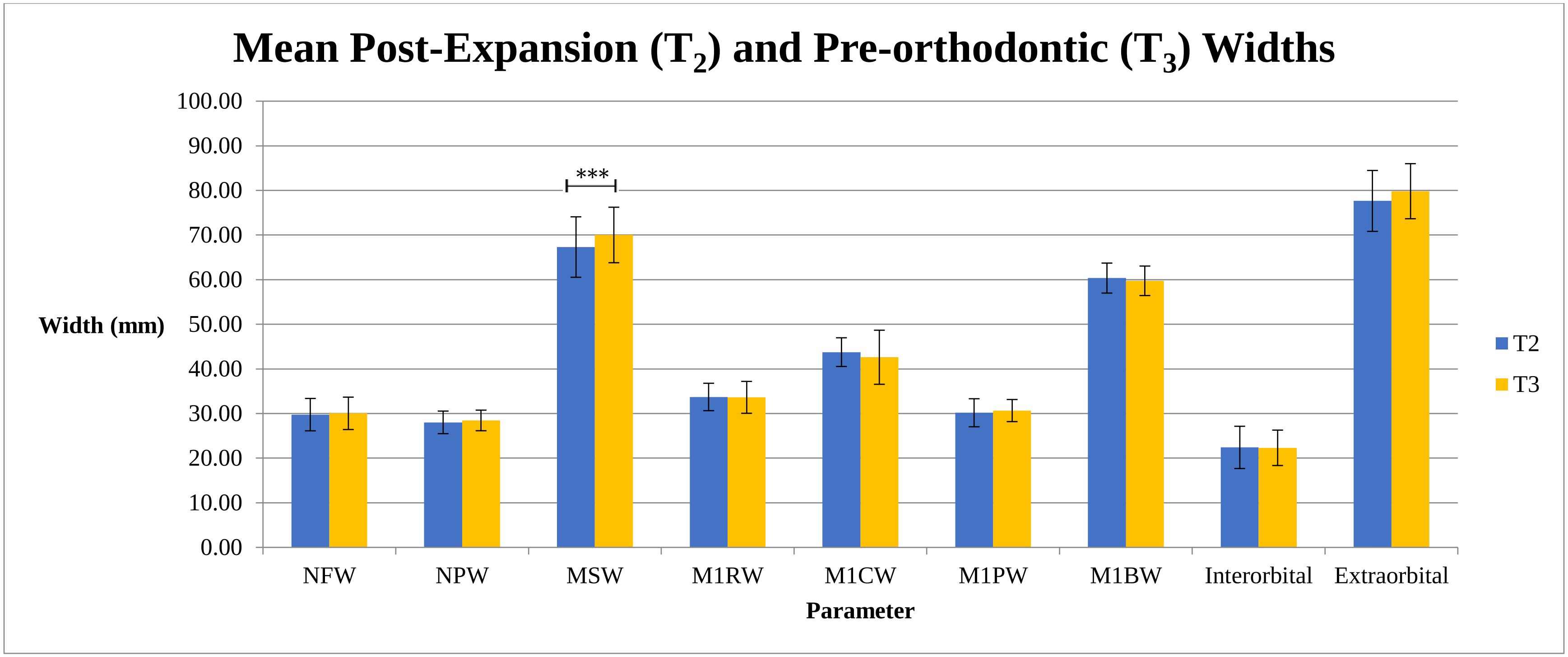

Figure 5.3: Mean Widths of the Nasomaxillary Complex after Expansion and before Orthodontic Treatment

(Significance: * - p ≤0.05; ** - p ≤0.01; *** - p ≤0.001; **** - p ≤0.0001)

Mean widths of the nasomaxillary complex after expansion and prior to orthodontic treatment are shown above. Nasal floor width (NFW), nasal passage width (NPW), maxillary sinus width (MSW), maxillary first molar palatal root width (M1RW), maxillary first molar mesiolingual cusp width (M1CW), maxillary first molar palatal cortical bone width (M1PW), maxillary first molar buccal cortical bone width (M1BW), interorbital width, and extraorbital width are shown with error bars representing standard deviations. Statistical significance is shown above the bar for each parameter. Only the maxillary sinus width increase was significant.

5.5 Changes between Post-Expansion and Pre-Orthodontic Measurements (T_2 vs. T_3)

The mean amount of time between post-expansion and pre-orthodontic treatment CBCTs was 19.00 months (SD ± 8.84). The average age for patients at T_2 was 10.08 years old versus 11.66 years old at T_3. From the post-expansion CBCT to the pre-orthodontic treatment CBCT, the mean change in nasal floor width was 0.29mm, the mean change in nasal passage width was 0.43mm, the mean change in maxillary sinus width was 2.71mm, the mean change maxillary first molar palatal root width was -0.09mm, the mean change in maxillary first molar mesiolingual cusp tip width was -1.15mm, the mean change in maxillary first molar palatal cortical bone width was 0.49mm, the mean change in maxillary first molar buccal cortical bone width was -0.62mm, the mean change in interorbital width was -0.09mm, and the mean change in extraorbital width was 2.18mm. These changes in measurement between T_2 and T_3 measurements are shown in Figure 5.4. Error bars represent the standard deviation of each measurement group. The nasal floor width, nasal passage width, maxillary sinus width, maxillary first molar palatal cortical bone width, and extraorbital measurements all increased during the retention phase between the post-expansion and pre-orthodontic treatment CBCTs. The maxillary first molar palatal root width, maxillary first molar mesiolingual cusp tip width, maxillary first molar buccal cortical bone width, and the interorbital width measurements decreased, or relapsed, during the retention phase between the post-expansion and pre-orthodontic treatment CBCTs, though not significantly. Standard t-test statistics were used to test for significant differences in the measurements following expansion until the beginning of orthodontic treatment. A statistically significant difference was only found for the mean width increase of the maxillary sinus width (p=0.0006) during the retention phase between the post-expansion and pre-orthodontic treatment CBCTs.

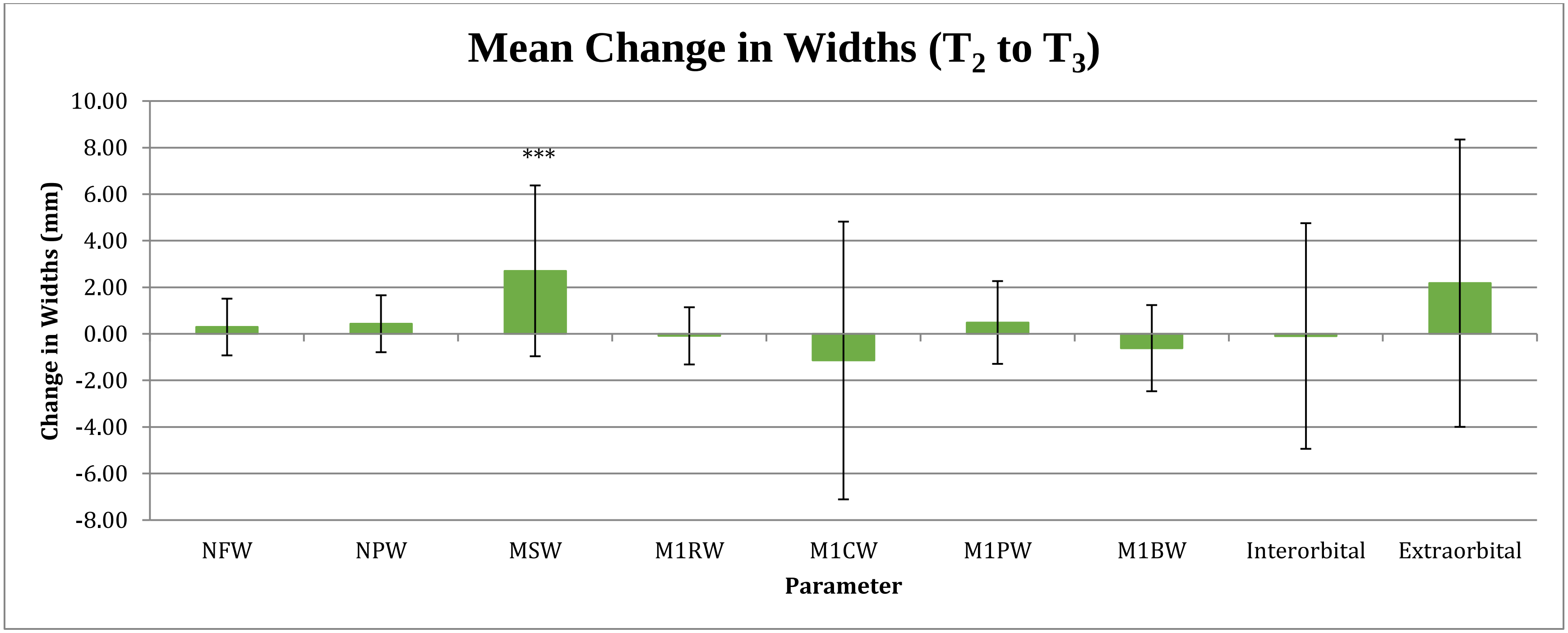

Figure 5.4: Mean Change in the Nasomaxillary Complex Widths from Post-expansion to Pre-orthodontic Treatment

(Significance: * - p $\leq$0.05; ** - p $\leq$0.01; *** - p $\leq$0.001; **** - p $\leq$0.0001)

Mean width changes of the nasomaxillary complex from after expansion to pre-orthodontic treatment are shown above. Nasal floor width (NFW), nasal passage width (NPW), maxillary sinus width (MSW), maxillary first molar palatal root width (M1RW), maxillary first molar mesiolingual cusp width (M1CW), maxillary first molar palatal cortical bone width (M1PW), maxillary first molar buccal cortical bone width (M1BW), interorbital width, and extraorbital width are shown with error bars representing standard deviations. Statistical significance is shown above the bar for each parameter. Only the maxillary sinus width increase was significant.

5.6 Middle or End of Orthodontic Treatment Measurements of the Nasomaxillary Complex on CBCTs (T_4)

Seventeen of the twenty-eight patients had middle-of-orthodontic-treatment or end-of-orthodontic-treatment CBCTs on which measurements were made. Of the seventeen patients who had T_4 CBCTs, the average age was 14.42 years old. For these patients, the average age at T_1 was 9.57 years old, at T_2 was 10.56 years old, and at T_3 was 11.93 years old. All of these mean ages were slightly higher, or older, than that seen when all twenty-eight patients were considered together. All raw data for each patient's age can be found in Table G.

The mean nasal floor width was 29.95mm (SD ± 4.36mm), the mean nasal passage width was 30.03mm (SD ± 2.11mm), the mean maxillary sinus width was 73.84mm (SD ± 5.21mm), the mean maxillary first molar palatal root width was 34.21mm (SD ± 3.23mm), the mean maxillary first molar mesiolingual cusp tip width was 41.72mm (SD ± 2.11mm), the mean maxillary first molar palatal cortical bone width was 31.62mm (SD ± 3.42mm), the mean maxillary first molar buccal cortical bone width was 60.11mm (SD ± 2.50mm), the mean interorbital width was 23.25mm (SD ± 3.93mm), and the mean extraorbital width was 82.23mm (5.33mm). These mean middle or end of orthodontic treatment measurements are shown in Figures 5.5 and 5.6. Error bars represent the standard deviation of each measurement group. Means and standard deviations for each parameter evaluated are shown in Table 5.1 and Figure 5.9. All raw data from each patient are shown in Table E.

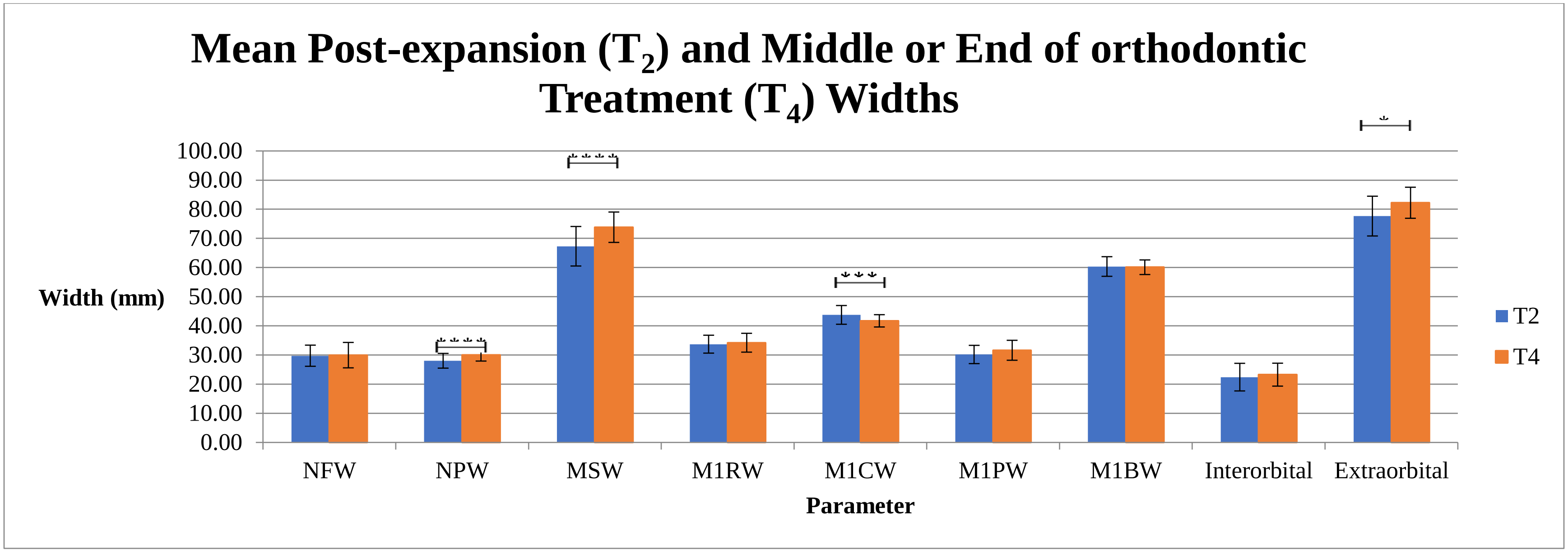

Figure 5.5: Mean Widths of the Nasomaxillary Complex after Expansion and at the Middle or End of Orthodontic Treatment

(Significance: * - p ≤0.05; ** - p ≤0.01; *** - p ≤0.001; **** - p ≤0.0001)

Mean widths of the nasomaxillary complex after expansion and at the middle or end of orthodontic treatment are shown above. Nasal floor width (NFW), nasal passage width (NPW), maxillary sinus width (MSW), maxillary first molar palatal root width (M1RW), maxillary first molar mesiolingual cusp width (M1CW), maxillary first molar palatal cortical bone width (M1PW), maxillary first molar buccal cortical bone width (M1BW), interorbital width, and extraorbital width are shown with error bars representing standard deviations. Statistical significance is shown above the bar for each parameter. Nasal passage width, maxillary sinus width, and extraorbital width statistically significantly increased. Maxillary first molar cusp width significantly decreased. Nasal floor width, root width, and palatal cortical bone width increased, though not significantly. The buccal cortical bone width and interorbital width decreased, though not significantly.

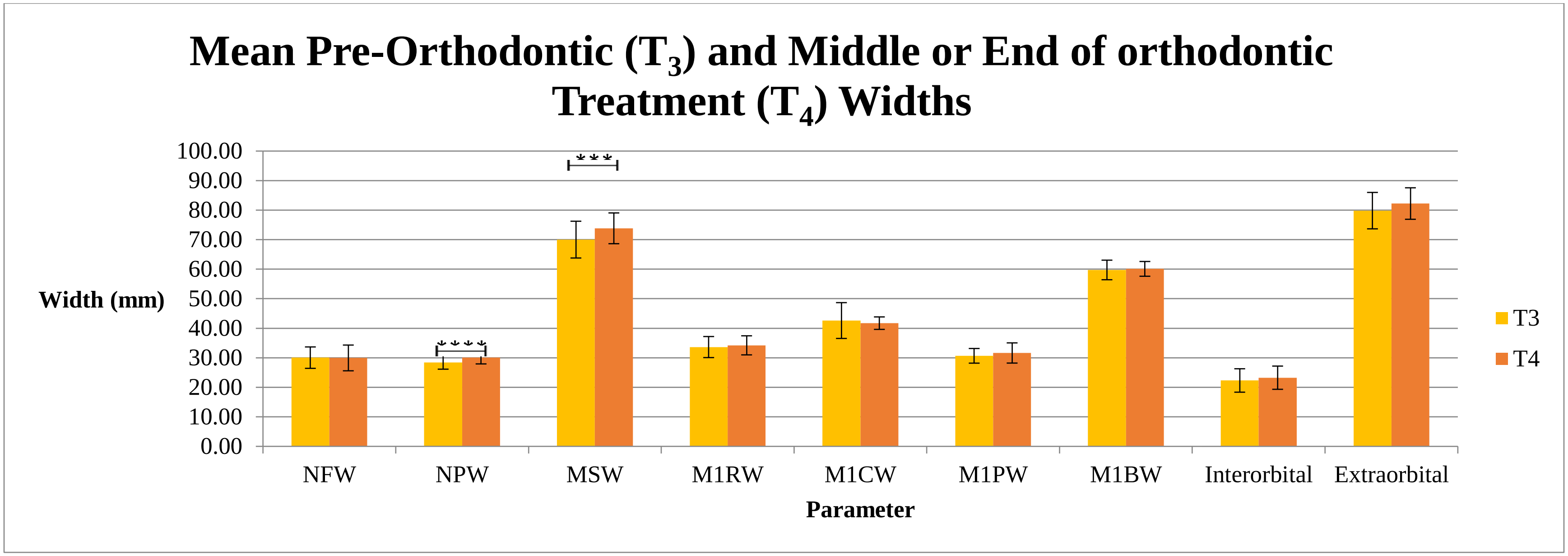

Figure 5.6: Mean Widths of the Nasomaxillary Complex before and at the Middle or End of Orthodontic Treatment

(Significance: * - p ≤0.05; ** - p ≤0.01; *** - p ≤0.001; **** - p ≤0.0001)

Mean widths of the nasomaxillary complex before orthodontic treatment and at the middle or end of orthodontic treatment are shown above. Nasal floor width (NFW), nasal passage width (NPW), maxillary sinus width (MSW), maxillary first molar palatal root width (M1RW), maxillary first molar mesiolingual cusp width (M1CW), maxillary first molar palatal cortical bone width (M1PW), maxillary first molar buccal cortical bone width (M1BW), interorbital width, and extraorbital width are shown with error bars representing standard deviations. Statistical significance is shown above the bar for each parameter. Nasal passage width and maxillary sinus width statistically significantly increased. Nasal floor width, root width, palatal cortical bone width, interorbital width and extraorbital width increased, though not significantly. The cusp width and buccal cortical bone width decreased, though not significantly.

5.7 Changes between Post-expansion and Middle or End of Orthodontic Treatment Measurements (T_2 vs. T_4)

The mean amount of time between the post-expansion and middle or end of orthodontic treatment CBCTs for the seventeen patients that had the middle or end of orthodontic treatment CBCT was 46.43 months (SD ± 12.72). The average age for the seventeen patients at T_2 was 10.56 years old versus 14.42 years old at T_4. From the pre-expansion CBCT to the middle or end of treatment CBCT, the mean change in nasal floor width was 0.49mm, the mean change in nasal passage width was 1.85mm, the mean change in maxillary sinus width was 4.57mm, the mean change maxillary first molar palatal root width was 0.43mm, the mean change in maxillary first molar mesiolingual cusp tip width was -2.54mm, the mean change in maxillary first molar palatal cortical bone width was 1.62mm, the mean change in maxillary first molar buccal cortical bone width was -0.52mm, the mean change in interorbital width was -0.08mm, and the mean change in extraorbital width was 3.12mm for the seventeen patients that had middle or end of treatment CBCTs. These changes comparing T_2 and T_4 measurements are shown in Figure 5.7. Error bars represent the standard error of each measurement group. Overall, from the post-expansion CBCT to the middle or end of treatment CBCT, the nasal floor width, nasal passage width, maxillary sinus width, first molar palatal root width, palatal cortical bone width, and extraorbital width all increased. The maxillary first molar mesiolingual cusp tip width, the maxillary first molar buccal cortical bone width, and the interorbital width decreased, or relapsed, during the time between the post-expansion CBCT and the middle or end of treatment CBCT. Standard t-test statistics were used to test for significant differences in the measurements following expansion until the middle or the end of orthodontic treatment. A statistically significant difference was found for the mean measurement increase of the nasal passage ($p<0.0001$), maxillary sinus width ($p<0.0001$), and extraorbital ($p=0.018$) between the post-expansion and middle or end of orthodontic treatment CBCTs. A statistically significant difference was found for the mean measurement decrease of the maxillary molar cusp tip width ($p=0.0002$) between the post-expansion and middle or end of orthodontic treatment CBCTs.

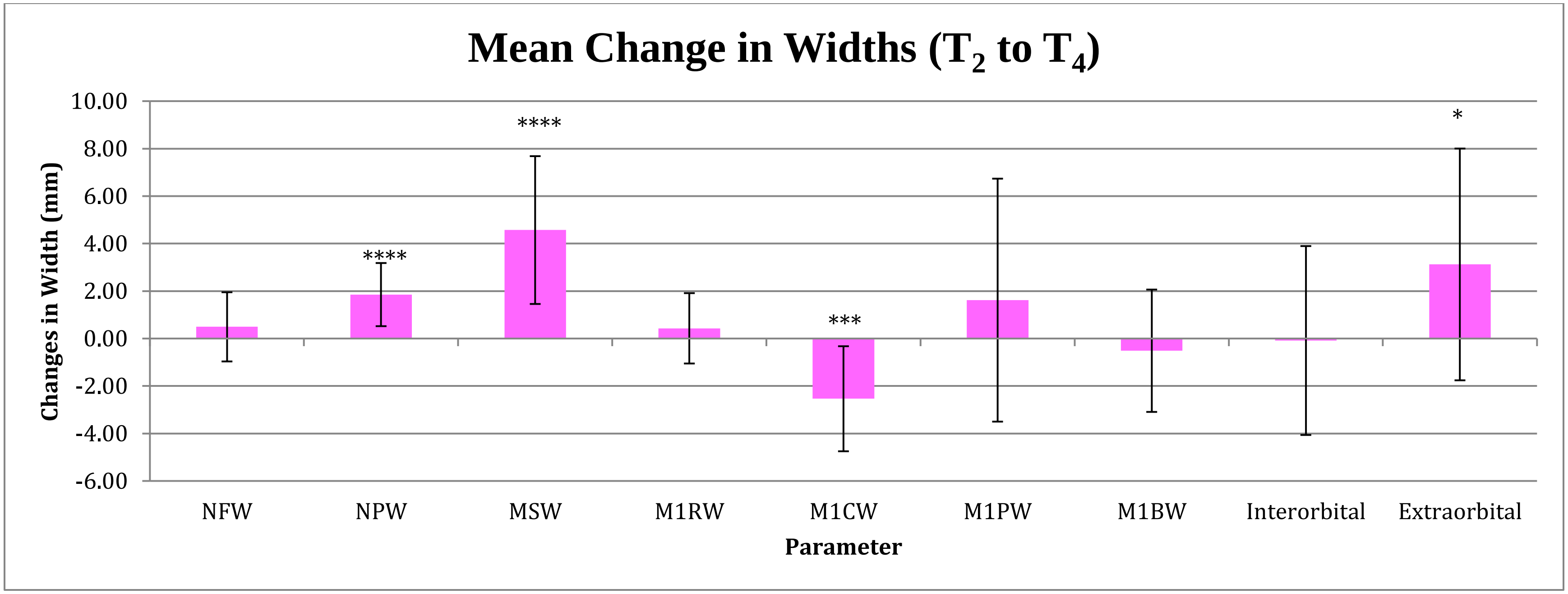

Figure 5.7: Mean Change in the Nasomaxillary Complex Widths from Post-expansion to Middle or End of Orthodontic Treatment

(Significance: * - $p \leq 0.05$; ** - $p \leq 0.01$; *** - $p \leq 0.001$; **** - $p \leq 0.0001$)

Mean width changes of the nasomaxillary complex from after expansion and to pre-orthodontic treatment are shown above. Nasal floor width (NFW), nasal passage width (NPW), maxillary sinus width (MSW), maxillary first molar palatal root width (M1RW), maxillary first molar mesiolingual cusp width (M1CW), maxillary first molar palatal cortical bone width (M1PW), maxillary first molar buccal cortical bone width (M1BW), interorbital width, and extraorbital width are shown with error bars representing standard deviations. Statistical significance is shown above the bar for each parameter. Nasal passage width and maxillary sinus width statistically significantly increased. Nasal floor width, root width, palatal cortical bone width, interorbital width and extraorbital width increased, though not significantly. The cusp width and buccal cortical bone width decreased, though not significantly.

5.8 Changes between Pre-Orthodontic Measurements and Middle or End of Orthodontic Treatment Measurements (T_3 vs. T_4)

The mean amount of time between pre-orthodontic treatment and middle or end of orthodontic treatment CBCTs for the seventeen patients that had the middle or end of orthodontic treatment CBCT was 30.00 months (SD ± 11.34). The average age for the seventeen patients at T_3 was 11.93 years old versus 14.42 years old at T_4. From the pre-orthodontic treatment CBCT to the middle or end of treatment CBCT, the mean change in nasal floor width was 0.16mm, the mean change in nasal passage width was 1.39mm, the mean change in maxillary sinus width was 2.92mm, the mean change in maxillary first molar palatal root width was 0.45mm, the mean change in maxillary first molar mesiolingual cusp tip width was -0.36mm, the mean change in maxillary first molar palatal cortical bone width was 1.13mm, the mean change in maxillary first molar buccal cortical bone width was -0.12mm, the mean change in interorbital width was 1.04mm, and the mean change in extraorbital width was 1.92mm for the seventeen patients that had middle or end of treatment CBCTs. These changes between T_3 and T_4 measurements are shown in Figure 5.8. Error bars represent the standard error of each measurement group. The nasal floor width, nasal passage width, maxillary sinus width, maxillary first molar cortical bone width, interorbital width, and extraorbital width all increased during orthodontic treatment, though only nasal passage width and maxillary sinus width changes were statistically significant. The maxillary first molar mesiolingual cusp tip width and maxillary first molar buccal cortical bone width both decreased (or relapsed) during orthodontic treatment, though this decrease was not statistically significant for either parameter. Standard t-test statistics were used to test for significant differences in the measurements between the start of orthodontic treatment to the middle or end of orthodontic treatment. A statistically significant difference was found for the mean measurement increase of the nasal passage width ($p<0.0001$) and maxillary sinus width ($p=0.0002$) during the orthodontic treatment phase between the pre-orthodontic and middle or end of orthodontic treatment CBCTs.

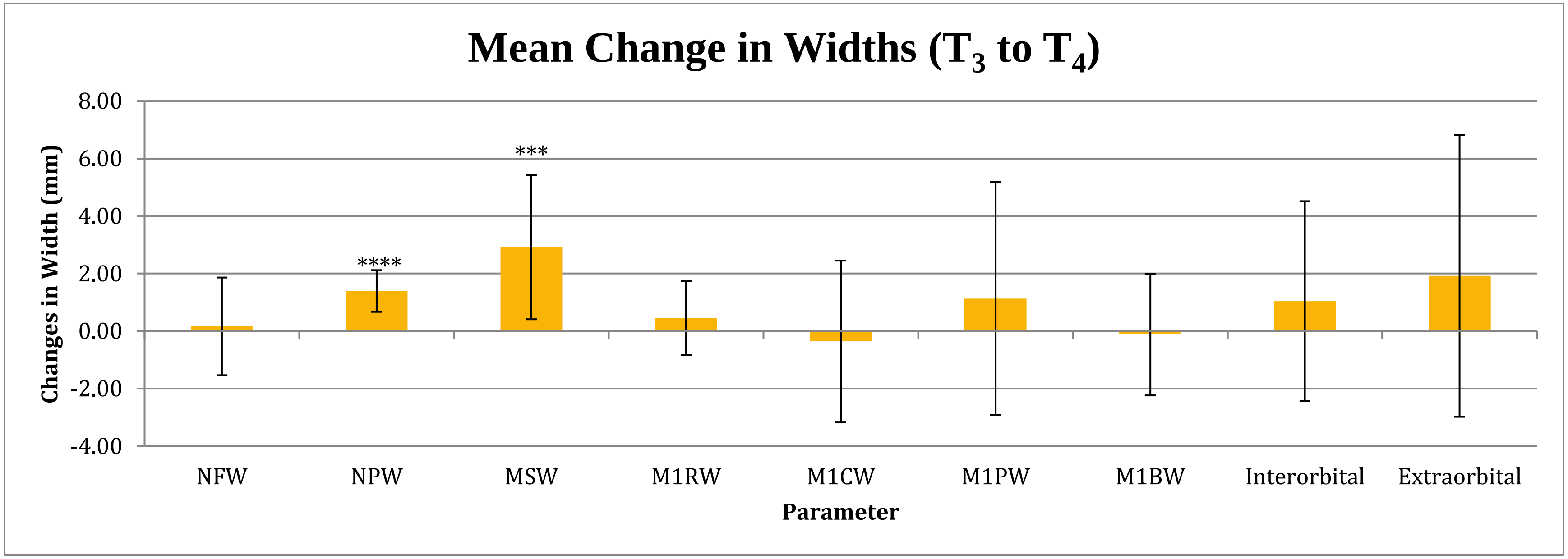

Figure 5.8: Mean Change in the Nasomaxillary Complex Widths from Pre-orthodontic Treatment to Middle or End of Orthodontic Treatment

(Significance: * - p ≤0.05; ** - p ≤0.01; *** - p ≤0.001; **** - p ≤0.0001)

Mean width changes of the nasomaxillary complex from after expansion and to pre-orthodontic treatment are shown above. Nasal floor width (NFW), nasal passage width (NPW), maxillary sinus width (MSW), maxillary first molar palatal root width (M1RW), maxillary first molar mesiolingual cusp width (M1CW), maxillary first molar palatal cortical bone width (M1PW), maxillary first molar buccal cortical bone width (M1BW), interorbital width, and extraorbital width are shown with error bars representing standard deviations. Statistical significance is shown above the bar for each parameter. Nasal passage width and maxillary sinus width statistically significantly increased. Nasal floor width, root width, palatal cortical bone width, interorbital width and extraorbital width increased, though not significantly. The cusp width and buccal cortical bone width decreased, though not significantly.

	T_1		T_2		T_3		T_4	
	Mean (mm)	SD	Mean (mm)	SD	Mean (mm)	SD	Mean (mm)	SD
NFW	28.54	3.20	29.75	3.62	30.04	3.62	29.95	4.36
NPW	26.31	2.59	28.02	2.52	28.45	2.31	30.03	2.11
MSW	64.39	6.85	67.31	6.77	70.01	6.22	73.84	5.21
M1RW	31.29	4.06	33.71	3.07	33.63	3.57	34.21	3.23
M1CW	39.17	3.14	43.76	3.21	42.61	6.06	41.72	2.11
M1PW	27.22	2.14	30.17	3.14	30.66	2.48	31.62	3.42
M1BW	57.35	3.85	60.36	3.36	59.74	3.31	60.11	2.50
Interorbital	21.41	3.69	22.41	4.74	22.31	3.97	23.25	3.93
Extraorbital	76.66	6.86	77.65	6.82	79.83	6.17	82.23	5.33

Table 5.1: Means and Standard Deviations for Each Parameter at Each Time Point

The mean width changes of the nasomaxillary complex for all time points are shown above. Nasal floor width (NFW), nasal passage width (NPW), maxillary sinus width (MSW), maxillary first molar palatal root width (M1RW), maxillary first molar mesiolingual cusp width (M1CW), maxillary first molar palatal cortical bone width (M1PW), maxillary first molar buccal cortical bone width (M1BW), interorbital width, and extraorbital width are shown with the mean width measurements and standard deviations for each time point. Twenty-eight images were evaluated for T_1, T_2, and T_3. Seventeen images were evaluated for T_4.

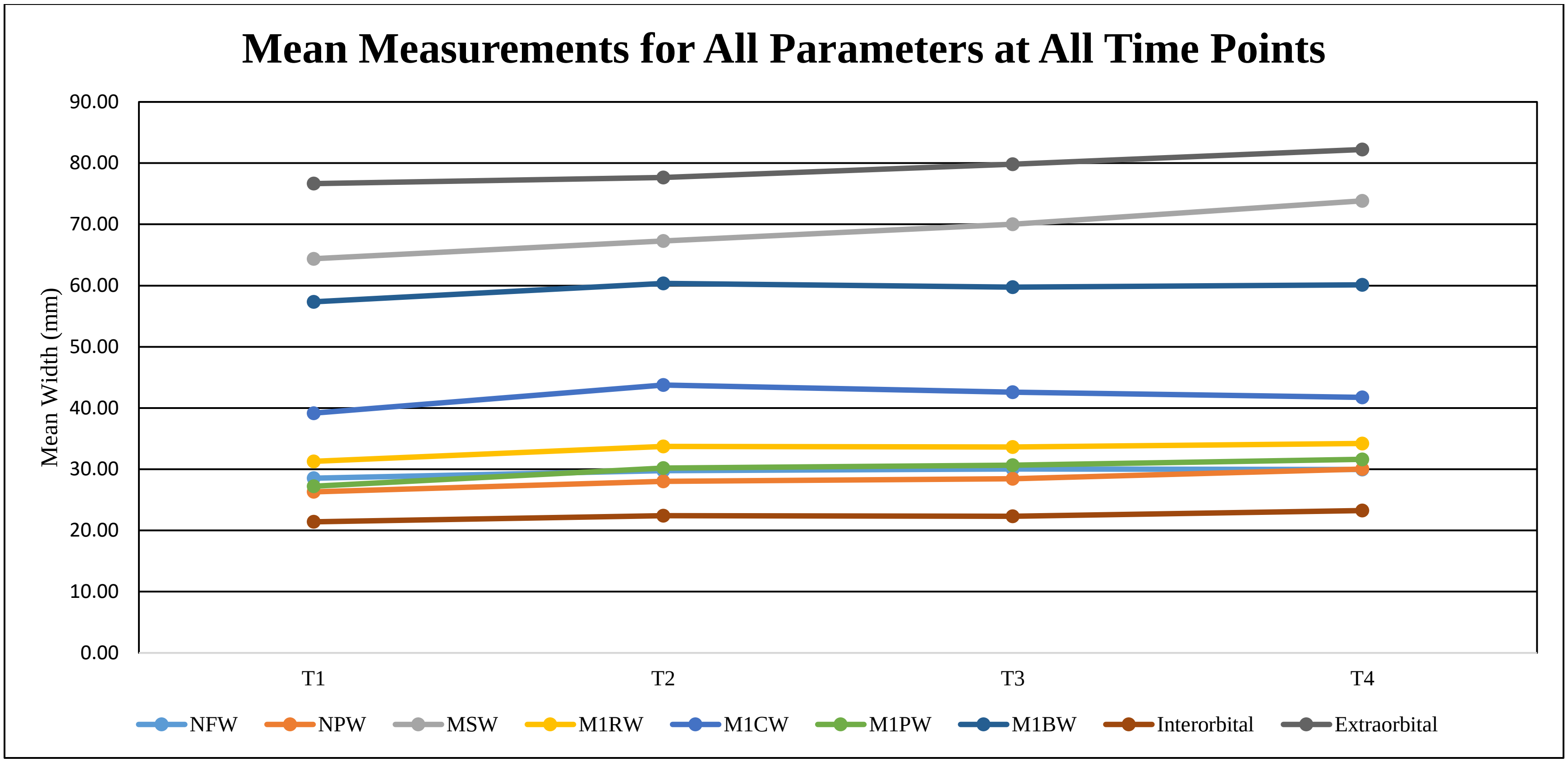

Figure 5.9: Mean Widths of All Parameters at All Time Points

Mean widths of the nasomaxillary complex for all time points are shown above. Nasal floor width (NFW), nasal passage width (NPW), maxillary sinus width (MSW), maxillary first molar palatal root width (M1RW), maxillary first molar mesiolingual cusp width (M1CW), maxillary first molar palatal cortical bone width (M1PW), maxillary first molar buccal cortical bone width (M1BW), interorbital width, and extraorbital width are shown. Twenty-eight images were evaluated for T_1, T_2, and T_3. Seventeen images were evaluated for T_4. The general trends for each parameter can be observed on this graph.

5.9 Comparisons by Cervical Vertebrae Maturation Stage (CVMS) As Recorded Pre-Expansion (T_1)

CVMS was also measured for T_1, T_2, T_3, and T_4. At T_1, all patients had CVMS I or II, indicating that the pubertal growth spurt has not yet occurred. Specifically, at T_1, the average age was 9.13 years old, and twenty-two patients had CVMS I, and six patients had CVMS II. At T_2, the average age was 10.08 years old, and twelve patients were CVMS I, fifteen patients were CVMS II, and one patient was CVMS III. At T_3, the average age was 11.66 years old, and two patients were CVMS I, twelve were CVMS II, thirteen were CVMS III, and one was CVMS IV. For the seventeen patients with a T_4 CBCT, the average age was 14.41 years old, and five patients were CVMS III, and twelve patients were CVMS IV. This meant that for all of the seventeen patients with T_4 CBCTs, the pubertal growth peak had already occurred based on their CVMS. All raw data for CVMS can be found in Table G.

CVMS as evaluated on the pre-expansion (T_1) CBCT was correlated to changes in width measurements. Mean changes in width comparing CVMS I and CVMS II for each parameter are shown in Figures 5.10-13. Error bars represent the standard deviation of each measurement. Standard t-test statistics were used to test the differences in the measurements at all four time points. A statistically significant difference was found only for extraorbital width changes from T_3 to T_4. The CVMS I patients had 0.55 mm increased width from T_3 to T_4, whereas the CVMS II patients had 6.37 mm increased width from T_3 to T_4 ($p<0.05$). Means and standard deviations for each time point change and the parameter are shown in Table 5.2.

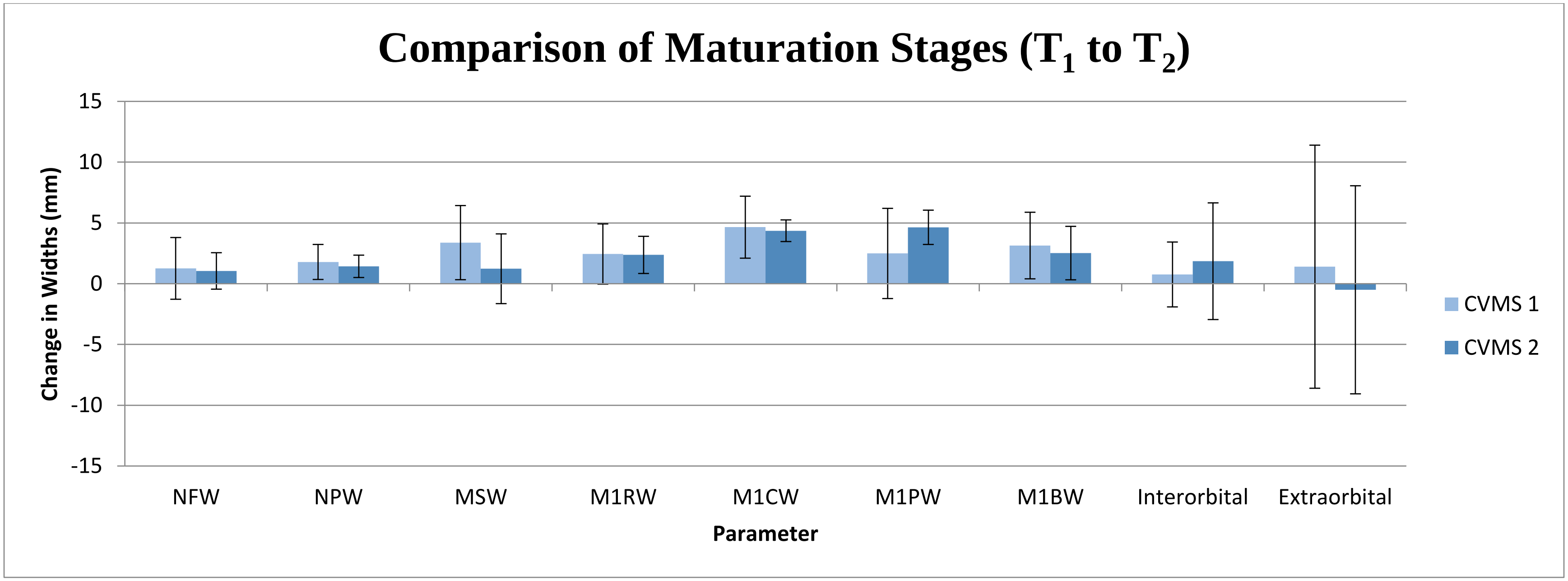

Figure 5.10: Comparison of the Mean Changes in the Nasomaxillary Complex Widths from Pre-expansion to Post-expansion for Each Parameter for CVMS I and II Patients

(Significance: * - p ≤0.05; ** - p ≤0.01; *** - p ≤0.001; **** - p ≤0.0001)

Mean width changes of the nasomaxillary complex from before expansion to after expansion are shown above. Nasal floor width (NFW), nasal passage width (NPW), maxillary sinus width (MSW), maxillary first molar palatal root width (M1RW), maxillary first molar mesiolingual cusp width (M1CW), maxillary first molar palatal cortical bone width (M1PW), maxillary first molar buccal cortical bone width (M1BW), interorbital width, and extraorbital width are shown with error bars representing standard deviations. Statistical significance is shown above the bar for each parameter. Between the patients who were CVMS I and CVMS II, there were no statistically significant differences in the mean changes from T_1 to T_2. All parameters had positive change in widths, except the CVMS II extraorbital width change.

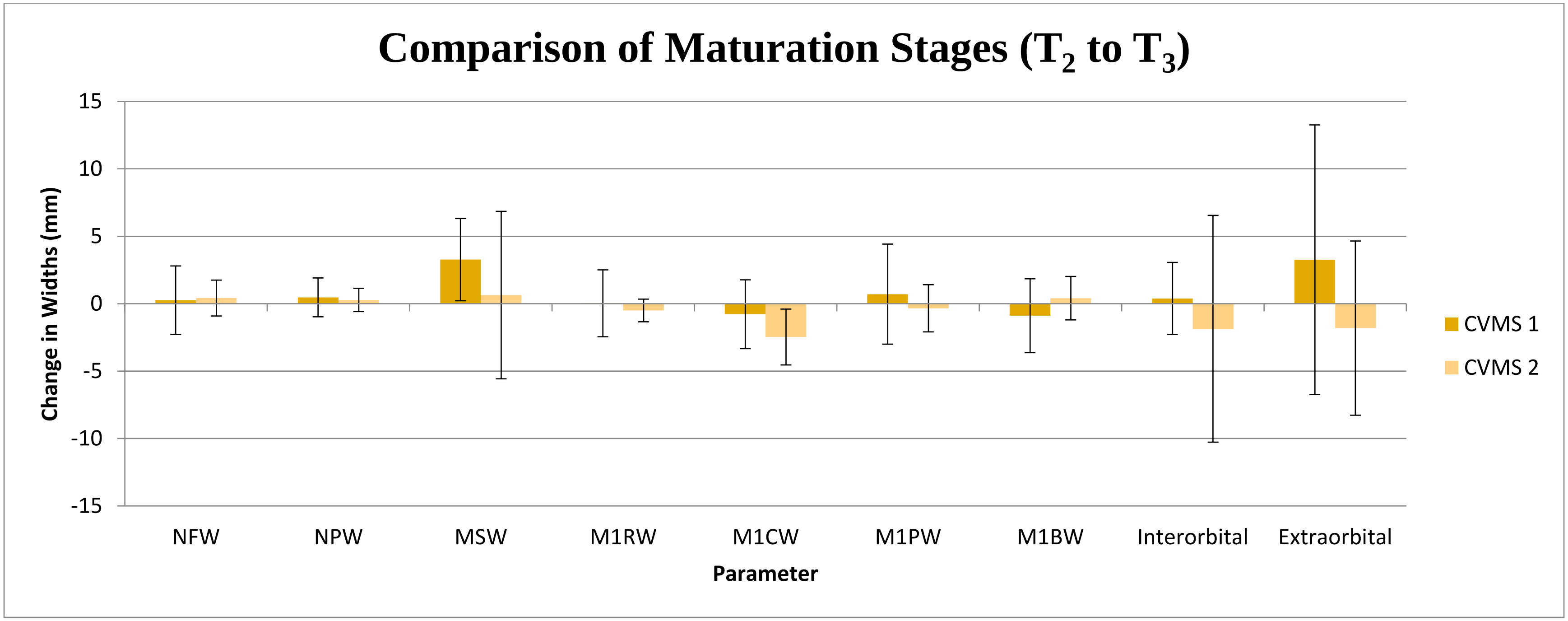

Figure 5.11: Comparison of the Mean Changes in the Nasomaxillary Complex Widths from Post-expansion to Pre-orthodontic Treatment for Each Parameter for CVMS I and CVMS II

(Significance: * - p ≤0.05; ** - p ≤0.01; *** - p ≤0.001; **** - p ≤0.0001)

Mean width changes of the nasomaxillary complex from after expansion to before orthodontic treatment are shown above. Nasal floor width (NFW), nasal passage width (NPW), maxillary sinus width (MSW), maxillary first molar palatal root width (M1RW), maxillary first molar mesiolingual cusp width (M1CW), maxillary first molar palatal cortical bone width (M1PW), maxillary first molar buccal cortical bone width (M1BW), interorbital width, and extraorbital width are shown with error bars representing standard deviations. Statistical significance is shown above the bar for each parameter. Between the patients who were CVMS I and CVMS II, there were no statistically significant differences in the mean changes from T_2 to T_3.

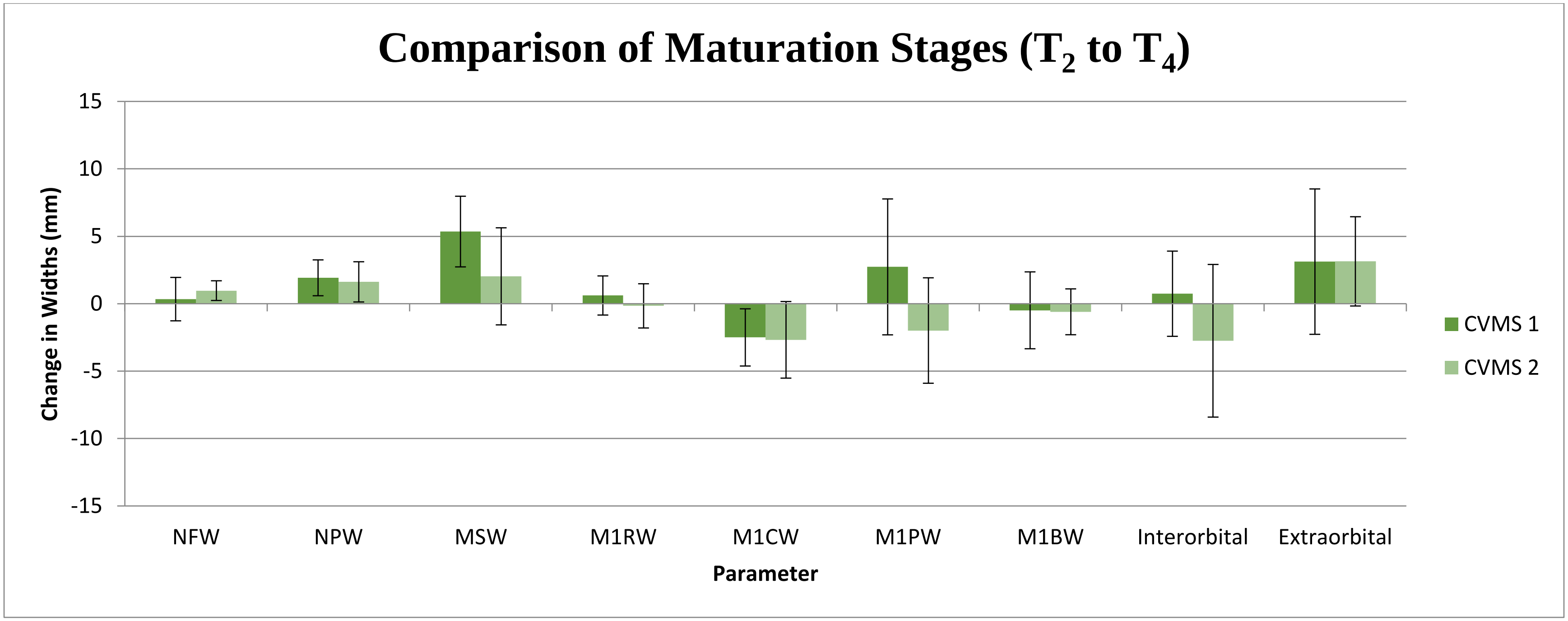

Figure 5.12: Comparison of the Mean Changes in the Nasomaxillary Complex Widths from Post-expansion to Middle or End of Orthodontic Treatment for Each Parameter for CVMS I and CVMS II

(Significance: * - $p \leq 0.05$; ** - $p \leq 0.01$; *** - $p \leq 0.001$; **** - $p \leq 0.0001$)

Mean width changes of the nasomaxillary complex from after expansion to the middle or end of orthodontic treatment are shown above. Nasal floor width (NFW), nasal passage width (NPW), maxillary sinus width (MSW), maxillary first molar palatal root width (M1RW), maxillary first molar mesiolingual cusp width (M1CW), maxillary first molar palatal cortical bone width (M1PW), maxillary first molar buccal cortical bone width (M1BW), interorbital width, and extraorbital width are shown with error bars representing standard deviations. Statistical significance is shown above the bar for each parameter. Between the patients who were CVMS I and CVMS II, there were no statistically significant differences in the mean changes from T_2 to T_4.

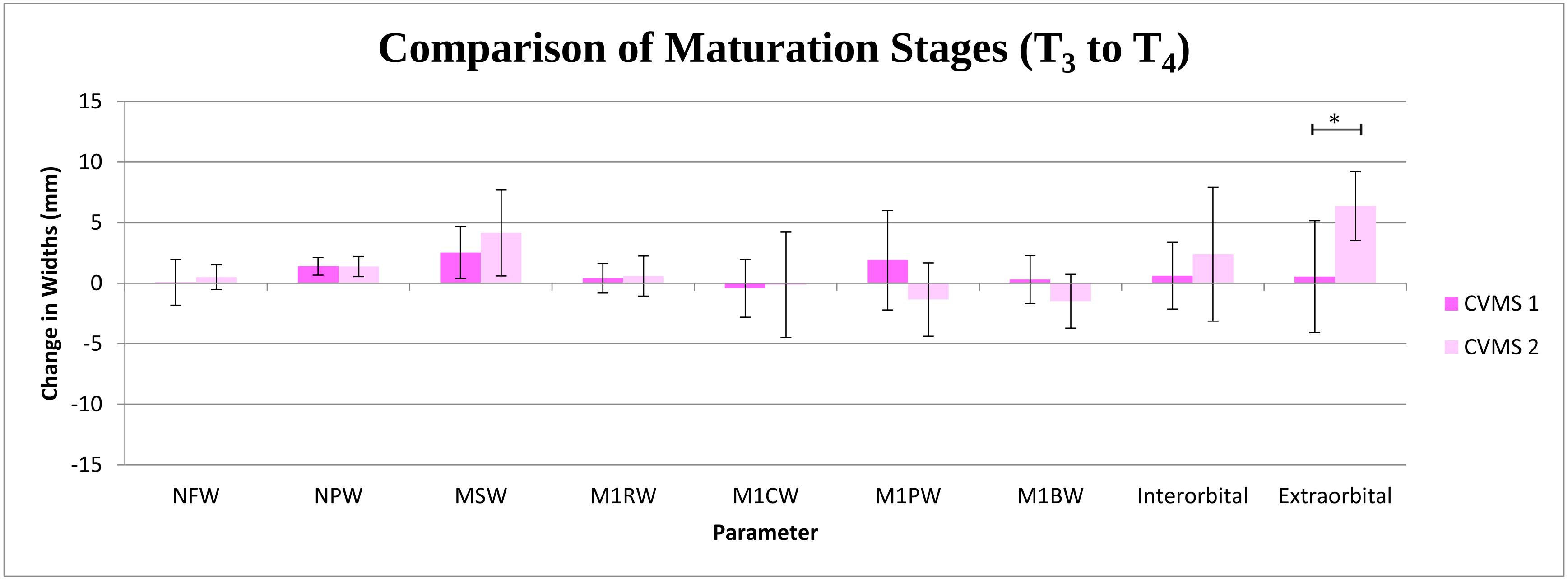

Figure 5.13: Comparison of the Mean Changes in the Nasomaxillary Complex Widths from Pre-orthodontic Treatment to Middle or End of Orthodontic Treatment for Each Parameter for CVMS I and CVMS II

(Significance: * - $p \leq 0.05$; ** - $p \leq 0.01$; *** - $p \leq 0.001$; **** - $p \leq 0.0001$)

Mean width changes of the nasomaxillary complex from before orthodontic treatment to the middle or after orthodontic treatment are shown above. Nasal floor width (NFW), nasal passage width (NPW), maxillary sinus width (MSW), maxillary first molar palatal root width (M1RW), maxillary first molar mesiolingual cusp width (M1CW), maxillary first molar palatal cortical bone width (M1PW), maxillary first molar buccal cortical bone width (M1BW), interorbital width, and extraorbital width are shown with error bars representing standard deviations. Statistical significance is shown above the bar for each parameter. Between the patients who were CVMS I and CVMS II, only the mean changes of the extraorbital widths were statistically significantly different from T_3 to T_4.

		CVMS I		CVMS II		
Measurement	Time	Mean	SD	Mean	SD	p-value
NFW	T_1 vs. T_2	1.23	2.54	1.05	1.50	0.852
	T_2 vs. T_3	0.26	1.22	0.42	1.33	0.777
	T_2 vs. T_4	0.34	1.61	0.97	0.73	0.469
	T_3 vs. T_4	0.06	1.88	0.50	1.02	0.665
NPW	T_1 vs. T_2	1.79	1.44	1.43	0.92	0.573
	T_2 vs. T_3	0.47	1.32	0.28	0.86	0.740
	T_2 vs. T_4	1.92	1.33	1.62	1.49	0.703
	T_3 vs. T_4	1.40	0.73	1.38	0.83	0.974
MSW	T_1 vs. T_2	3.38	3.05	1.23	2.87	0.133
	T_2 vs. T_3	3.27	2.56	0.64	6.21	0.122
	T_2 vs. T_4	5.35	2.62	2.03	3.60	0.059
	T_3 vs. T_4	2.54	2.14	4.15	3.55	0.275
M1RW	T_1 vs. T_2	2.44	2.48	2.37	1.53	0.950
	T_2 vs. T_3	0.03	1.31	-0.50	0.84	0.363
	T_2 vs. T_4	0.61	1.45	-0.16	1.64	0.380
	T_3 vs. T_4	0.41	1.22	0.59	1.66	0.819
M1CW	T_1 vs. T_2	4.65	2.55	4.36	0.89	0.783
	T_2 vs. T_3	-0.78	6.64	-2.47	2.07	0.550
	T_2 vs. T_4	-2.50	2.12	-2.68	2.84	0.892
	T_3 vs. T_4	-0.42	2.39	-0.13	4.35	0.863
M1PW	T_1 vs. T_2	2.49	3.71	4.64	1.41	0.181
	T_2 vs. T_3	0.71	1.76	-0.34	1.75	0.204
	T_2 vs. T_4	2.73	5.04	-1.99	3.91	0.109
	T_3 vs. T_4	1.90	4.11	-1.35	3.03	0.168
M1BW	T_1 vs. T_2	3.14	2.74	2.52	2.20	0.617
	T_2 vs. T_3	-0.09	1.85	0.41	1.61	0.129
	T_2 vs. T_4	-0.49	2.85	-0.60	1.70	0.945
	T_3 vs. T_4	0.30	1.98	-1.49	2.22	0.144
Interorbital	T_1 vs. T_2	0.76	2.67	1.85	4.80	0.469
	T_2 vs. T_3	0.39	3.49	-1.86	8.41	0.323
	T_2 vs. T_4	0.74	3.16	-2.75	5.66	0.129
	T_3 vs. T_4	0.62	2.76	2.40	5.53	0.390
Extraorbital	T_1 vs. T_2	1.40	10.00	-0.50	8.56	0.675
	T_2 vs. T_3	3.26	5.77	-1.81	6.46	0.074
	T_2 vs. T_4	3.12	5.39	3.14	3.31	0.994
	T_3 vs. T_4	0.55	4.62	6.37	2.85	0.033*

Table 5.2: Comparison of Outcomes by Maturation
(Significance: * - $p \leq 0.05$; ** - $p \leq 0.01$; *** - $p \leq 0.001$)

Mean width changes of the nasomaxillary complex for all time points are shown above. Nasal floor width (NFW), nasal passage width (NPW), maxillary sinus width (MSW), maxillary first molar palatal root width (M1RW), maxillary first molar mesiolingual cusp width (M1CW), maxillary first molar palatal cortical bone width (M1PW), maxillary first molar buccal cortical bone width (M1BW), interorbital width, and extraorbital width are shown with standard deviations. Twenty-eight images were evaluated for T_1 vs. T_2 and T_2 vs. T_3. Seventeen images were evaluated for T_2 vs. T_4 and T_3 vs. T_4. Between the patients who were CVMS I and CVMS II, only the mean changes of the extraorbital widths were statistically significantly different from T_3 to T_4.

5.10 Comparisons by Sex

The average age for all patients at T_1 was 9.13 years old. The average age for males was 9.30 years old and females was 9.03 years old at T_1. Mean changes in width comparing males and females for each parameter are found in Figures 5.14-17. Error bars represent the standard deviation of each measurement. Standard t-test statistics were used to test the differences in the measurements at all four time points. Statistically significant differences were found for nasal floor width, nasal passage width, and interorbital width changes from T_1 to T_2. Males had 2.52 mm positive change in nasal floor width, 2.54 mm positive change in nasal passage width, and 2.75 mm positive change in interorbital width, whereas females had 0.49 mm, 1.25 mm, and 0.02mm positive change, respectively, differing significantly ($p<0.05$). Males had significantly greater increases than females for the above-listed width changes from T_1 to T_2. This difference was not due to males being prescribed more turns as males were prescribed 40.4 turns and females were prescribed 54.3 turns on average. Means and standard deviations for each time point's change and the parameter are shown in Table 5.3.

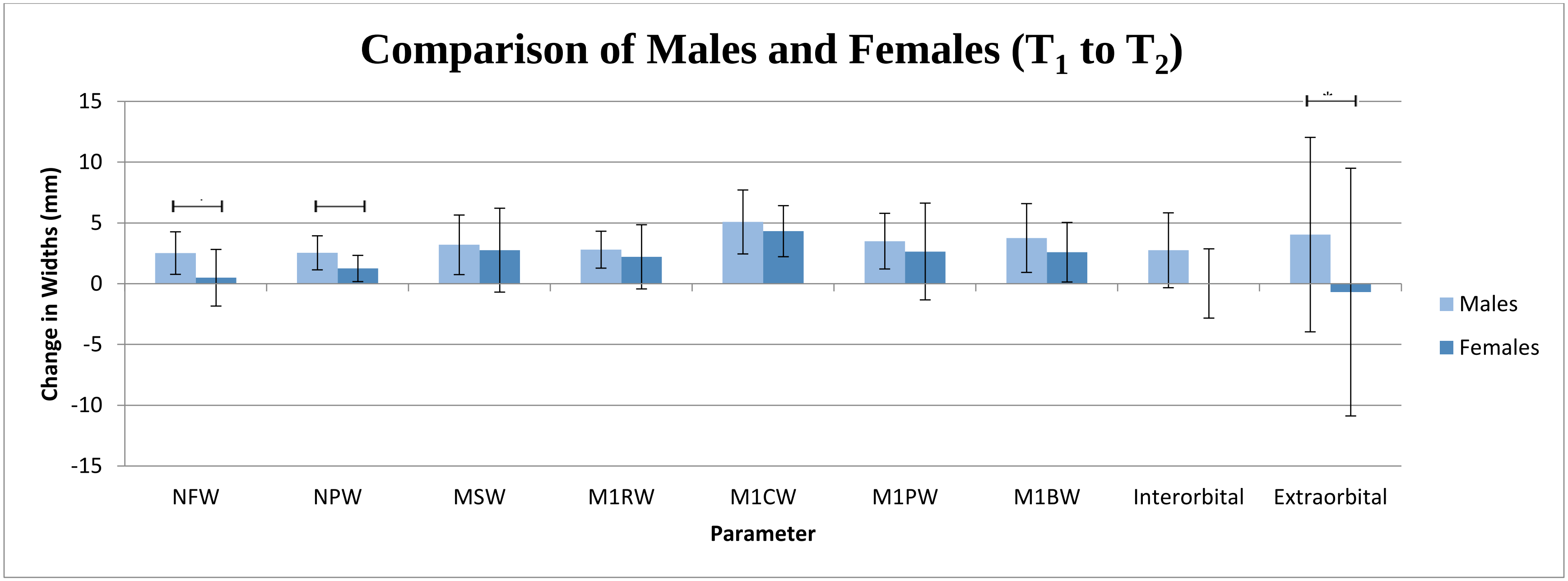

Figure 5.14: Comparison of the Mean Changes in the Nasomaxillary Complex Widths from Pre-expansion to Post-expansion for Male and Female Patients

(Significance: * - p ≤0.05; ** - p ≤0.01; *** - p ≤0.001; **** - p ≤0.0001)

Mean width changes of the nasomaxillary complex from before expansion to after expansion are shown above. Nasal floor width (NFW), nasal passage width (NPW), maxillary sinus width (MSW), maxillary first molar palatal root width (M1RW), maxillary first molar mesiolingual cusp width (M1CW), maxillary first molar palatal cortical bone width (M1PW), maxillary first molar buccal cortical bone width (M1BW), interorbital width, and extraorbital width are shown with error bars representing standard deviations. Statistical significance is shown above the bar for each parameter. For all parameters, males had a larger positive increase in width, though not all were statistically significant. Between the male and females, the mean changes of the nasal floor widths, nasal passage widths, and the extraorbital widths were statistically significantly different from T_1 to T_2.

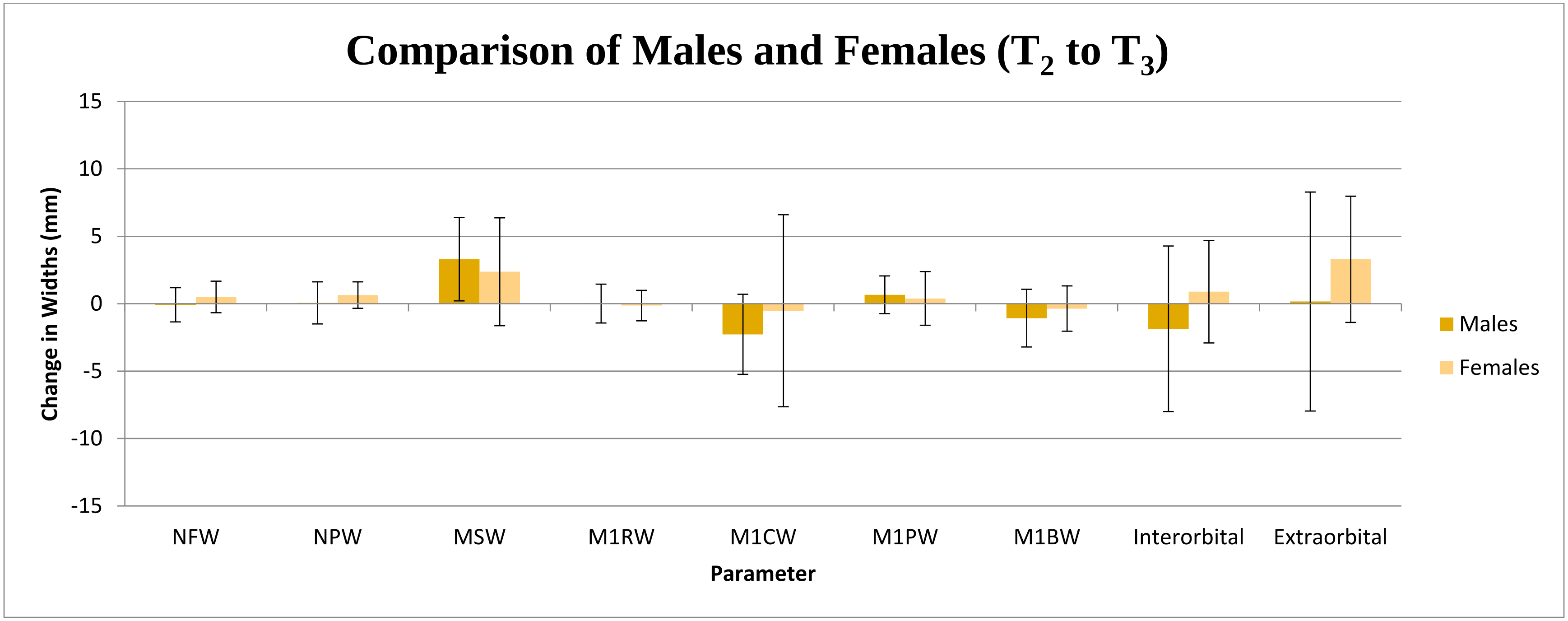

Figure 5.15: Comparison of the Mean Changes in the Nasomaxillary Complex Widths from Post-expansion to Pre-orthodontic Treatment for Male and Female Patients

(Significance: * - p ≤0.05; ** - p ≤0.01; *** - p ≤0.001; **** - p ≤0.0001)

Mean width changes of the nasomaxillary complex from after expansion to before orthodontic treatment are shown above. Nasal floor width (NFW), nasal passage width (NPW), maxillary sinus width (MSW), maxillary first molar palatal root width (M1RW), maxillary first molar mesiolingual cusp width (M1CW), maxillary first molar palatal cortical bone width (M1PW), maxillary first molar buccal cortical bone width (M1BW), interorbital width, and extraorbital width are shown with error bars representing standard deviations. Statistical significance is shown above the bar for each parameter. Between the male and females, none of the mean changes were statistically significantly different from T_2 to T_3.

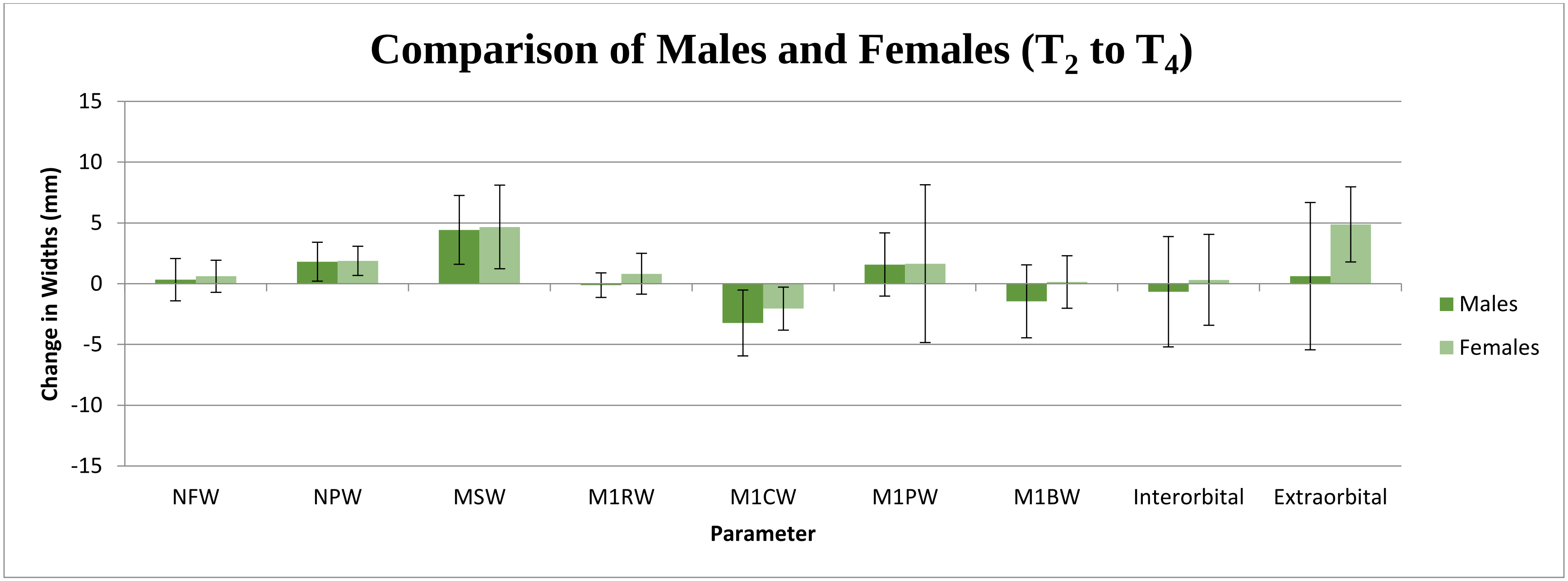

Figure 5.16: Comparison of the Mean Changes in the Nasomaxillary Complex Widths from Post-expansion to Middle or End of Orthodontic Treatment for Male and Female patients

(Significance: * - p ≤0.05; ** - p ≤0.01; *** - p ≤0.001; **** - p ≤0.0001)

Mean width changes of the nasomaxillary complex from after expansion to the middle or end of orthodontic treatment are shown above. Nasal floor width (NFW), nasal passage width (NPW), maxillary sinus width (MSW), maxillary first molar palatal root width (M1RW), maxillary first molar mesiolingual cusp width (M1CW), maxillary first molar palatal cortical bone width (M1PW), maxillary first molar buccal cortical bone width (M1BW), interorbital width, and extraorbital width are shown with error bars representing standard deviations. Statistical significance is shown above the bar for each parameter. Between the male and females, none of the mean changes were statistically significantly different from T_2 to T_4. For all parameters, males had greater increases or lesser decreases from T_2 to T_4.

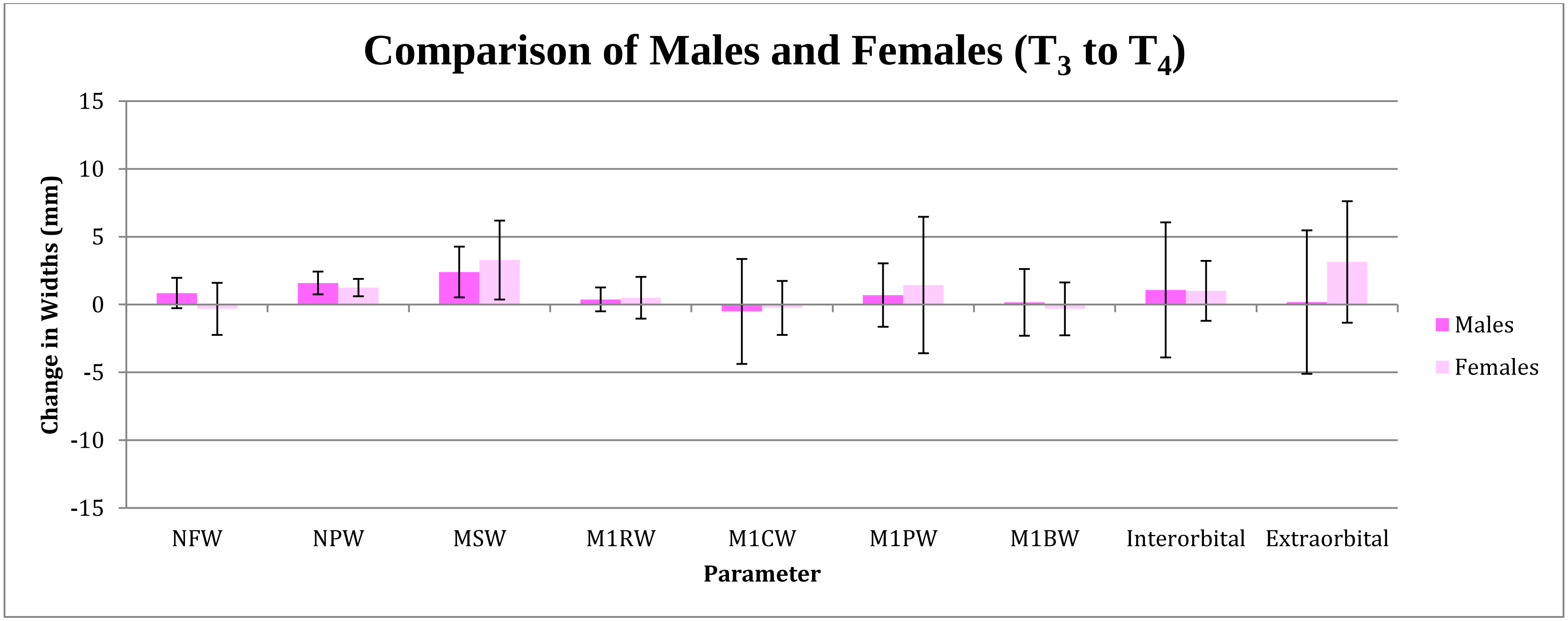

Figure 5.17: Comparison of the Mean Changes in the Nasomaxillary Complex Widths from Pre-orthodontic Treatment to Middle or End of Orthodontic Treatment for Male and Female Patients

(Significance: * - p ≤0.05; ** - p ≤0.01; *** - p ≤0.001; **** - p ≤0.0001)

Mean width changes of the nasomaxillary complex from before orthodontic treatment to the middle or after orthodontic treatment are shown above. Nasal floor width (NFW), nasal passage width (NPW), maxillary sinus width (MSW), maxillary first molar palatal root width (M1RW), maxillary first molar mesiolingual cusp width (M1CW), maxillary first molar palatal cortical bone width (M1PW), maxillary first molar buccal cortical bone width (M1BW), interorbital width, and extraorbital width are shown with error bars representing standard deviations. Statistical significance is shown above the bar for each parameter. Between the male and females, none of the mean changes were statistically significantly different from T_3 to T_4.

		Males		Females		
Measurement	Time	Mean	SD	Mean	SD	p-value
NFW	T_1 vs. T_2	2.52	1.75	0.49	2.33	0.024*
	T_2 vs. T_3	-0.08	1.27	0.50	1.17	0.235
	T_2 vs. T_4	0.33	1.74	0.61	1.32	0.707
	T_3 vs. T_4	0.85	1.12	-0.32	1.92	0.173
NPW	T_1 vs. T_2	2.54	1.40	1.25	1.08	0.012*
	T_2 vs. T_3	0.06	1.56	0.64	0.98	0.235
	T_2 vs. T_4	1.81	1.60	1.88	1.20	0.916
	T_3 vs. T_4	1.59	0.84	1.25	0.64	0.359
MSW	T_1 vs. T_2	3.20	2.45	2.76	3.45	0.726
	T_2 vs. T_3	3.30	3.09	2.37	4.00	0.532
	T_2 vs. T_4	4.43	2.83	4.67	3.44	0.882
	T_3 vs. T_4	2.40	1.87	3.28	2.91	0.494
M1RW	T_1 vs. T_2	2.80	1.52	2.21	2.64	0.527
	T_2 vs. T_3	0.01	1.44	-0.14	1.13	0.771
	T_2 vs. T_4	-0.12	1.01	0.82	1.68	0.209
	T_3 vs. T_4	0.38	0.88	0.50	1.54	0.851
M1CW	T_1 vs. T_2	5.08	2.63	4.32	2.10	0.406
	T_2 vs. T_3	-2.27	2.97	-0.52	7.12	0.469
	T_2 vs. T_4	-3.23	2.71	-2.05	1.77	0.293
	T_3 vs. T_4	-0.51	3.87	-0.25	1.99	0.857
M1PW	T_1 vs. T_2	3.50	2.29	2.65	3.98	0.539
	T_2 vs. T_3	0.66	1.40	0.39	1.99	0.706
	T_2 vs. T_4	1.58	2.60	1.65	6.49	0.980
	T_3 vs. T_4	0.70	2.34	1.44	5.03	0.725
M1BW	T_1 vs. T_2	3.76	2.83	2.59	2.45	0.261
	T_2 vs. T_3	-1.07	2.14	-0.36	1.68	0.339
	T_2 vs. T_4	-1.45	3.00	0.14	2.16	0.223
	T_3 vs. T_4	0.16	2.46	-0.32	1.95	0.661
Interorbital	T_1 vs. T_2	2.75	3.08	0.02	2.85	0.026*
	T_2 vs. T_3	-1.86	6.14	0.89	3.80	0.153
	T_2 vs. T_4	-0.66	4.54	0.32	3.74	0.636
	T_3 vs. T_4	1.08	4.98	1.01	2.21	0.970
Extraorbital	T_1 vs. T_2	4.04	8.00	-0.69	10.19	0.218
	T_2 vs. T_3	0.16	8.12	3.29	4.68	0.204
	T_2 vs. T_4	0.62	6.06	4.88	3.09	0.075
	T_3 vs. T_4	0.18	5.29	3.14	4.48	0.231

Table 5.3: Comparison of Outcomes by Sex
(Significance: * - p ≤0.05; ** - p ≤0.01; *** - p ≤0.001)

This table represents the mean changes in nasomaxillary complex width measurements and standard deviations for each time point. Twenty-eight images were evaluated for T_1 vs. T_2 and T_2 vs. T_3. Seventeen images were evaluated for T_2 vs. T_4 and T_3 vs. T_4. Between the male and female patients, only the mean changes of the nasal floor widths, nasal passage widths, and extraorbital widths from T_1 to T_2 were statistically significantly different, with males having larger changes for the three parameters.

5.11 Correlations of Changes between Time Points

Pearson correlations were used to correlate the changes in width for each parameter between time intervals. A statistically significant negative correlation was found between T_1/T_2 and T_2/T_3 for nasal floor width ($p<0.01$), nasal passage width ($p<0.05$), maxillary first molar palatal root width ($p=0.001$), maxillary first molar palatal cortical bone width ($p<0.001$), maxillary first molar buccal cortical bone width ($p<0.01$), interorbital width ($p<0.001$), and extraorbital width ($p<0.05$). This meant that a greater increase in width from T_1 to T_2 was correlated with less increase in width from T_2 to T_3 for these parameters. A statistically significant negative correlation was found between T_1/T_2 and T_3/T_4 for maxillary first molar palatal cortical bone width ($p<0.001$) and interorbital width ($p<0.01$). This meant that a greater increase in width from T_1 to T_2 was correlated with less increase in width from T_3 to T_4 for maxillary first molar palatal cortical bone width and interorbital width. A statistically significant negative correlation was also found between T_2/T_3 and T_3/T_4 for nasal floor width ($p<0.05$), maxillary sinus width ($p<0.05$), maxillary first molar mesiolingual cusp width ($p<0.01$), and interorbital width ($p<0.05$). This meant that a greater increase in width from T_2 to T_3 was correlated with less increase in width from T_3 to T_4 for these parameters. A statistically significant positive correlation was found between T_2/T_3 and T_3/T_4 for maxillary first molar palatal cortical bone width ($p<0.05$). This meant that a greater increase in width from T_2 to T_3 was correlated with a greater increase in width from T_3 to T_4 for the maxillary first molar palatal cortical bone. Correlations and p-values for each time point change and parameter are shown in Table 5.4.

	Change T_1/T_2 vs. T_2/T_3			Change T_1/T_2 vs. T_3/T_4			Change T_2/T_3 vs. T_3/T_4		
Measurement	N	Correlation	p-value	N	Correlation	p-value	N	Correlation	p-value
NFW	28	-0.501	0.007**	17	0.075	0.774	17	-0.561	0.019*
NPW	28	-0.454	0.015*	17	-0.379	0.133	17	-0.228	0.380
MSW	28	0.056	0.778	17	0.269	0.296	17	-0.523	0.031*
M1RW	28	-0.606	0.001***	17	-0.466	0.060	17	-0.250	0.334
M1CW	28	-0.177	0.369	17	-0.170	0.515	17	-0.652	0.005**
M1PW	28	-0.687	<0.001***	17	-0.886	<0.001***	17	0.497	0.043*
M1BW	28	-0.498	0.007**	17	-0.403	0.109	17	-0.228	0.379
Interorbital	28	-0.741	<0.001***	17	-0.687	0.002**	17	-0.584	0.014*
Extraorbital	28	-0.384	0.044*	17	-0.430	0.085	17	-0.387	0.125

Table 5.4: Correlations of Changes between Time Points
(Significance: * - $p \leq 0.05$; ** - $p \leq 0.01$; *** - $p \leq 0.001$)

This table represents the correlations between the mean change in nasomaxillary complex width measurements at time point intervals and standard deviations for each time correlation. Twenty-eight images were evaluated for T_1/T_2 vs. T_2/T_3. Seventeen images were evaluated for T_1/T_2 vs. T_3/T_4 and T_2/T_3 vs. T_3/T_4. All parameters had a statistically significant negative correlation for T_1/T_2 vs. T_2/T_3 except the maxillary sinus width and cusp width. A statistically significant negative correlation was found for T_1/T_2 vs. T_3/T_4 for maxillary first molar palatal cortical bone width and interorbital width. A statistically significant negative correlation was also found for T_2/T_3 vs. T_3/T_4 for nasal floor width, maxillary sinus width, maxillary first molar mesiolingual cusp width, and interorbital width. A statistically significant positive correlation was found for T_2/T_3 vs. T_3/T_4 for maxillary first molar palatal cortical bone width.

5.12 Correlations between Width Measurement Changes between Time Points based on Age at T_1

The average age of the twenty-eight patients at T_1 was 9.13 years old. Pearson correlations were used to correlate the age at the start of treatment to the change in width for each parameter between time intervals. A statistically significant negative correlation was found for maxillary sinus widths from T_2 to T_3 and T_2 to T_4 ($p<0.01$) as well as maxillary buccal bone width from T_3 to T_4 ($p<0.05$) and extraorbital width from T_2 to T_4 ($p<0.05$). This meant that the younger the patient was at the start, the more increase in width the patient had for the above variables in the specified time intervals. Correlations and p-values for each time point change and parameter are shown in Table 5.5. Raw data of ages at each time point are found in Tables AR and AS.

		Age at Start	
Measurement	Time	Correlation	p-value
NFW	T_1 vs. T_2	-0.037	0.852
	T_2 vs. T_3	-0.063	0.752
	T_2 vs. T_4	0.134	0.609
	T_3 vs. T_4	0.168	0.519
NPW	T_1 vs. T_2	-0.129	0.512
	T_2 vs. T_3	-0.295	0.128
	T_2 vs. T_4	-0.402	0.110
	T_3 vs. T_4	-0.030	0.908
MSW	T_1 vs. T_2	-0.244	0.211
	T_2 vs. T_3	-0.494	0.008**
	T_2 vs. T_4	-0.656	0.004**
	T_3 vs. T_4	-0.167	0.522
M1RW	T_1 vs. T_2	0.027	0.892
	T_2 vs. T_3	0.012	0.952
	T_2 vs. T_4	0.045	0.864
	T_3 vs. T_4	0.235	0.364
M1CW	T_1 vs. T_2	-0.068	0.733
	T_2 vs. T_3	-0.056	0.776
	T_2 vs. T_4	-0.473	0.055
	T_3 vs. T_4	-0.271	0.293
M1PW	T_1 vs. T_2	-0.020	0.919
	T_2 vs. T_3	-0.011	0.956
	T_2 vs. T_4	-0.066	0.803
	T_3 vs. T_4	-0.016	0.952
M1BW	T_1 vs. T_2	-0.065	0.741
	T_2 vs. T_3	0.126	0.524
	T_2 vs. T_4	-0.372	0.141
	T_3 vs. T_4	-0.600	0.011*
Interorbital	T_1 vs. T_2	0.063	0.749
	T_2 vs. T_3	-0.352	0.066
	T_2 vs. T_4	-0.215	0.407
	T_3 vs. T_4	0.098	0.707
Extraorbital	T_1 vs. T_2	0.172	0.382
	T_2 vs. T_3	-0.196	0.317
	T_2 vs. T_4	-0.548	0.023*
	T_3 vs. T_4	-0.311	0.224

Table 5.5: Correlations of Changes Based on Age at the Start of Treatment
(Significance: * - $p \leq 0.05$; ** - $p \leq 0.01$; *** - $p \leq 0.001$)

This table represents the correlations between the patients' age at the start of expansion treatment to the mean change in nasomaxillary complex width measurements at each time point intervals. Standard deviations for each time interval correlation are shown above. A statistically significant negative correlation was found for maxillary sinus widths from T_2 to T_3 and T_2 to T_4 as well as maxillary buccal bone width from T_3 to T_4 and extraorbital width from T_2 to T_4.

5.13 Correlations Based on Number of RPE Turns Instructed

Pearson correlations were determined to correlate the number of expansion turns instructed for the patient to complete to the change in width for each parameter at the time intervals. There were no correlations between change in any measurement and number of RPE turns instructed from T_1 to T_2. A statistically significant positive correlation was found for nasal passage width, maxillary sinus width, and maxillary first molar mesiolingual cusp tip width from T_2 to T_4 as well as maxillary molar cusp width from T_2 to T_3 ($p<0.05$). This meant that the more turns the patient was instructed to complete, the more increase in width the patient had for the above variables in the specified time intervals. Failure to properly follow the number of RPE turns instructed may be a reason that there were limited statistically significant correlations. Correlations and p-values for each time point change and parameter can be found in Table 5.6.

		Number of RPE Turns Instructed	
Measurement	Time	Correlation	p-value
NFW	T_1 vs. T_2	-0.130	0.508
	T_2 vs. T_3	0.092	0.643
	T_2 vs. T_4	0.113	0.666
	T_3 vs. T_4	-0.008	0.976
NPW	T_1 vs. T_2	-0.261	0.179
	T_2 vs. T_3	0.360	0.060
	T_2 vs. T_4	0.641	0.006**
	T_3 vs. T_4	-0.015	0.953
MSW	T_1 vs. T_2	-0.050	0.801
	T_2 vs. T_3	0.013	0.948
	T_2 vs. T_4	0.493	0.044*
	T_3 vs. T_4	-0.048	0.854
M1RW	T_1 vs. T_2	-0.220	0.260
	T_2 vs. T_3	0.161	0.413
	T_2 vs. T_4	0.025	0.925
	T_3 vs. T_4	-0.264	0.306
M1CW	T_1 vs. T_2	-0.221	0.259
	T_2 vs. T_3	0.451	0.016*
	T_2 vs. T_4	0.486	0.048*
	T_3 vs. T_4	-0.085	0.075
M1PW	T_1 vs. T_2	-0.239	0.220
	T_2 vs. T_3	0.362	0.058
	T_2 vs. T_4	0.374	0.139
	T_3 vs. T_4	0.255	0.323
M1BW	T_1 vs. T_2	-0.272	0.161
	T_2 vs. T_3	-0.053	0.789
	T_2 vs. T_4	0.404	0.108
	T_3 vs. T_4	0.444	0.074
Interorbital	T_1 vs. T_2	-0.156	0.427
	T_2 vs. T_3	0.030	0.879
	T_2 vs. T_4	0.309	0.228
	T_3 vs. T_4	0.069	0.793
Extraorbital	T_1 vs. T_2	-0.081	0.681
	T_2 vs. T_3	0.144	0.464
	T_2 vs. T_4	0.157	0.549
	T_3 vs. T_4	0.100	0.704

Table 5.6: Correlations of Changes Based on Number of RPE Turns Instructed
(Significance: * - $p \leq 0.05$; ** - $p \leq 0.01$; *** - $p \leq 0.001$)

This table represents the correlations between the number of RPE turns the patient was instructed to complete and the mean change in nasomaxillary complex width measurements at each time point interval. It also lists standard deviations for each time correlation. A statistically significant positive correlation was found for nasal passage width, maxillary sinus width, and maxillary molar cusp width from T_2 to T_4 as well as maxillary molar cusp width from T_2 to T_3.

5.14 Intra-Examiner Reliability

Measurements were repeated after two weeks on all T_1 CBCT scans by the same examiner, AS. All previously measured variables were calculated again and compared with the original values. Intra-class correlation statistics were calculated for each measurement. The intra-class correlation coefficient (ICC) for nasal floor width was 0.946, nasal passage width was 0.974, maxillary sinus width was 0.985, maxillary first molar palatal root width was 0.983, maxillary first molar mesiolingual cusp width was 0.973, maxillary first molar palatal cortical bone width was 0.969, maxillary first molar buccal cortical bone width was 0.986, interorbital width was 0.714, and extraorbital width was 0.905. All of these ICCs were interpreted as "excellent" with the exception of interorbital width which was interpreted as "good" (Koo & Li, 2016). The ICCs and 95% confidence interval can also be found in Table 5.7. The raw data are shown in Table F.

Measurement	ICC	95% CI
NFW T1	0.946	0.888, 0.975
NPW T1	0.974	0.944, 0.988
MSW T1	0.985	0.968, 0.993
M1RW T1	0.983	0.965, 0.992
M1CW T1	0.973	0.942, 0.987
M1PW T1	0.968	0.934, 0.985
M1BW T1	0.986	0.970, 0.993
Interorbital T1	0.714	0.473, 0.856
Extraorbital T1	0.905	0.807, 0.955

Table 5.7: Intra-class Correlation Coefficients and 95% Confidence Interval for All T_1 Measurements

This table represents the intra-class correlation coefficients at the 95% confidence interval for each correlation coefficient. All T_1 time points were measured twice, two weeks apart, and the values were compared to give the correlation coefficient.

CHAPTER 6: DISCUSSION

Many studies have been conducted examining the effects of rapid palatal expansion on the width of the nasomaxillary complex. These studies utilized dental casts, two-dimensional radiographs, and CBCTs to evaluate the changes associated with palatal expansion. However, most of these studies documented the changes immediately after or soon after expansion, and did not examine the changes after a period of retention. For example, Babacan et al. examined patients before expansion and after long-term retention for a total observation time of seven months, Christie et al. had a total observation time of sixty-six days, and Chung and Font had a total observation time on 96.5 days (Babacan et al., 2006, Christie et al., 2010, Chung & Font, 2004). The studies that did examine the patient after retention were often limited by the low number of patients evaluated. Haas evaluated only 10 patients, all of whom had not been in retention for at least six years prior to the observations being recorded (Haas, 1980). Other studies had shortcomings in their study design. For example, Cameron et al. did not take measurements soon after expansion, but did take measurements before expansion and 10 years later (Cameron et al., 2002). Chamberland evaluated adults who had surgically assisted rapid palatal expansion (Chamberland & Proffit, 2011). However, adults are not the traditional patients on whom non-surgical, orthopedic rapid palatal expansion is usually performed. Many studies made use of posteroanterior cephalograms, before CBCTs were available. This present study tried to fill these gaps in research and was completed utilizing the benefits of an increased number of patients, a longer observation time, increased time points at which measurements were made, and CBCTs. In addition, the present study evaluated patients of younger age who are expected to have a patent palatal suture for orthopedic expansion, unlike Chamberland's study on adults whose sutures were not patent and therefore, required surgically-assisted expansion (Chamberland & Proffit, 2011).

With the recent focus on airway, efforts have been made to determine the long-term skeletal effects and its effects on the airway for procedures common in orthodontics. The goal of the present study was to evaluate the long-term transverse effects of the nasomaxillary complex and the maxillary sinuses of patients who received rapid palatal expansion. The present study may provide directions for future research regarding how the nasal and sinus width changes associated with rapid palatal expansion could impact airway dimensions.

In the present study, CBCT images were used to evaluate the changes in the nasal floor, nasal passage, maxillary sinuses, maxillary first molar cusp tips, maxillary first molar roots, maxillary first molar buccal cortical bone, maxillary first molar palatal cortical bone, interorbital and extraorbital widths. The CBCT images were examined prior to expansion (T_1), after the completion of expansion (T_2), prior to comprehensive orthodontic treatment (T_3), and during or after orthodontic treatment (T_4). CBCT imaging allows for visualization of the nasomaxillary complex in all dimensions to identify landmarks for making accurate measurements. This retrospective study was able to utilize CBCTs for all the time points measured.

6.1 Measurements and Changes in the Maxillary Dentition

6.1.1 Pre-expansion (T_1) to Post-expansion (T_2)

The pre-expansion width to post-expansion width changes for the average duration of eleven months for the maxillary dentition was significant for all dental parameters investigated. The average increase of the maxillary first molar cusp tip width was greater than the average increase of the root tip width. This difference in width changes of the cusp tip and root tip supported the angular buccal tipping of the crown seen in previous studies and were attributed to the effects of the nature of the RPE being attached to the crowns of the dentition (Ciambotti et al., 2001, Kilic et al., 2008, Christie et al., 2010).

The mean width increase achieved in the maxillary first molar palatal cortical bone was 2.95mm and the buccal cortical bone was 3.01mm ($p \leq 0.0001$) (Figure 5.2). Garrett et al. reported a mean maxillary first molar palatal cortical bone width of 2.67mm and the buccal cortical bone width of 3.39, with a mean appliance expansion of 5.08mm. The width increases of the cortical bone were about equal in the present study and the study by Garrett et al (Garrett et al., 2008). Because the buccal and palatal cortical bone width changes in the present study were close to the increases observed by Garrett et al., it follows that the mean appliance expansion in present study was approximately 5mm. This was also close to the 4.59mm of increase observed in the mesiolingual cusp tips from T_1 to T_2 in the present study ($p \leq 0.0001$) (Figure 5.2). There was a range of 1.06mm to 9.31mm of increase in maxillary first molar mesiolingual cusp tip width (Tables B and C). There were no correlations for any dental measurements and number of RPE turns instructed for the expansion time interval. This highlights the likelihood that the number of RPE turns instructed was not an accurate representation of the amount of expansion achieved on the RPE due to lack of patient and/or parent compliance.

6.1.2 Post-expansion (T_2) to Pre-orthodontic Treatment (T_3)

The average time interval between T_2 and T_3 was 19 months. During this period, there was a decrease in the widths of the following parameters: maxillary first molar mesiolingual cusp tips, maxillary first molar palatal roots, and maxillary first molar buccal cortical bones. However, none of these decreases were statistically significant. During this period, there was an increase in the widths of the following parameters: maxillary first molar palatal cortical bone width. This increase was also not statistically significance (Figure 5.4). The results agreed with a previous study by Gurel which measured dental casts post-expansion and pre-orthodontic treatment over a period of 2.2 years (Gurel et al., 2010).

In the present study, 75% of the expansion gained from T_1 to T_2 was maintained in the cusp tips at time point T_3, 97% of the expansion gained from T_1 to T_2 was maintained in the palatal roots, and 79% of the expansion gained from T_1 to T_2 was maintained in the buccal cortical plates after the observed decrease in width during the nineteen months of the retention phase. All of the measurements of the stability of the transverse dimension were greater than the 70% maintenance that Vargo et al. found after eleven months, the two-thirds maintenance found by McNamara et al. after six years one month of the retention phase, and the 45% maintenance found by Linder-Aronson and Lindgren after five years of the retention phase (Vargo et al., 2007, McNamara et al., 2003, Linder-Aronson & Lindgren, 1979). The higher percent of expansion maintained to T_3 that was observed in the present study could be due to the utilization of CBCTs, which may have resulted in improved accuracy of identifying landmarks over the study models used by Vargo et al. and McNamara et al. and the posteroanterior cephalograms used by Linder-Aronson and Lindgren (Vargo et al., 2007, McNamara et al., 2003, Linder-Aronson & Lindgren, 1979).

The increased stability of the expansion observed in the present study may also be due to the retention protocol utilized by the practitioner or the length of time the expander was left in place after the last turn of the RPE. The retention protocol varied between patients in the present study, and therefore, no recommendations on the retention protocol can be made based on the results obtained. However, there was a range, from those patients who retained almost 100% of the expansion to those patients who lost 95.32% of the expansion during the retention period. The increase in the stability of the expansion found in the present study may also be attributed to the younger age of the patients. The average age of patients in the present study was 9.13-years-old at T_1, which was most similar in percentage of expansion retained and age of patients at T_1 to Vargo et al. where the mean age was 8.8-years-old (Vargo et al., 2007). This was in comparison to the 12 years and 2 months in the study by McNamara et al. where the relapse was 33% (McNamara et al., 2003). However, Gurel et al. found no statistically significant differences in transverse width measurements after rapid palatal expansion in patients who were 13.2 years of age before expansion began (Gurel et al., 2010). The results of previous studies showed that younger patients were not a requirement to have acceptable maintenance of expansion during the retention phase. In summary, these results indicate that retention of more than 70% of the expansion width is possible with appropriate retention protocols and when expansion is performed before the pubertal growth spurt is expected.

6.1.3 Pre-orthodontic Treatment (T_3) to Middle or End of Orthodontic Treatment (T_4)

The change in width for the maxillary dentition from T_3 to T_4 was not significant for all parameters investigated. During this time interval, there was a decrease during orthodontic treatment for the cusp tips and an increase for the root width, palatal cortical bone width, and buccal cortical bone width. However, these changes were not statistically significant (Figure 5.8 and Tables D and E).

The decrease in cusp width and increase in root width, palatal cortical bone width, and buccal cortical bone width from T_3 to T_4 may be due to the expression of the torque in the bracket during orthodontic treatment rendered during that period. All of the patients in the present study were treated by the same practitioner (MB) with Roth prescription brackets resulting in the above mentioned changes for all first molars based on bracket prescription. Gurel found that the maxillary molar cusp tip width relapsed about 34% during orthodontic treatment (Gurel et al., 2010). Compared to Gurel, the relapse of the maxillary first molar cusp tips during orthodontic treatment in the present study was 19.4% of the expansion achieved. This may be due to the difference bracket prescription or arch wire protocols used during orthodontic treatment between the practitioners in the present study and the study by Gurel et al (Gurel et al., 2010).

The orthodontic treatment did not compromise the expansion achieved and in fact, a majority of patients showed increases in widths. For the palatal root width changes, twelve of the seventeen patients showed an increase in width during orthodontic treatment. The average palatal root width increase was 0.45mm with the largest increase being 2.98mm and the largest decrease being 1.93mm. The average increase of 0.45mm was not statistically significant and would not be clinically significant as well. For mesiolingual cusp tip width changes, ten of the seventeen patients showed a decrease in width during orthodontic treatment. The average cusp tip width decrease was -0.36mm with the largest decrease being -6.49mm and the largest increase being 5.48mm. Again, the average cusp tip width change of -0.36mm may not be clinically significant (Figure 5.8 and Tables D and E). Again, these changes could be attributed to bracket prescriptions, wire sequences, and the original expansion measurements achieved during treatment.

6.1.4 Post-expansion (T_2) to Middle or End of Orthodontic Treatment (T_4)

The average time interval between T_2 and T_4 was 46 months. During this period, there was a decrease in width of the following parameters: maxillary first molar mesiolingual cusp tips and maxillary first molar buccal cortical bones. However, these decreases in width were not statistically significant. During this period, there was an increase in width of the following parameters: maxillary first molar palatal roots and the maxillary first molar palatal cortical bones. However, these increases in width were also not statistically significant (Figure 5.7 and Tables C and E).

56% of the expansion gained in the cusp tips from T_1 to T_2 was maintained to T_4. This disagrees with findings of a study of similar length which reported little difference in the widths from after expansion and after 5 years of follow-up (Gurel et al., 2010). The present study observed that although the cusp tip width was mostly maintained during orthodontic treatment (T_3 to T_4), the net result after expansion (T_2) to the middle or end of orthodontic treatment (T_4) was a relapse of 44%. These data provide the justification for the need for overexpansion of the dentition during the expansion phase to compensate for the expected relapse. However, 92% of the expansion gained in the buccal cortical plates from T_1 to T_2 was maintained to T_4. The root tip and palatal cortical bone widths were not only 100% maintained, but there was 0.5mm of width gain after expansion after 46 months (Figure 5.5). Overall, in agreement with the five-year follow-up study, there were no statistically significant differences in the buccal cortical plate, root tip, and palatal cortical plate widths after expansion (Gurel et al., 2010). The present study, along with other studies, justifies the need for the overexpansion for the cusp tip width correction. The root positions seem to be stable. Even though the reduction in cusp tip width was not statistically significant, the relapse has been observed by practitioners, indicating the relapse's clinical significance. Since most of the transverse discrepancies are manifested as posterior crossbites, overcorrection during expansion is necessary to compensate for the relapse of the mesiolingual cusp tip width while achieving a stable cusp-fossa occlusion.

6.2 Measurements and Changes in the Nasomaxillary Complex

6.2.1 Pre-expansion (T_1) to Post-expansion (T_2)

Width changes in the nasomaxillary complex during the eleven month period between T_1 and T_2 was significant for all the parameters investigated, except interorbital and extraorbital widths (Figure 5.2). The millimetric measurements of the changes in the width of the nasal floor and nasal passage found in the present study were similar to the range of 1.06mm to 2.08mm increase reported in the previous studies ($p \leq 0.01$) (Filho, 1995, Cross, 2000, Wertz, 1970, Krebs, 1958). These studies did not report the amount of expansion achieved but indicated the changes that happened (Filho, 1995, Cross, 2000, Wertz, 1970, Krebs, 1958). Only Krebs reported the amount of expansion completed, 9mm in a single male patient (Krebs, 1958). The changes in the transverse measurements reported in the other studies were on patients with different age groups, even though the amount of expansion was similar (Filho, 1995, Cross, 2000, Wertz, 1970, Krebs, 1958). Cross observed this expansion in patients with a mean age of thirteen years four months, Filho observed patients with a mean age of eight years, and Wertz did not give a mean age but gave a range of seven to twenty-nine years old (Filho, 1995, Cross, 2000, Wertz, 1970, Krebs, 1958). All of these studies found nasal width increases which were within 0.5mm of the nasal passage width increase observed in the present study (1.71mm) (Figure 5.2 and Tables B and C) (Filho, 1995, Cross, 2000, Wertz, 1970, Krebs, 1958). In summary, age of the patient may have little impact on the changes observed in nasal width during treatment.

When examining the nasal passage change as a percentage of the expansion completed, Krebs noted that the expansion in the nasal passage increase was less than or equal to 50% of the total expansion accomplished (Krebs, 1958). Two studies found that the amount of increase in the nasal passage width to be one-third of the expander's opening (Garib et al., 2007, Christie et al., 2010). Similarly, another study reported that the nasal passage width increase to be 37.2% of the expander's opening (Garrett et al., 2008). Chung found a smaller amount of nasal passage width increase, 23.1%, of the expander's opening (Chung & Font, 2004). In the present study, the nasal floor and nasal passage experienced 26% and 37% of the expansion measured at the maxillary first molar cusp tip width, respectively. The results from the present study agree with the results from Chung and Font, Garib et al., Christie et al. and Garrett et al., suggesting that the nasal width increase is a relatively consistent percent of the width increase at the cusp tip level (approximately 33%) (Chung & Font, 2004, Christie et al., 2010, Garib et al., 2007, Garrett et al., 2008). The greater percentage of expansion observed at the nasal passage as compared to the nasal floor was not expected due to the triangular nature of the opening of the nasal cavity during expansion with the widest part being the nasal floor, as a result of the maxillary bones separating around the fulcrum of the frontonasal suture (Haas, 1961, Wertz, 1970, Storey, 1973, Garrett et al., 2008). However, the nasal passage width in the present study was measured as the widest point of the nasal cavity, as measured parallel to a line connecting the most cervical point of the maxillary first molar furcation, and the nasal floor width was measured from the intersection of the palatine process of the maxilla and the medial wall of the maxillary sinus to the same intersection on the contralateral side. The nasal floor width was measured from bony intersection to bony intersection and not as a widest point. The nasal floor width was affected by the pneumatization of the maxillary sinus as the patient matured. Lorkiewicz-Muszynska observed the maxillary sinuses increased in size until fifteen or sixteen years old (Lorkiewicz-Muszynska et al., 2015). Therefore, the increasing pneumatization of the maxillary sinus may have affected the nasal floor width in the present study, but would not have affected the nasal passage width. This was likely the reason for the decreased percentage of width observed when compared to the nasal passage width. Contrary to our findings of maxillary sinus width increase during expansion, Garrett et al. found that the maxillary sinus width decreased as the nasal width increased during expansion (Garrett et al., 2008). The difference in maxillary sinus width changes in the present study and the study by Garrett et al. could have been because the mean age of patients at the start of treatment in the present study was 9.13 years old and in the study by Garrett et al. was

13.8 years old (Garrett et al., 2008). As hypothesized by Almuzian et al., the differences in the sinus measurement could be due to anatomical, physiological, maturational and chronological differences (Almuzian et al., 2018).

This was the only time interval for which there was statistically significant difference observed in the change in width between males and females. Males had statistically significantly larger changes in nasal floor width, nasal passage width, and interorbital width than females from T_1 to T_2 ($p \leq 0.05$ for all parameters). Males had a 2.03mm greater increase in nasal floor width than females, 1.29mm greater increase in nasal passage width, and 2.73mm greater increase in interorbital width (Figure 5.2 and Tables B and C). This finding of statistically significant increases of widths for males more than females does not match with the patients' growth pattern as it was described in a different study in which patients were examined from ten to fourteen years of age. The results showed that males demonstrated a greater increase from twelve to fourteen and females had a greater increase from ten to twelve. They were expanded for an average of eleven months. As all of the patients in the present study started at eleven years of age or younger, the eleven months of expansion treatment would have kept them in the range of ten to twelve year olds studied by Yavuz et al (Yavuz et al., 2004). The greater increase in the male patients who were younger than twelve years old in the present study contradicted the conclusion from Yavuz et al (Yavuz et al., 2004). The patients may have experienced growth that was different than that described by Yavuz et al (Yavuz et al., 2004). In addition, these changes could be due to the "variations in anatomical, physiological, maturational, and chronological differences between genders" (Almuzian et al., 2018).

During the 11 month period from T_1 to T_2, both male and female nasal passage widths in our study increased more than the 0.5mm of expected growth in a single year found by Ricketts (Ricketts, 1982). This was not surprising because the patients were treated with expansion which increased the nasal passage width, in addition to growth changes.

6.2.2 Post-expansion (T_2) to Pre-orthodontic Treatment (T_3)

The post-expansion width to pre-orthodontic treatment width changes for the average duration of nineteen months for the nasomaxillary complex was significant for the increase in the maxillary sinus width ($p \leq 0.001$) (Figure 5.4). However, there were increases in the width of the nasal floor, nasal passage, and extraorbital parameters that were not statistically significant. The decrease in interorbital width was not statistically significant.

90% of the expansion gained from T_1 to T_2 was maintained in the interorbital width to T_3. All of the expansion was maintained in the nasal floor, nasal passage, maxillary sinus, and extraorbital widths, and there was also “growth” during the nineteen months of retention that resulted in increased the nasal floor, nasal passage, maxillary sinus, and extraorbital widths. The changes reflected the patients’ growth. The modeling in the orbital region results in deposition of bone in the interorbital region and a decreased width, and the resorption of the frontal process of the zygomatic bone increases the extraorbital width (Figure 6.1). These findings suggested that the growth that occurred overcame the relapse that occurred during this time interval, if any relapse occurred at all showing stability. Gurel attributed the stability to midpalatal repair and new bone formation (Gurel et al., 2010).

Ricketts found that the nasal passage gained 0.5mm of width every year from three to nineteen years old (Ricketts, 1982). In the present study, the nasal floor and nasal passage width gained during the 19 months from T_2 to T_3 were less than 0.5mm per year. The decreased rate of nasal passage width increase during the retention period may be attributable to relapse in the width of the nasal passage or a deceleration of the growth following the accelerated growth that occurred during the expansion treatment.

6.2.3 Pre-orthodontic Treatment (T_3) to Middle or End of Orthodontic Treatment (T_4)

The pre-orthodontic treatment width to middle or end of orthodontic treatment width changes were significant for the nasal passage width and maxillary sinus width increases ($p \leq 0.001$ and $p \leq 0.0001$, respectively) (Figure 5.8). From T_3 to T_4, there was a decrease for the nasal floor width and an increase for the interorbital and extraorbital widths. The changes in the nasal floor width, interorbital width, and extraorbital width were not statistically significant.

Unlike previous studies, there were no statistically significant changes in width when comparing males and females from T_3 to T_4 (Figure 5.17). Lux found that males outgrew females by 2.68mm from seven to fifteen years old (Lux et al., 2004). Yavuz also found that transverse widths were statistically significantly greater in males (Yavuz et al., 2004). The lack of statistically significant changes between males and females in the present study may be due to the changes induced by the rapid palatal expansion, when comparing the treated patients to the untreated controls of Yavuz et al. (Yavuz et al., 2004). In addition, at T_3, the average age of the patients in our study was 11.66 years old, and the males may not have yet reached their pubertal growth spurt. This growth spurt may contribute to additional growth with time in males and may become significant later compared to females as indicated by Yavuz et al. (Yavuz et al., 2004).

The extraorbital width increase of 2.40mm during orthodontic treatment was the only statistically significant difference found between patients that were CVMS I or CVMS II at the start of treatment ($p \leq 0.05$) (Figure 5.13). It was only statistically significant during this time period of orthodontic treatment, T_3 to T_4. There was no credible explanation as to why this was the only statistically significant difference between the patients who were CVMS I or CVMS II at the start of treatment. However, the frontal process of zygomatic bone undergoes modeling changes, and deposition of new bone at this region could be a possibility.

6.2.4 Post-expansion (T_2) to Middle or End of Orthodontic Treatment (T_4)

The post-expansion width to middle or end of orthodontic treatment time interval was an average of 46 months. The increases in width for the nasomaxillary complex parameters was statistically significant for the nasal passage width, maxillary sinus width, and extraorbital width ($p \leq 0.0001$, $p \leq 0.0001$, and $p \leq 0.001$, respectively) (Figure 5.7). Over this time interval, there was an increase from T_2 to T_4 for the nasal floor width and a decrease in interorbital width. The nasal floor and interorbital changes were not statistically significant for this time period. The decrease of 0.09mm in interorbital width was not statistically significant and would be too small to be differentiated on a single CBCT image due to the voxel size of 0.3mm. From T_2 to T_4, the 1.85mm nasal passage increase over four years agrees with the research done by Ricketts on untreated controls that stated an increase of 0.5mm per year (Ricketts, 1982). This may mean that after expansion was completed, the nasal passage increased in width, even after the decreased rate of growth during the retention phase (T_2 to T_3). If this was true, then it could be concluded that rapid palatal expansion increases the width of the nasal passage beyond what would occur with growth alone.

Unlike previous studies, there were no statistically significant changes in width when comparing males and females from T_2 to T_4 (Figure 5.12). Lux found that males outgrew females by 2.68mm from seven to fifteen years old (Lux et al., 2004). Yavuz also found that transverse widths were statistically significantly greater in males (Yavuz et al., 2004). Both the study by Lux et al. and Yavuz et al. were completed on patients who were not treated with rapid palatal expansion (Lux et al., 2004, Yavuz et al., 2004). In the present study, patients were treated with rapid palatal expansion. The lack of significant changes seen in the present study between males and females over the 46 months after expansion was completed may also be due to the induced changes caused during rapid palatal expansion, masking the natural growth pattern differences between the sexes when comparing them to other studies that evaluated untreated controls like Lux et al. and Yavuz et al. (Lux et al., 2004, Yavuz et al., 2004). The differences between the present study and studies like Lux et al. and Yavuz et al. may also include maturational differences between the patients which is not accounted for when analyzing chronological age (Lux et al., 2004, Yavuz et al., 2004).

6.3 Correlations of Changes between Time Points

Statistically significant negative correlations were found between nasal floor width, nasal passage width, maxillary first molar palatal root width, maxillary first molar palatal cortical bone width, maxillary first molar buccal cortical bone width, interorbital width, and extraorbital width measurement changes between the time intervals T_1/T_2

compared to T_2/T_3 (See Table 5.4 for correlations and p-values). This meant that the more increase in width that was seen from T_1 to T_2, the less increase or more decrease was seen in the measurement from T_2 to T_3. This suggested that, for the above listed parameters, the change that occurred during expansion relapsed during the retention phase as the changes were not in accordance with the natural growth pattern.

A statistically significant negative correlation was also found between the time intervals T_1/T_2 and T_3/T_4 for the maxillary first molar palatal cortical bone width and interorbital width ($p \leq 0.001$ and $p \leq 0.01$, respectively) (Table 5.4). This meant that the greater the increase between T_1 to T_2, the smaller the increase from T_3 to T_4. The fewer correlations of parameters between T_1/T_2 vs. T_3/T_4 (compared to T_1/T_2 vs. T_2/T_3) may be indicative of the lack of correlation between the changes during expansion and changes during orthodontic treatment, specifically with a retention phase between the two time intervals. This could have been due to the average age of our patients at the start of expansion treatment which was 9.13 years old and whether the expansion treatment was in accordance with their growth status. It could also have been due to modeling changes which would mask the results as well.

A statistically significant negative correlation was also found between the time intervals of T_2/T_3 and T_3/T_4 for nasal floor width, maxillary sinus width, maxillary first molar mesiolingual cusp width, and interorbital width (See Table 5.4 for correlations and p-values). This meant that the greater the increase from T_2 to T_3, the less the increase from T_3 to T_4. For nasal floor width, maxillary sinus width, and interorbital width, this may be attributable to the slowing or cessation of growth. In addition, the changes that occur during orthodontic treatment were not expected to affect these parameters.

Orthodontic tooth movement is limited to dentoalveolar changes, and it will not contribute to skeletal changes beyond the alveolar processes of the maxilla. For the maxillary first molar mesiolingual cusp width, this meant that the greater the decrease from T_2 to T_3, the less the increase from T_3 to T_4. This may be due to how the practitioner uses arch wires and sequence the treatment in addition to the prescription built into the brackets. A statistically significant positive correlation was found between T_2 to T_3 and T_3 to T_4 for the maxillary first molar palatal cortical bone width. This meant that the greater width increase from T_2 to T_3, the greater width increase from T_3 to T_4. This again could be attributed to the bracket prescription used in the present study contributing to the changes in the root positions and palatal bone thickness.

6.4 Correlations between Measurement Changes and Age at T_1

For four measurements, a statistically significant negative correlation was found based on the age of the patient at the start of treatment. These four measurements and time points were maxillary sinus width from T_2 to T_3 ($p \leq 0.01$), maxillary sinus width from T_3 to T_4 ($p \leq 0.01$), maxillary first molar buccal cortical bone from T_3 to T_4 ($p \leq 0.05$), and extraorbital width from T_2 to T_4 ($p \leq 0.05$). For these measurements and time points, the younger the patient was at the start of treatment, the more the widths increased during these specific time points. This may have been due to the growth potential of younger patients. However, for almost all time points and measurements, the age at the start of treatment did not strongly correlate to the change in width that was seen for the measurements. This was an indication that chronologic age was not an accurate representation of skeletal maturity.

6.5 CVMS Analysis

At T_1, all patients were CVMS I or II as measured on the midsagittal slice of the CBCT. One patient went from CVMS II to III during the expansion treatment (T_1 to T_2), thirteen patients went from CVMS II to CVMS III during the retention phase (T_2 to T_3), and fourteen patients were CVMS I or CVMS II at the start of orthodontic treatment. These fourteen patients likely experienced their peak growth during orthodontic treatment. At T_4, the seventeen patients were all CVMS III or IV. This meant that the seventeen patients with T_4 CBCTs had all passed their peak pubertal growth spurt before the middle or end of treatment CBCT was taken. As noted earlier, the pubertal peak growth of the mandible as well as the maxilla occurred before CVMS III (Baccetti et al., 2002); therefore, all patients with T_4 CBCTs had already experienced their peak maxillary growth and came to a plateau by the time their middle or end of orthodontic treatment CBCT was taken (Figure 2.8).

6.6 Correlations between Measurement Changes and Number of RPE Turns Instructed

No correlations were found for any dental measurements and the number of RPE turns instructed. If the patients were following the instructions properly, then a higher number of RPE turns instructed should have resulted in an increased amount of expansion measured. This highlights the likelihood that the number of RPE turns instructed was not an accurate representation of the amount of expansion achieved on the RPE due to lack of patient and/or parent compliance.

6.7 Limitations of the Study

In the present study, there were no age-matched controls who did not have any expansion or controls who had expansion but did not have orthodontic treatment. Taking CBCTs on control patients who will not have any treatment is not acceptable on an ethical basis. The second was that the number of males and females in the study was not equal. This was limited by the number of patients that the practitioner had who fit the inclusion and exclusion criteria. To reduce the variation in treatment modalities, no other practitioner's CBCT images were sought or collected.

Another limitation was that the amount of expansion was not recorded from the expander, only the number of RPE turns instructed was recorded. This limited the correlations between the amount of expansion achieved and the changes received on each patient to evaluate the correlation between the expected expansion and the achieved expansion.

Furthermore, the CBCTs were not taken at the same interval on each patient, and not all patients had middle or end of treatment CBCT images. This was because the images were taken by the practitioner in their normal course of treatment, and this was a retrospective study. Also, the post-expansion CBCTs were not taken on the day expansion was stopped because of the practitioner's schedule. Therefore, even though the study had CBCTs after the expansion treatment, they were taken at different time points after the expansion treatment, however all were within a year of the completion of expansion.

6.8 Conclusions

Rapid palatal expansion is utilized to increase the transverse dimension of the dentition, which causes changes in the nasomaxillary complex. Results of the present study found a significant increase in the transverse dimension for the nasal floor, nasal passage, maxillary sinus, maxillary first molar palatal roots, maxillary first molar mesiolingual cusps, maxillary first molar palatal cortical bones, and maxillary first molar buccal cortical bones during expansion. The results also showed a significant increase in the transverse dimension of the nasal passage, maxillary sinus and extraorbital widths after expansion through comprehensive orthodontic treatment and increases in nasal floor width, maxillary first molar palatal root width, and maxillary first molar palatal cortical bone width which were not statistically significant. The results showed a significant decrease in the transverse dimension of the maxillary first molar mesiolingual cusp width after expansion through comprehensive orthodontic treatment and decreases in maxillary first molar buccal cortical bone width (0.52mm decrease) and interorbital width (0.08mm decrease) that were not statistically significant. These decreases in width that are not statistically significant are also not clinically significant. This meant that the expansion that was achieved did not significantly decrease or relapse in the transverse measurement with the exception of the maxillary first molar mesiolingual cusp tip width, and the expansion was relatively stable. These findings suggest that the growth that occurred post-expansion overcame the relapse that occurred.

Only a few of the measurements at specific time points were statistically significant between males and females, between maturation stages as measured by CVMS at the start of treatment, or based on the age at the start of treatment. Males and females were only statistically significantly different from T_1 to T_2 for three parameters—nasal floor width, nasal passage width, and interorbital width. This was only three of thirty-six possible parameter and time interval correlations that was significant. CVMS I and CVMS II patients were only statistically significant for the extraorbital width from T_3 to T_4. This was only one of thirty-six possible parameter and time interval correlations that was significant. For the vast majority of measurements and time intervals, sex, maturation stage at the start of treatment, and age at the start of treatment did not significantly correlate with the width changes. This showed the general stability of the transverse dimension following the rapid palatal expansion for the parameters measured.

6.9 Future Research

The change in nasomaxillary complex widths to 4 years post-expansion with a bonded RPE was reported in this paper. A randomized, controlled prospective clinical study with age, sex, and ethnicity controlled patients with and without expansion and followed through the completion of puberty with post-orthodontic treatment images would be ideal. In addition, standardizing the retention protocol and measuring the actual expansion on the instrument would allow for increased quality of analysis. Secondly, with the growing interest in sleep apnea and airway parameters, patients with diagnosed sleep apnea could be evaluated for changes in airway parameters to identify correlations with expansion treatment.

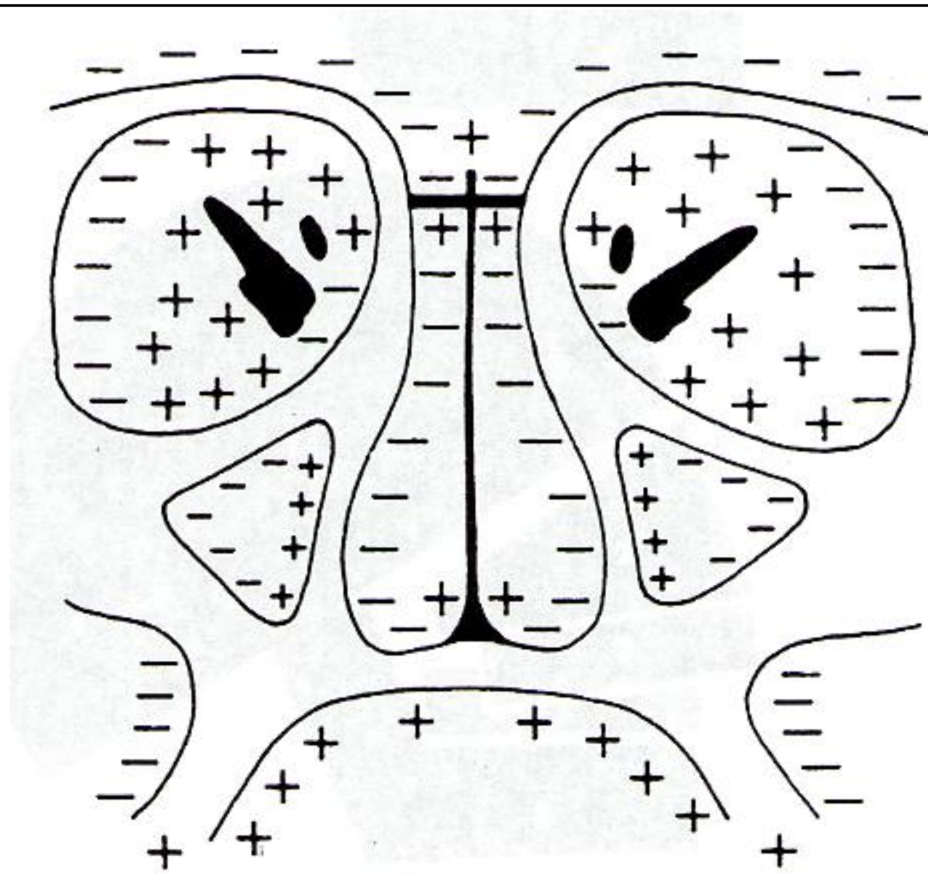

Figure 6.1 Modeling of the Nasomaxillary Complex and Orbit during the Pubertal Growth Spurt (Enlow & Hans, 1996)

The + indicates deposition of bone and the – indicates resorption of bone. In the present study, a decrease in the interorbital width and an increase in the extraorbital width was observed.

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Patient	Sex	Maturation	Turns Instructed (T1-T2)	CBCT T1	Expansion End Date	CBCT T2	CBCT T3	CBCT T4
4dc	F	1	42	4/8/2014	7/28/2014	1/6/2015	10/11/2017	
3fc	M	1	21	8/21/2012	10/24/2012	8/20/2013	4/5/2016	
2b0	F	1	49	10/18/2010	4/4/2011	12/7/2011	7/1/2013	11/22/2016
19d	F	2	21	3/15/2010	4/13/2010	6/22/2010	9/29/2011	8/25/2014
3c0	F	2	42	3/19/2012	10/23/2012	11/20/2012	8/13/2013	7/24/2017
3bc	M	2	56	4/2/2012	7/16/2012	5/1/2013	4/2/2014	6/26/2017
3c5	M	1	35	5/8/2012	6/12/2012	4/15/2013	11/27/2013	8/30/2016
2f3	M	1	35	1/25/2011	5/26/2012	8/8/2011	11/4/2013	4/18/2016
51f	F	1	77	9/23/2015	3/14/2016	6/23/2016	6/5/2017	
302	F	2	42	2/15/2011	9/6/2011	2/28/2012	1/29/2014	
495	F	1	27	1/13/2014	3/17/2014	10/28/2014	9/12/2016	8/16/2017
465	F	1	35	6/24/2013	8/12/2013	3/24/2014	2/10/2015	3/28/2016
2f9	F	1	56	2/8/2011	6/8/2011	9/22/2011	7/30/2013	
f4	M	1	42	12/17/2009	3/17/2010	3/2/2011	11/14/2012	12/19/2016
434	F	1	42	2/18/2013	11/6/2013	7/1/2014	2/28/2015	1/16/2017
3da	F	1	91	6/21/2012	12/10/2012	8/20/2013	5/20/2014	
1ca	M	1	42	3/15/2010	6/1/2010	3/28/2011	3/12/2013	3/17/2015
271	F	1	35	8/2/2010	10/12/2010	7/25/2011	8/15/2012	4/8/2014
42c	F	2	42	3/26/2013	5/6/2013	12/23/2013	8/19/2014	6/27/2017
2f5	F	1	82	1/26/2011	8/4/2011	5/22/2012	11/18/2014	10/2/2017
527	M	1	35	9/3/2014	12/16/2014	9/21/2015	6/5/2017	
312	M	1	28	3/22/2011	7/18/2011	10/11/2011	7/8/2013	2/2/2016
470	F	1	35	7/2/2013	8/20/2013	7/7/2014	9/12/2016	
374	M	1	65	10/4/2011	9/5/2012	4/2/2014	1/18/2016	2/13/2017
390	M	2	45	11/22/2011	7/5/2012	5/6/2013	7/1/2015	
ba	F	1	63	11/19/2009	2/9/2010	11/1/2010	11/29/2011	8/20/2014
3f2	F	1	56	9/5/2012	1/15/2013	1/15/2013	11/6/2013	
355	F	1	21	6/30/2011	11/9/2011	3/26/2012	7/27/2015	

Table A: Patient Demographics Raw Data

Patient	NFW T1	NPW T1	MSW T1	M1RW T1	M1CW T1	M1PW T1	M1BW T1	Interorbital T1	Extraorbital T1
4dc	22.74	20.81	62.05	30.01	36.55	25.12	54.36	20.07	80.61
3fc	26.55	23.98	51.32	29.26	39.81	25.26	56.91	16.29	75.51
2b0	28.29	25.80	57.91	26.67	33.48	24.70	53.23	22.21	65.55
19d	24.20	25.69	80.59	29.44	40.62	29.20	55.34	23.66	82.36
3c0	25.95	24.21	59.49	32.56	37.57	26.30	54.48	17.52	70.62
3bc	27.84	25.24	69.47	30.26	41.81	26.68	58.40	34.30	69.99
3c5	29.87	26.23	64.64	34.72	39.34	28.44	59.29	20.73	66.35
2f3	26.35	29.40	77.02	36.98	41.66	27.41	65.30	24.20	86.82
51f	25.43	22.63	61.59	27.65	37.10	25.23	55.28	20.14	77.60
302	22.09	25.76	70.08	26.50	37.47	25.92	55.26	24.20	82.15
495	30.61	27.77	62.96	31.59	39.29	27.45	58.06	23.22	72.49
465	30.33	27.80	65.03	30.84	42.79	27.97	58.63	23.16	63.23
2f9	31.05	28.36	63.64	29.47	40.60	26.23	56.72	16.11	68.42
f4	29.37	26.38	63.68	31.85	39.35	26.84	58.22	19.06	81.06
434	26.83	23.97	71.30	31.89	38.23	27.14	58.23	18.42	75.92
3da	30.49	26.32	67.15	32.49	37.75	28.49	60.07	18.32	77.14
1ca	34.61	29.98	73.85	37.43	45.68	32.20	63.99	21.03	79.13
271	31.76	27.83	64.09	29.22	39.79	28.42	57.63	21.04	79.40
42c	31.93	28.12	62.10	27.75	38.25	25.29	55.50	23.72	87.12
2f5	29.69	27.55	62.65	42.16	35.63	28.50	61.24	18.99	74.88
527	31.16	28.77	68.43	41.10	46.36	33.40	65.59	22.98	79.94
312	28.75	25.41	59.22	27.17	39.66	27.42	55.02	17.68	78.70
470	28.74	26.00	64.32	27.96	35.98	26.39	53.96	23.20	80.18
374	23.10	20.16	57.75	26.31	32.86	22.65	48.01	26.47	63.37
390	34.23	31.79	49.00	31.79	43.33	28.35	61.75	19.15	84.14
ba	27.54	25.04	60.14	29.71	40.77	26.35	56.50	18.13	76.48
3f2	29.87	27.75	70.35	31.64	37.67	27.40	54.98	23.10	81.78
355	29.74	27.84	63.06	31.71	37.25	27.47	53.84	22.44	85.44

Table B: Pre-expansion (T1) Raw Data

Patient	NFW T2	NPW T2	MSW T2	M1RW T2	M1CW T2	M1PW T2	M1BW T2	Interorbital T2	Extraorbital T2
4dc	24.74	22.74	65.16	34.44	40.88	29.04	57.63	19.16	80.20
3fc	30.22	28.81	57.92	34.24	46.07	31.48	64.04	22.37	83.78
2b0	21.95	28.96	70.76	30.62	40.76	32.48	59.22	25.01	84.46
19d	23.37	26.57	80.64	29.13	45.79	31.78	56.75	30.00	76.79
3c0	26.87	25.59	63.52	34.84	41.56	32.12	56.80	19.31	78.19
3bc	30.54	28.15	72.92	33.82	46.52	32.84	62.55	39.8	78.30
3c5	32.96	29.09	67.47	37.15	44.34	31.72	62.56	23.26	75.86
2f3	31.03	31.58	79.97	40.11	48.41	26.97	68.68	26.97	82.30
51f	28.20	24.18	60.36	33.55	42.85	32.56	60.17	20.70	64.35
302	24.81	26.69	67.33	29.01	42.19	29.27	58.72	17.62	68.56
495	28.80	27.79	65.45	34.04	42.86	28.83	59.74	21.65	77.23
465	33.41	30.02	68.71	35.68	47.95	31.53	63.24	20.91	87.61
2f9	33.63	30.97	67.62	33.16	47.96	30.83	61.16	15.97	70.08
f4	29.64	28.41	66.20	34.43	44.06	31.05	62.59	19.19	87.02
434	24.57	24.37	77.52	33.38	43.96	27.17	60.14	19.41	70.77
3da	29.88	26.08	68.20	34.33	36.78	27.86	59.74	19.22	67.91
1ca	35.30	31.02	76.80	39.15	46.85	34.44	65.89	19.83	88.53
271	32.49	29.76	67.68	32.82	44.85	33.23	61.37	23.13	83.00
42c	33.13	30.22	65.76	31.86	43.09	30.43	60.45	23.44	83.65
2f5	29.53	28.16	67.53	36.91	39.75	20.06	58.27	18.27	76.51
527	35.52	30.55	69.63	40.64	48.38	33.49	66.21	29.74	76.74
312	32.17	30.04	62.22	31.01	48.97	30.99	61.03	20.61	67.12
470	31.19	28.35	67.60	32.05	41.43	33.80	59.75	21.83	75.88
374	25.83	22.88	65.36	30.45	41.06	27.57	55.96	24.17	77.81
390	33.82	32.18	47.91	33.85	46.04	33.12	60.60	23.45	87.90
ba	29.13	26.48	59.08	28.89	41.67	26.85	55.37	21.78	69.66
3f2	29.76	27.22	70.66	31.61	41.59	26.81	56.53	21.07	80.51
355	30.55	27.64	64.64	32.77	38.57	26.53	54.83	19.53	73.53

Table C: Post-expansion (T2) Raw Data

Patient	NFW T3	NPW T3	MSW T3	M1RW T3	M1CW T3	M1PW T3	M1BW T3	Interorbital T3	Extraorbital T3
4dc	25.52	24.28	68.32	32.93	39.10	31.14	57.89	20.34	77.17
3fc	30.19	27.82	63.98	33.50	42.89	30.60	63.29	20.34	73.04
2b0	22.81	29.86	77.33	32.04	39.25	32.04	58.54	25.56	89.61
19d	25.61	25.77	70.88	28.91	40.18	30.19	60.38	24.23	74.86
3c0	27.12	26.73	64.27	33.96	39.25	29.01	56.88	19.04	74.96
3bc	30.59	28.67	72.26	33.28	46.77	34.31	62.65	24.94	73.37
3c5	32.96	28.88	71.98	35.21	43.92	31.72	63.44	22.57	78.19
2f3	28.39	30.61	81.13	40.26	42.57	30.19	62.89	21.61	83.17
51f	28.08	23.18	61.81	32.33	69.65	31.92	58.15	21.69	67.53
302	23.67	27.97	76.79	27.98	38.42	30.29	58.07	28.50	79.07
495	28.62	27.22	67.49	34.78	41.64	28.37	60.17	20.58	84.15
465	32.91	30.72	69.03	35.06	45.18	31.80	62.16	21.86	85.94
2f9	32.04	29.48	67.01	32.96	40.65	30.94	57.67	16.85	79.36
f4	29.27	29.46	69.43	34.61	42.44	31.52	60.57	21.92	90.40
434	27.02	25.30	77.68	34.93	42.98	29.88	59.29	19.08	75.80
3da	30.62	27.71	69.63	34.41	38.02	30.62	59.97	16.19	76.69
1ca	36.47	32.80	76.53	39.38	46.17	36.04	66.00	23.10	83.30
271	34.39	30.84	71.23	31.95	43.94	32.62	61.91	22.44	86.29
42c	32.48	30.30	66.94	30.51	40.60	31.09	60.21	23.76	80.83
2f5	30.88	30.04	71.58	38.66	39.33	23.19	59.43	18.18	80.05
527	36.62	31.16	79.51	43.94	48.85	35.34	67.97	26.76	94.48
312	31.13	27.01	64.91	30.84	40.11	29.63	58.66	15.38	70.60
470	32.41	29.07	72.35	31.07	39.73	29.74	56.81	31.14	78.05
374	25.02	25.24	68.89	29.02	39.17	28.31	53.79	32.15	80.99
390	35.59	31.65	50.79	34.87	45.15	32.63	60.12	21.98	79.44
ba	30.65	27.40	64.06	30.49	41.87	28.37	56.92	21.2	72.75
3f2	30.42	28.48	73.63	32.16	37.59	28.29	54.25	21.48	80.94
355	29.73	28.96	70.92	31.46	37.70	28.71	54.68	21.91	84.13

Table D: Pre-Orthodontic Treatment (T3) Raw Data

Patient	NFW T4	NPW T4	MSW T4	M1RW T4	M1CW T4	M1PW T4	M1BW T4	Interorbital T4	Extraorbital T4
4dc									
3fc									
2b0	20.58	30.44	78.62	30.11	37.23	24.74	56.72	27.72	90.80
19d	24.83	26.83	79.25	30.84	42.63	32.10	56.68	20.42	78.87
3c0	28.58	28.78	69.74	33.77	42.16	24.58	58.15	21.28	84.43
3bc	30.75	30.73	72.41	31.90	40.28	30.96	59.84	34.58	77.25
3c5	34.02	31.60	71.77	36.71	41.51	36.15	64.27	24.59	70.24
2f3	27.84	31.57	83.88	40.97	41.82	32.15	61.97	18.71	83.96
51f									
302									
495	30.35	28.82	65.15	34.15	39.47	30.03	58.12	22.51	77.47
465	33.96	31.22	73.17	35.47	43.7	34.46	61.43	21.26	88.70
2f9									
f4	29.33	31.51	74.31	34.72	40.48	31.48	59.91	21.81	85.48
434	22.77	27.37	82.1	35.84	41.66	33.42	59.34	20.50	81.02
3da									
1ca	37.12	33.62	79.52	39.89	45.68	36.40	63.99	23.90	82.92
271	33.88	31.96	72.05	32.77	42.97	34.85	62.10	25.94	87.91
42c	33.64	30.66	69.56	32.50	41.19	31.57	59.49	25.27	88.93
2f5	31.58	31.95	75.07	37.41	41.04	35.06	62.60	21.07	80.92
527									
312	33.02	29.08	68.91	31.48	45.59	30.13	62.36	19.40	78.37
470									
374	27.67	25.71	71.14	29.59	42.22	29.35	56.79	26.25	83.04
390									
ba	29.17	28.69	68.61	33.47	39.68	30.12	58.09	20.09	77.57
3f2									
355									

Table E: Middle- or End-of-Orthodontic Treatment (T4) Raw Data

Patient	NFW T1	NPW T1	MSW T1	M1RW T1	M1CW T1	M1PW T1	M1BW T1	Interorbital T1	Extraorbital T1
4dc	22.94	20.67	62.83	29.63	35.95	25.15	53.65	20.53	81.72
3fc	26.66	24.17	51.34	28.77	39.97	25.59	56.34	18.23	75.01
2b0	23.41	24.06	59.89	26.79	33.07	24.28	53.08	22.31	66.84
19d	23.88	25.54	80.44	28.19	39.93	28.95	54.88	26.08	80.06
3c0	25.92	24.31	59.92	31.91	37.77	24.96	54.49	18.44	71.63
3bc	28.07	25.43	68.74	29.12	40.07	26.33	57.58	22.80	83.35
3c5	29.99	26.15	63.83	34.64	40.76	28.46	59.47	20.97	69.64
2f3	26.90	29.62	76.20	37.10	41.53	27.13	65.62	23.26	85.90
51f	25.23	21.44	60.21	27.97	36.34	24.99	54.5	18.17	76.49
302	21.95	25.25	68.39	27.01	36.53	25.84	54.98	23.66	81.73
495	30.51	27.94	64.26	31.28	39.58	27.70	58.44	22.12	73.13
465	29.49	26.57	61.28	30.86	42.65	27.00	58.5	22.71	63.86
2f9	30.46	28.60	63.47	30.86	40.67	26.15	56.32	16.09	68.16
f4	28.99	26.00	64.60	30.14	38.87	26.23	58.04	19.22	79.11
434	26.44	24.21	71.55	32.49	37.19	26.38	56.86	17.74	75.96
3da	30.12	27.30	66.03	32.73	38.33	28.12	60.21	19.27	77.29
1ca	33.27	30.73	74.76	36.87	45.14	32.67	63.13	21.87	77.80
271	31.72	28.05	64.09	28.05	40.14	27.84	57.19	22.38	78.60
42c	31.27	27.51	61.89	27.01	37.47	24.88	56.39	25.11	89.09
2f5	29.29	27.47	64.02	43.20	36.61	28.16	60.26	19.60	73.72
527	31.13	28.33	69.02	41.90	47.50	33.18	65.15	23.97	79.44
312	29.51	26.27	58.14	26.30	38.83	27.16	54.55	16.86	75.72
470	29.11	25.74	64.92	27.09	36.06	26.86	55.29	24.85	82.83
374	23.80	20.34	56.19	25.41	32.63	22.74	48.67	24.08	63.13
390	34.05	31.81	48.14	32.07	42.93	27.15	61.29	19.40	83.28
ba	28.13	25.81	60.83	29.73	41.71	26.27	55.54	18.90	73.09
3f2	30.51	28.06	69.59	31.15	38.45	27.17	55.23	23.68	83.22
355	29.32	27.73	64.09	31.00	36.36	26.42	53.89	23.03	86.33

Table F: Repeated Measurements from T1 Raw Data

Patient	T_1	T_2	T_3	T_4
4dc	I	I	III	
3fc	I	I	I	
2b0	I	I	III	IV
19d	II	II	III	IV
3c0	II	II	III	IV
3bc	II	II	II	IV
3c5	I	II	II	III
2f3	I	I	II	III
51f	I	I	II	
302	II	II	III	
495	I	I	II	III
465	I	II	II	III
2f9	I	I	I	
f4	I	II	III	IV
434	I	II	III	IV
3da	I	I	II	
1ca	I	I	III	IV
271	I	II	III	IV
42c	II	II	II	IV
2f5	I	II	III	IV
527	I	I	II	
312	I	II	III	IV
470	I	I	II	
374	I	II	III	III
390	II	III	IV	
ba	I	II	III	IV
3f2	I	II	II	
355	I	I	II	

Table G: CMVS Raw Data

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	28.53964	29.75143
Variance	10.21835	13.13733
Observations	28	28
Pearson Correlation	0.773162	
Hypothesized Mean Difference	0	
df	27	
t Stat	-2.74931	
P(T<=t) one-tail	0.00526	
t Critical one-tail	1.703288	
P(T<=t) two-tail	0.010521	
t Critical two-tail	2.051831	

Table H: NFW T-test for T_1 to T_2

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	26.30679	28.01786
Variance	6.694193	6.373906
Observations	28	28
Pearson Correlation	0.863797	
Hypothesized Mean Difference	0	
df	27	
t Stat	-6.78008	
P(T<=t) one-tail	1.39E-07	
t Critical one-tail	1.703288	
P(T<=t) two-tail	2.79E-07	
t Critical two-tail	2.051831	

Table I: NPW T-test for T_1 to T_2

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	64.38857143	67.3078571
Variance	46.90492381	45.8844249
Observations	28	28
Pearson Correlation	0.896991501	
Hypothesized Mean Difference	0	
df	27	
t Stat	-4.995232333	
P(T<=t) one-tail	1.54242E-05	
t Critical one-tail	1.703288446	
P(T<=t) two-tail	3.08484E-05	
t Critical two-tail	2.051830516	

Table J: MSW T-test for T_1 to T_2

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	31.29036	33.71214
Variance	16.44709	9.412306
Observations	28	28
Pearson Correlation	0.829135	
Hypothesized Mean Difference	0	
df	27	
t Stat	-5.60512	
P(T<=t) one-tail	3.01E-06	
t Critical one-tail	1.703288	
P(T<=t) two-tail	6.02E-06	
t Critical two-tail	2.051831	

Table K: M1CW T-test for T_1 to T_2

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	39.16607	43.75679
Variance	9.876099	10.33338
Observations	28	28
Pearson Correlation	0.741028	
Hypothesized Mean Difference	0	
df	27	
t Stat	-10.6144	
P(T<=t) one-tail	1.95E-11	
t Critical one-tail	1.703288	
P(T<=t) two-tail	3.89E-11	
t Critical two-tail	2.051831	

Table L: M1RW T-test for T_1 to T_2

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	27.22214286	30.1732143
Variance	4.582691534	9.85111892
Observations	28	28
Pearson Correlation	0.189705974	
Hypothesized Mean Difference	0	
df	27	
t Stat	-4.529678244	
P(T<=t) one-tail	5.38808E-05	
t Critical one-tail	1.703288446	
P(T<=t) two-tail	0.000107762	
t Critical two-tail	2.051830516	

Table M: M1PW T-test for T_1 to T_2

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	57.34964	60.35679
Variance	14.79156	11.29249
Observations	28	28
Pearson Correlation	0.746078	
Hypothesized Mean Difference	0	
df	27	
t Stat	-6.10245	
P(T<=t) one-tail	8.08E-07	
t Critical one-tail	1.703288	
P(T<=t) two-tail	1.62E-06	
t Critical two-tail	2.051831	

Table N: M1BW T-test for T_1 to T_2

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	21.41214	22.40714
Variance	13.61191	22.42707
Observations	28	28
Pearson Correlation	0.744249	
Hypothesized Mean Difference	0	
df	27	
t Stat	-1.66232	
P(T<=t) one-tail	0.054009	
t Critical one-tail	1.703288	
P(T<=t) two-tail	0.108017	
t Critical two-tail	2.051831	

Table O: Interorbital T-test for T_1 to T_2

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	76.65642857	77.6517857
Variance	47.02076455	46.5243041
Observations	28	28
Pearson Correlation	0.016030509	
Hypothesized Mean Difference	0	
df	27	
t Stat	-0.548980145	
P(T<=t) one-tail	0.293765427	
t Critical one-tail	1.703288446	
P(T<=t) two-tail	0.587530855	
t Critical two-tail	2.051830516	

Table P: Extraorbital T-test for T_1 to T_2

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	29.75143	30.04321
Variance	13.13733	13.14049
Observations	28	28
Pearson Correlation	0.943566	
Hypothesized Mean Difference	0	
df	27	
t Stat	-1.26788	
P(T<=t) one-tail	0.107833	
t Critical one-tail	1.703288	
P(T<=t) two-tail	0.215666	
t Critical two-tail	2.051831	

Table Q: NFW T-tests for T_2 to T_3

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	28.01785714	28.4503571
Variance	6.373906349	5.34550728
Observations	28	28
Pearson Correlation	0.875730833	
Hypothesized Mean Difference	0	
df	27	
t Stat	-1.871139579	
P(T<=t) one-tail	0.036099955	
t Critical one-tail	1.703288446	
P(T<=t) two-tail	0.07219991	
t Critical two-tail	2.051830516	

Table R: NPW T-test for T_2 to T_3

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	67.30786	70.01286
Variance	45.88442	38.72416
Observations	28	28
Pearson Correlation	0.843964	
Hypothesized Mean Difference	0	
df	27	
t Stat	-3.90169	
P(T<=t) one-tail	0.000287	
t Critical one-tail	1.703288	
P(T<=t) two-tail	0.000574	
t Critical two-tail	2.051831	

Table S: MSW T-test for T_2 to T_3

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	33.71214	33.625
Variance	9.412306	12.73178
Observations	28	28
Pearson Correlation	0.942523	
Hypothesized Mean Difference	0	
df	27	
t Stat	0.375424	
P(T<=t) one-tail	0.355139	
t Critical one-tail	1.703288	
P(T<=t) two-tail	0.710279	
t Critical two-tail	2.051831	

Table T: M1CW T-test for T_2 to T_3

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	43.75678571	42.6114286
Variance	10.33337817	36.7447831
Observations	28	28
Pearson Correlation	0.295102369	
Hypothesized Mean Difference	0	
df	27	
t Stat	1.016089704	
P(T<=t) one-tail	0.159302946	
t Critical one-tail	1.703288446	
P(T<=t) two-tail	0.318605892	
t Critical two-tail	2.051830516	

Table U: M1RW T-test for T_2 to T_3

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	30.17321	30.66071
Variance	9.851119	6.151607
Observations	28	28
Pearson Correlation	0.824823	
Hypothesized Mean Difference	0	
df	27	
t Stat	-1.45094	
P(T<=t) one-tail	0.079158	
t Critical one-tail	1.703288	
P(T<=t) two-tail	0.158316	
t Critical two-tail	2.051831	

Table V: M1PW T-test for T_2 to T_3

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	60.35679	59.74143
Variance	11.29249	10.95048
Observations	28	28
Pearson Correlation	0.846078	
Hypothesized Mean Difference	0	
df	27	
t Stat	1.759213	
P(T<=t) one-tail	0.044935	
t Critical one-tail	1.703288	
P(T<=t) two-tail	0.089871	
t Critical two-tail	2.051831	

Table W: M1BW T-test for T_2 to T_3

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	22.40714286	22.3135714
Variance	22.42706561	15.7235868
Observations	28	28
Pearson Correlation	0.390504441	
Hypothesized Mean Difference	0	
df	27	
t Stat	0.102172068	
P(T<=t) one-tail	0.459687569	
t Critical one-tail	1.703288446	
P(T<=t) two-tail	0.919375139	
t Critical two-tail	2.051830516	

Table X: Interorbital T-test for T_2 to T_3

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	77.65179	79.82714
Variance	46.5243	38.0697
Observations	28	28
Pearson Correlation	0.552536	
Hypothesized Mean Difference	0	
df	27	
t Stat	-1.86519	
P(T<=t) one-tail	0.036529	
t Critical one-tail	1.703288	
P(T<=t) two-tail	0.073058	
t Critical two-tail	2.051831	

Table Y: Extraorbital T-test for T_2 to T_3

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	29.45411765	29.9464706
Variance	14.59061324	19.0050243
Observations	17	17
Pearson Correlation	0.944915736	
Hypothesized Mean Difference	0	
df	16	
t Stat	-1.392312	
P(T<=t) one-tail	0.091438969	
t Critical one-tail	1.745883676	
P(T<=t) two-tail	0.182877938	
t Critical two-tail	2.119905299	

Table Z: NFW T-tests for T_2 to T_4

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	28.18176	30.03176
Variance	5.59799	4.468753
Observations	17	17
Pearson Correlation	0.829587	
Hypothesized Mean Difference	0	
df	16	
t Stat	-5.73626	
P(T<=t) one-tail	1.53E-05	
t Critical one-tail	1.745884	
P(T<=t) two-tail	3.06E-05	
t Critical two-tail	2.119905	

Table AA: NPW T-test for T_2 to T_4

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	69.27	73.83882353
Variance	39.46305	27.16981103
Observations	17	17
Pearson Correlation	0.869464	
Hypothesized Mean Difference	0	
df	16	
t Stat	-6.05077	
P(T<=t) one-tail	8.42E-06	
t Critical one-tail	1.745884	
P(T<=t) two-tail	1.68E-05	
t Critical two-tail	2.119905	

Table AB: MSW T-test for T_2 to T_4

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	33.78176471	34.2111765
Variance	10.89592794	10.437336
Observations	17	17
Pearson Correlation	0.89722117	
Hypothesized Mean Difference	0	
df	16	
t Stat	-1.19448395	
P(T<=t) one-tail	0.124848191	
t Critical one-tail	1.745883676	
P(T<=t) two-tail	0.249696383	
t Critical two-tail	2.119905299	

Table AC: M1CW T-test for T_2 to T_4

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	44.26176	41.72412
Variance	7.988803	4.450576
Observations	17	17
Pearson Correlation	0.632856	
Hypothesized Mean Difference	0	
df	16	
t Stat	4.730453	
P(T<=t) one-tail	0.000113	
t Critical one-tail	1.745884	
P(T<=t) two-tail	0.000226	
t Critical two-tail	2.119905	

Table AD: M1RW T-test for T_2 to T_4

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	30.00353	31.62058824
Variance	12.04885	11.68484338
Observations	17	17
Pearson Correlation	-0.1035	
Hypothesized Mean Difference	0	
df	16	
t Stat	-1.30282	
P(T<=t) one-tail	0.105539	
t Critical one-tail	1.745884	
P(T<=t) two-tail	0.211077	
t Critical two-tail	2.119905	

Table AE: M1PW T-test for T_2 to T_4

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	60.62411765	60.1088235
Variance	12.44151324	6.25227353
Observations	17	17
Pearson Correlation	0.683312558	
Hypothesized Mean Difference	0	
df	16	
t Stat	0.824477481	
P(T<=t) one-tail	0.210894979	
t Critical one-tail	1.745883676	
P(T<=t) two-tail	0.421789958	
t Critical two-tail	2.119905299	

Table AF: M1BW T-test for T_2 to T_4

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	23.33765	23.25294
Variance	27.34894	15.44312
Observations	17	17
Pearson Correlation	0.655888	
Hypothesized Mean Difference	0	
df	16	
t Stat	0.087771	
P(T<=t) one-tail	0.465574	
t Critical one-tail	1.745884	
P(T<=t) two-tail	0.931148	
t Critical two-tail	2.119905	

Table AG: Interorbital T-test for T_2 to T_4

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	79.10647	82.22823529
Variance	39.38416	28.39305294
Observations	17	17
Pearson Correlation	0.657086	
Hypothesized Mean Difference	0	
df	16	
t Stat	-2.63664	
P(T<=t) one-tail	0.008976	
t Critical one-tail	1.745884	
P(T<=t) two-tail	0.017951	
t Critical two-tail	2.119905	

Table AH: Extraorbital T-test for T_2 to T_4

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	29.78353	29.94647
Variance	12.78195	19.00502
Observations	17	17
Pearson Correlation	0.927145	
Hypothesized Mean Difference	0	
df	16	
t Stat	-0.39546	
P(T<=t) one-tail	0.348865	
t Critical one-tail	1.745884	
P(T<=t) two-tail	0.697729	
t Critical two-tail	2.119905	

Table AI: NFW T-tests for T_3 to T_4

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	28.63824	30.03176
Variance	4.881203	4.468753
Observations	17	17
Pearson Correlation	0.944869	
Hypothesized Mean Difference	0	
df	16	
t Stat	-7.93678	
P(T<=t) one-tail	3.07E-07	
t Critical one-tail	1.745884	
P(T<=t) two-tail	6.15E-07	
t Critical two-tail	2.119905	

Table AJ: NPW T-test for T_3 to T_4

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	70.91882	73.83882
Variance	24.42969	27.16981
Observations	17	17
Pearson Correlation	0.879255	
Hypothesized Mean Difference	0	
df	16	
t Stat	-4.79878	
P(T<=t) one-tail	9.84E-05	
t Critical one-tail	1.745884	
P(T<=t) two-tail	0.000197	
t Critical two-tail	2.119905	

Table AK: MSW T-test for T_3 to T_4

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	33.75824	34.21118
Variance	11.69034	10.43734
Observations	17	17
Pearson Correlation	0.927678	
Hypothesized Mean Difference	0	
df	16	
t Stat	-1.4613	
P(T<=t) one-tail	0.081647	
t Critical one-tail	1.745884	
P(T<=t) two-tail	0.163293	
t Critical two-tail	2.119905	

Table AL: M1CW T-test for T_3 to T_4

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	42.08059	41.72412
Variance	6.145406	4.450576
Observations	17	17
Pearson Correlation	0.26046	
Hypothesized Mean Difference	0	
df	16	
t Stat	0.523859	
P(T<=t) one-tail	0.303779	
t Critical one-tail	1.745884	
P(T<=t) two-tail	0.607558	
t Critical two-tail	2.119905	

Table AM: M1RW T-test for T_3 to T_4

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	30.48706	31.62059
Variance	7.968585	11.68484
Observations	17	17
Pearson Correlation	0.16859	
Hypothesized Mean Difference	0	
df	16	
t Stat	-1.15408	
P(T<=t) one-tail	0.132707	
t Critical one-tail	1.745884	
P(T<=t) two-tail	0.265413	
t Critical two-tail	2.119905	

Table AN: M1PW T-test for T_3 to T_4

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	60.22882	60.10882
Variance	8.357199	6.252274
Observations	17	17
Pearson Correlation	0.70067	
Hypothesized Mean Difference	0	
df	16	
t Stat	0.233762	
P(T<=t) one-tail	0.409067	
t Critical one-tail	1.745884	
P(T<=t) two-tail	0.818135	
t Critical two-tail	2.119905	

Table AO: M1BW T-test for T_3 to T_4

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	22.21176	23.25294
Variance	13.24473	15.44312
Observations	17	17
Pearson Correlation	0.581173	
Hypothesized Mean Difference	0	
df	16	
t Stat	-1.23594	
P(T<=t) one-tail	0.117159	
t Critical one-tail	1.745884	
P(T<=t) two-tail	0.234319	
t Critical two-tail	2.119905	

Table AP: Interorbital T-test for T_3 to T_4

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	80.30941	82.22824
Variance	35.69887	28.39305
Observations	17	17
Pearson Correlation	0.629539	
Hypothesized Mean Difference	0	
df	16	
t Stat	-1.61471	
P(T<=t) one-tail	0.062959	
t Critical one-tail	1.745884	
P(T<=t) two-tail	0.125918	
t Critical two-tail	2.119905	

Table AQ: Extraorbital T-test for T_3 to T_4

Birthdate	CBCT T_1	Age at T_1	CBCT T_2	Age at T_2	CBCT T_3	Age at T_3
8/29/2006	4/8/2014	7.61	1/6/2015	8.35	10/11/2017	11.12
6/18/2004	8/21/2012	8.18	8/20/2013	9.17	4/5/2016	11.80
9/30/2002	10/18/2010	8.05	12/7/2011	9.19	7/1/2013	10.75
9/18/1999	3/15/2010	10.49	6/22/2010	10.76	9/29/2011	12.03
4/1/2003	3/19/2012	8.97	11/20/2012	9.64	8/13/2013	10.37
6/1/2002	4/2/2012	9.84	5/1/2013	10.92	4/2/2014	11.84
6/26/2002	5/8/2012	9.87	4/15/2013	10.80	11/27/2013	11.42
5/30/2001	1/25/2011	9.65	8/8/2011	10.19	11/4/2013	12.43
7/25/2006	9/23/2015	9.16	6/23/2016	9.91	6/5/2017	10.86
9/4/2002	2/15/2011	8.45	2/28/2012	9.48	1/29/2014	11.40
7/2/2002	1/13/2014	11.53	10/28/2014	12.32	9/12/2016	14.19
11/29/2002	6/24/2013	10.57	3/24/2014	11.32	2/10/2015	12.20
4/7/2002	2/8/2011	8.84	9/22/2011	9.46	7/30/2013	11.31
4/4/2000	12/17/2009	9.70	3/2/2011	10.91	11/14/2012	12.61
4/5/2004	2/18/2013	8.87	7/1/2014	10.24	2/28/2015	10.90
4/1/2004	6/21/2012	8.22	8/20/2013	9.39	5/20/2014	10.14
1/2/1999	3/15/2010	11.20	3/28/2011	12.24	3/12/2013	14.19
9/18/2000	8/2/2010	9.87	7/25/2011	10.85	8/15/2012	11.91
5/12/2003	3/26/2013	9.87	12/23/2013	10.61	8/19/2014	11.27
4/23/2003	1/26/2011	7.76	5/22/2012	9.08	11/18/2014	11.57
3/15/2006	9/3/2014	8.47	9/21/2015	9.52	6/5/2017	11.22
8/15/2001	3/22/2011	9.60	10/11/2011	10.16	7/8/2013	11.90
5/14/2006	7/2/2013	7.13	7/7/2014	8.15	9/12/2016	10.33
1/29/2004	10/4/2011	7.68	4/2/2014	10.18	1/18/2016	11.97
2/23/2003	11/22/2011	8.75	5/6/2013	10.20	7/1/2015	12.36
9/19/2000	11/19/2009	9.17	11/1/2010	10.12	11/29/2011	11.19
9/13/2002	9/5/2012	9.98	1/15/2013	10.34	11/6/2013	11.15
5/21/2003	6/30/2011	8.11	3/26/2012	8.85	7/27/2015	12.18
AVERAGE		9.13		10.08		11.66

Table AR: Age at Each Time Point for the 28 patients

Birthdate	CBCT T_1	Age at T_1	CBCT T_2	Age at T_2	CBCT T_3	Age at T_3	CBCT T_4	Age at T_4
9/30/2002	10/18/2010	8.05	12/7/2011	9.19	7/1/2013	10.75	11/22/2016	14.14
9/18/1999	3/15/2010	10.49	6/22/2010	10.76	9/29/2011	12.03	8/25/2014	14.94
4/1/2003	3/19/2012	8.97	11/20/2012	9.64	8/13/2013	10.37	7/24/2017	14.31
6/1/2002	4/2/2012	9.84	5/1/2013	10.92	4/2/2014	11.84	6/26/2017	15.07
6/26/2002	5/8/2012	9.87	4/15/2013	10.80	11/27/2013	11.42	8/30/2016	14.18
5/30/2001	1/25/2011	9.65	8/8/2011	10.19	11/4/2013	12.43	4/18/2016	14.88
7/2/2002	1/13/2014	11.53	10/28/2014	12.32	9/12/2016	14.19	8/16/2017	15.12
11/29/2002	6/24/2013	10.57	3/24/2014	11.32	2/10/2015	12.20	3/28/2016	13.33
4/4/2000	12/17/2009	9.70	3/2/2011	10.91	11/14/2012	12.61	12/19/2016	16.71
4/5/2004	2/18/2013	8.87	7/1/2014	10.24	2/28/2015	10.90	1/16/2017	12.78
1/2/1999	3/15/2010	11.20	3/28/2011	12.24	3/12/2013	14.19	3/17/2015	16.21
9/18/2000	8/2/2010	9.87	7/25/2011	10.85	8/15/2012	11.91	4/8/2014	13.56
5/12/2003	3/26/2013	9.87	12/23/2013	10.61	8/19/2014	11.27	6/27/2017	14.13
4/23/2003	1/26/2011	7.76	5/22/2012	9.08	11/18/2014	11.57	10/2/2017	14.44
8/15/2001	3/22/2011	9.60	10/11/2011	10.16	7/8/2013	11.90	2/2/2016	14.46
1/29/2004	10/4/2011	7.68	4/2/2014	10.18	1/18/2016	11.97	2/13/2017	13.04
9/19/2000	11/19/2009	9.17	11/1/2010	10.12	11/29/2011	11.19	8/20/2014	13.92
AVERAGE		9.57		10.56		11.93		14.42

Table AS: Age at Each Time Point for the 17 patients with T_4 CBCT Images