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Two and three dimensional cephalometric assessment of dental and skeletal changes following orthodontic treatment with Damon passive self-ligating system

by

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Dedication

To my parents and my sister, for their love and endless support and encouragement

Abstract

Objectives: The aim of this study was to evaluate dental and/or skeletal changes following orthodontic treatment with Damon self-ligating (SL) brackets in non-extraction patients.

Methods: Frontal and lateral cephalomteric radiographs of 20 patients before and after non-extraction treatment with Damon SL brackets were analyzed in a three-dimensional (3D) analysis computer software program (3DCeph, UIC, IL., USA). Bolton templates, which were used as controls, were also analyzed in 3DCeph. Changes of upper and lower intermolar and intercanine distances (both crowns and roots), incisor positions and maxillary basal bone width of subjects treated with Damon SL brackets were compared to corresponding untreated controls. Comparisons between the two groups were made with Nonparametric (Mann-Whitney U) test.

Results: Distance between roots of upper molars increased 4.59 mm in Damon group compared with 0.8 mm in the Control group ($P < 0.001$). Distance between roots of lower canines increased 3.49 mm in Damon group, whereas it decreased by 0.01 mm in the control group ($P = 0.001$). Changes of other transverse dimensions, were not significantly different between the two groups ($P > 0.01$). Damon treatment resulted in statistically greater proclination of lower incisors and lingual root torque of upper incisors ($P<0.05$). In Damon group, interjugular distance increased, whereas angles made between first molars and *Crista Galli-*

A point line decreased, but their changes were not statistically significantly different compared to the control group ($P>0.05$).

Conclusion: Transverse changes in distances between crowns of upper and lower first molars and canines in patients treated with Damon SL system were similar to those of untreated individuals. However, changes of upper intermolar distances (roots) and lower intercanine distances (roots) were larger in Damon patients. Lingual root torque of upper incisors and proclination of lower incisors were larger in the Damon treated group. Damon treatment did not result in buccal tipping of molar crowns or maxillary base width increase. Overall, teeth alignment with Damon system appears to be accomplished with a combination of arch width changes and incisor proclination and/or lingual root torque.

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List of Abbreviations

J-J	Interjugular distance
L1	Lower incisor
LCC	Distance between Crowns of Lower Canines
LCR	Distance between Roots of Lower Canines
LMC	Distance between Crowns of Lower Molars
LMR	Distance between Roots of Lower Molars
SD	Standard Deviation
SL	Self-ligating
T1	Pre-treatment
T2	Post-treatment
U1	Upper Incisor
UCC	Distance between Crowns of Upper Canines
UCR	Distance between Roots of Upper Canines
UMC	Distance between Crowns of Upper Molars
UMR	Distance between Roots of Upper Molars
2D	Two-dimensional
3D	Three-dimensional

1 CHAPTER 1.Introduction and Literature review

1.1 Introduction

1.1.1 Three dimensional vs. two dimensional analysis

In orthodontics, it is usually difficult to diagnose and plan treatment of severe craniofacial problems using only the lateral cephalometric projection, without having the frontal image. In 1975, Broadbent and Bolton (1) suggested the coordination of the two views, i.e. lateral and frontal, for an accurate evaluation. In 1988, Grayson (2) noted that a radiographic landmark must be connected to the x-ray source in both projections so that it can be located in the head. In 1989, Brown and Abbot (3) used a computer system that transferred an imaginary line, which contains the reference point, from one projection to the other. Today, three-dimensional imaging systems have widespread use among orthodontists as it provides them with more accurate information for treatment planning, assessment of treatment outcome and studying craniofacial growth and development than lateral cephalomteric radiographs do.

1.1.2 Three dimensional analysis of two separate ordinary cephalograms vs. CT scan

Three-dimensional (3D) information and measurements may be obtained from either a 3D Computed Tomography (CT) scan or a 3D analysis of two separate two-dimensional (2D) projections. However, 3D analysis of two separate 2D projections (e.g. a Frontal and a Lateral view) has some advantages over the 3D CT scan.

The first drawback of a medical CT is its higher radiation exposure of the patient compared to the 3D analysis. According to Grayson (1988) (2), the skin dose radiation that a patient receives while taking a pair of cephalograms is about 26 milli rad, whereas a series of medical CT slices would expose the patient to 6.5 rad. Therefore, obviously it is more rational to use 3D analysis of two 2D images in longitudinal studies that require records to be taken repeatedly. It is noteworthy that the above mentioned properties do not apply to newer dental cone beam CT (CBCT) imaging techniques. Second, according to Grayson (1988) (2), there are baseline data to which results of a 3D analysis may be compared, whereas such normative baseline data for use in CT studies is not as abundant. Last but not least, the high cost of a CT record is an obstacle that calls for use of alternative imaging methods. According to Kusnoto (1999) (4), the cost of a 3D CT record is much higher than that of multiple regular cephalometric images.

Moreover, the existing normative data only exist in 2D; the only way to get somehow a representative in 3D is by using a constructive 3D from two 2D images.

1.1.3 **3DCeph** *system*

3DCeph is a system which uses different combinations of two-dimensional (2D) cephalometric projections to create an accurate three-dimensional (3D) computer model.

The system consists of two separate modules:

- The first module is the 3DCeph2000 which converts the 2D images into 2D wires which can be processed by the second module.
- The second module is the 3D-Aligner which aligns and converts the 2D wires into a 3D image and generates 3D measurements.

In the present study, 3DCeph was used for the purpose of construction of three-dimensional records.

1.1.4 Reliability of **3DCeph** *system*

Reliability of 3D measurements, both linear and angular, which were generated using different combinations of cephalometric projections, were assessed by Kusnoto et al in 1999. (4) In their study, they used four combinations of cephalometric projections with 20 landmarks and studied 22 linear and 10 angular measurements, using the 3DCeph computer program. They also reported no significant difference between the results of lateral-basilar and lateral-frontal combinations and therefore the latter combination which is a more practical choice was recommended.

1.1.5 Solving tooth size/arch size discrepancies and transverse problems

There are several possible approaches in case of tooth size discrepancies (Proffit, 2000) (5):

- Changing the inclination of incisors (torque): This will compensate for a small size differential.

- IPR (Interproximal reduction): Stripping of enamel reduces the width of the tooth.
- Building up the width of an anomalously small tooth: This can be done by adding composite resin or crown.
- Changing the extraction plan: For example larger lower second premolars can be extracted rather than first premolars.
- Accepting a small space in one of the arches: This is usually the space distal to the lateral incisors.
- Expansion: Transverse problems can be treated by either skeletal or dental expansion, depending on the anatomic basis of the problem. Skeletal expansion can be either rapid (changes occur in days) or slow (changes occur in weeks).

There are different opinions regarding these approaches though. According to McNamara (1998) (6), long-term effects of IPR on both periodontal structures and dentition are questionable. As for extraction therapy, McNamara (1998) (6) admits that this approach yields acceptable long-term results, however he points out that this strategy is usually associated with incisor irregularity during the post-retention period. As for expansion, McNamara considers Passive Expansion to be technically demanding and also conditional to patient cooperation. As for Rapid maxillary Expansion (RME), McNamara claims that the force generated by this technique comes up to 3-10 pounds, while according to Mahony (2006) (7), a 20-26 g/cm^2 force can collapse capillaries of the periodontal ligament. As Mahony (2006) (7) notes, use of low-force orthodontics, which will allow the alveolar bone to be reshaped and followed by bodily movement of the teeth, is recommended and promoted in today's orthodontic practice.

1.1.6 Self-ligation and self-ligating brackets

The term self-ligation in orthodontics infers that the orthodontic bracket has the ability to engage itself to the archwire. Self-ligating (SL) brackets have a mechanical device built into the bracket to close off the slot.

There are two categories of SL brackets:

- Active SL brackets: in which a spring clip actively presses against the archwire.
- Passive SL brackets: in which the SL clip closes the slot creating a tube. In this type, the clip does not actively press against the wire.

In a SL bracket, whether active or passive, the movable fourth wall of the bracket converts the slot into a tube. Although recently SL brackets have made a significant comeback, these brackets are not new to orthodontics; in 1930s, the first SL bracket, called the Russell attachment, was developed with the purpose of reducing ligation time and therefore increasing clinical efficiency. (8)

The reported advantages of SL brackets include: secured wire ligation, improved oral hygiene, chair-side time savings, improved ergonomics, minimizing chances of percutaneous injuries from the metal ligatures, quicker treatment times and longer appointment intervals. (8-14)

Although reduced friction between the archwire and bracket interface has been reported to be one of the advantages of self ligation (12), (13), (15), a systematic review (16) , which was conducted to compare the amount of expressed frictional resistance between orthodontic SL brackets and conventionally ligated brackets in an in vitro setting as reported in the literature, revealed that compared with conventional brackets, SL brackets maintain lower friction only when coupled with small round archwires in the absence of tipping and/or torque in an ideally aligned arch. It was also revealed that there is not enough evidence yet to claim that with large rectangular wires, in the presence of tipping and/or torque and in arches with considerable malocclusion, SL brackets produce lower resistance to sliding compared with conventional brackets.

One of the other claims regarding SL brackets and archwires is their ability to produce posterior dental transverse changes. Damon (1998) (15) claims that in non-extraction cases, light-forced mechanics [Damon system] produce posterior expansion with teeth and archform taking path of least resistance. Few studies have assessed the above-mentioned expansion. Two (17), (18) out of three (17-19) studies which compared expansion with SL brackets and with conventional brackets reported a significantly greater increase in intermolar width with SL brackets, whereas one study (19) reported no significant differences. All three studies reported no significant difference between changes of intercanine widths. As for interpremolar width, it was only investigated by one (18) of the studies and was reported not to be different among the two treatment groups. It is note-worthy that all these studies were done using dental casts and had different inclusion criteria for the subjects. Details of these studies can be found under the Literature Review section of this paper.

1.1.7 Damon passive self-ligating bracket

Damon self-ligating bracket is a passive SL bracket. According to D. H. Damon, inventor of this orthodontic bracket, Damon SL bracket has specific features (20):

- It is in agreement with Andrews straight-wire principles.
- It has a Twin bracket wing configuration.
- Its Passive slide is on the buccal face of the bracket.
- It slide opens with a downward motion.
- A complete tube is formed when the slide closes.

Damon (1998) (20) claims that unlike active SL brackets, which rely on their clip to create the force that moves the teeth, passive SL brackets are contingent upon the flexibility of the Copper Nickel Titanium (CNiTi) archwire. According to Damon (1998) (20), unlike the conventional orthodontic brackets, the Damon bracket-wire interface (reduced friction in all stages of treatment) and variable torque configurations built into the bracket take advantage of cheeks, tongue and periodontal forces in order to move teeth into the desired position. This dentoalveolar transverse adaptation occurs early in treatment with small round archwires. Therefore, a balance of all these tissues and forces will establish the position of the teeth and the archform. However, the mechanism is not fully understood and there is lack of abundant evidence that would support this claim.

D.H. Damon (1998) (15) recommends the following archwire (AW) sequence to be used with this system:

- Phase I: 0.014 ” Damon Copper Ni-Ti and 0.016” Ni-Ti SE

Light Copper Ni-Ti round wires are recommended so that cellular activity of periodontium is stimulated without disrupting its blood supply. Using a small AW in a large slot will allow sliding of the teeth with minimal resistance along the AW therefore minimizing anterior tipping.

- Phase II: 0.014” × 0.025” Damon Copper Ni-Ti (with 0.022” brackets), 0.018” × 0.025’’ Damon Copper Ni-Ti

  These combinations help with levelling, rotations, development of the archform and initial torque control.

- Phase III: 0.019”×.025” stainless steel (SS) (with 0.022” slot) or 0.016”× 0.025” stainless steel wire

  These combinations help with posterior space closure, buccolingual discrepancies, completion of torque and archform development, maintenance of vertical dimension and finishing the case.

- Phase IV: 0.019”×.025” stainless steel or TMA

  This AW helps with torque, details and making minimal adjustments.

1.1.8 Bolton Templates (standards)

Bolton templates are considered to be standard representations of average untreated individual’s facial and dental traits at any given age between 3 and 18.

These templates were created by studying serial cephalometric recordings of about 5,000 Caucasian males and females who, according to Broadbent, had optimum facial and dental developmental growth. The subjects of this longitudinal study were all in good health, had normal occlusion and had received no orthodontic treatment. Records of some of these subjects were taken in a longitudinal manner with either a six-month or a one-year interval until reaching adulthood. The Bolton study database contains over 22,000 recordings and is therefore one of the largest longitudinal studies of its kind.

Bolton templates and their corresponding linear and angular measurements are used as standards for comparative orthodontic studies in which outcomes of orthodontic interventions or developmental growth of subjects are being investigated. More information about the Bolton study and the templates can be found in “Bolton Standards of Dentofacial Developmental Growth” by Broadbent et al (1975) (1).

In the present study, we used templates of ages 10 to 18 as our control group.

1.2 Literature review

1.2.1 Studying expansion with SL brackets

1.2.2 Summary

Following a systematic search of the literature, three relevant papers were found. (17-19). The search included computerized search of electronic databases plus a manual search of reference lists of relevant papers up to December 2009. The selection criterion defined for this systematic search was “studying expansion with self-ligating brackets”. The search strategies, the results retrieved from each electronic database and the manual search are illustrated in Table 1.

Database	Search Strategy	Number of Results	Paper's Details: Author; Publishing Date
Medline (From 1950 to November Week 3 2009)	(((Orthodontic bracket*) OR (exp Orthodontic Brackets)) AND ((self ligat* OR self ligation))) AND (inter molar OR inter-molar OR intermolar OR arch width OR arch expansion)	2	• Fleming; 2009 (21) • Pandis; 2007 (17)
Pubmed (From 1950 to Dec 7, 2009)	Same as Medline	6	• Fleming; 2009 (21) • Scott; 2008 (19) • Pandis; 2007 (17) • Yeh; 2007(22) • Zachrisson; 2006 (23) • Bednar 1993 (24)
Embase	Same as Medline	0	N/A

(1980 to 2009 Week 49)			
Web of Science (Up to Dec 05, 2009)	[(TS=orthodontic bracket*) AND (TS=self ligat* OR self ligation)] AND [TS=(inter molar OR inter-molar OR intermolar OR arch width OR arch expansion)]	4	• Scott; 2008 (19) • Yeh; 2007 (22) • Loftus; 2001 (25) • Bednar; 1993 (24)
Cochrane Library (Up to Dec 07, 2009)	Same as Medline	2	• Pandis; 2007 (17) • Scott; 2008 (19)
Manual Search	Searched the reference lists of selected articles	1	• Jiang; 2008 (18)
Total	N/A	15	N/A
Duplicates	N/A	7	N/A
Total after removing duplicates	N/A	8	N/A
Irrelevant papers	N/A	5	• Fleming; 2009 (21) • Yeh; 2007 (22) • Zachrisson;

			2006 (23) • Loftus; 2001 (25) • Bednar; 1993 (24)
Total relevant results	N/A	3	• Scott; 2008 (19) • Jiang; 2008 (18) • Pandis; 2007 (17)

Table 1-1- Search dates, search strategies and number of results for each database

Author	Objective (√)	Sample size (√)	Baseline Characteristics (√)	Randomization (√)	Co interventions (√)	Measurement method (√)	Blinding (examiner√) (statistician√)	Reliability Testing (√)	Statistical Analysis (appropriate√) (combined subgroup√)	Confounders included in analysis (√)	Stat Significance (P-value√)(CI√)	Clinical significance (√)	Total score (out of 15)
Pandis et al 2007 (17)	√	√	√	√	√	√	××	√	√√	√	√√	√	13
Jiang et al 2008* (18)	√	√	√	-	√	-	- -	- -	√√	√	√-	-	-
Scott et al 2008 (19)	√	√	√	√	×	√	√×	√	√√	√	√√	√	13

Table 1-2- Methodological scores for the selected papers (Good √ , Poor ×, Not observed -)
* *Since the full text of this paper was not available in English, only the abstract could be reviewed. Therefore, some of the quality factors could not be scored for this paper.*

A recent study by Pandis et al (2007) (17) compared the arch expansion of the mandible of 54 subjects with mandibular irregularity index of greater than 2 who were treated with either Damon SL brackets or conventional brackets. All subjects were treated with a non-extraction approach in combination with no additional therapeutic interventions (i.e. lip bumpers, headgears, etc.). Intercanine (distance between cusp tips) and intermolar (distance between central grooves) widths were recorded using a digital calliper from dental casts taken before and after treatment. It was reported that both groups showed a small but statistically significant expansion in the mandibular arch. Intermolar width increase in the self-ligating Damon group (2 mm) was statistically greater compared to the conventional group (0.5 mm), whereas intercanine width increase was not significantly different between bracket groups.

A more recent study by Jiang et al in 2008 (18) compared transverse changes following non-extraction treatment with Damon MX (3) passive SL and conventional bracket systems. This study reported that compared with conventional appliances, treatment with Damon MX (3) brackets resulted in significantly greater intermolar width increases. No statistically significant differences in the changes of the intercanine and interpremolar widths were reported.

Another study in 2008 by Scott et al (19) compared the efficiency of mandibular tooth alignment and the clinical effectiveness of Damon 3 SL (Ormco, Glendora, California) and Synthesis (Ormco) conventional pre-adjusted edgewise orthodontic bracket systems; The Damon AW sequence was used in both groups though. As secondary outcome measures, changes in arch dimension were evaluated in this study. Sixty two subjects with permanent dentition, under the age of 30 and with a prescribed extraction pattern including the mandibular first premolars were randomly allocated to either of the two treatment groups. Changes in arch dimensions were measured with digital callipers from dental study casts taken before and after the treatment. Intercanine width (distance between the mandibular canine cusp tips) increased by 2.55 (±2.27) and 2.66 (±2.33) millimetres in Damon and conventional ligation groups, respectively.

Intermolar width (distance between the mandibular first molar's central grooves) increased by 0.63 (±2.12) mm in the conventional group, whereas this dimension showed a small decrease in the Damon group (0.09±2.4). Changes of either the intercanine or intermolar width were not significantly different between the two groups.

1.3 Objectives of this study

The objective of this study was to determine whether dental and/or skeletal changes following orthodontic treatment with Damon SL brackets in non-extraction patients are greater than what normally occurs as a result of growth. Therefore, intermolar, intercanine and interjugular distances as well as first molar angulations and incisor proclination were studied. (Figures 1-1, 1-2 and 1-3)

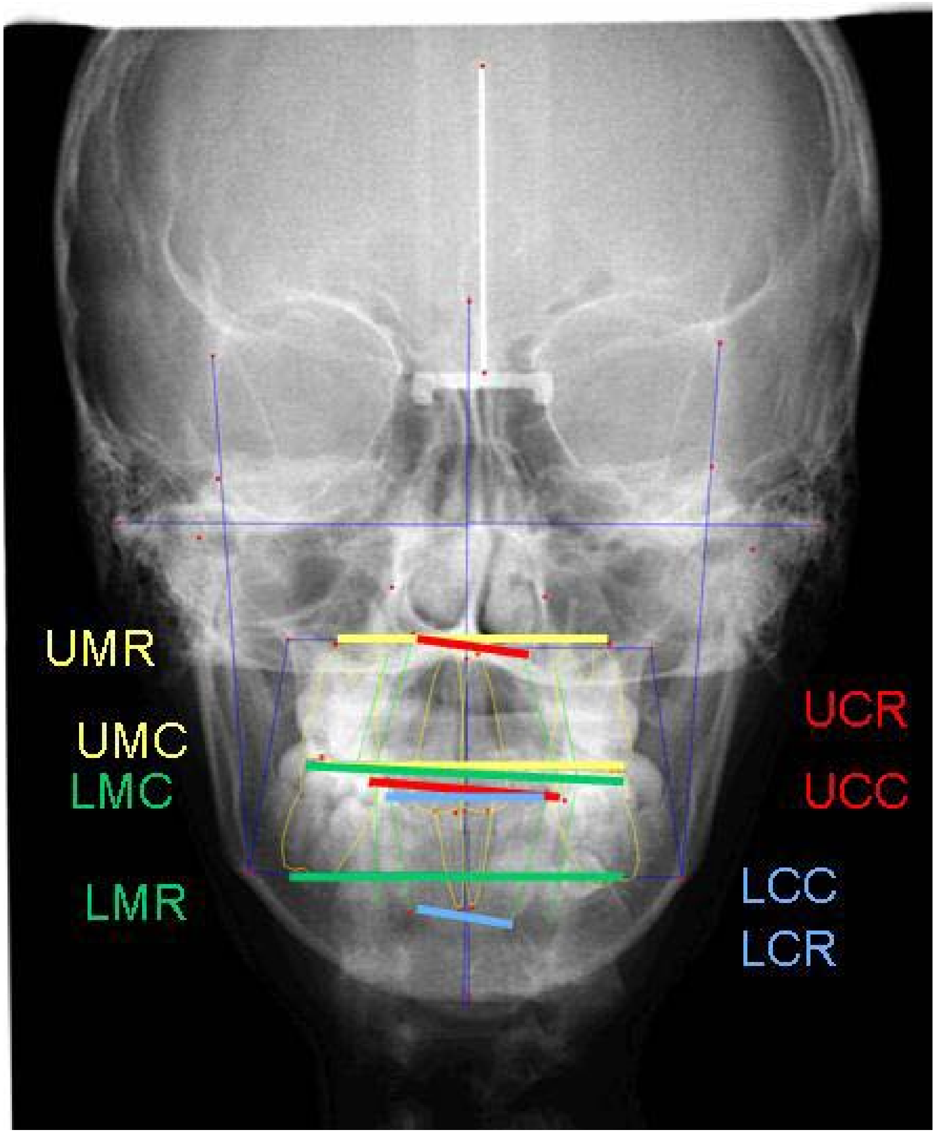

Figure 1-1-Dental measurements: UMR= distance between roots of upper molars, UMC=distance between crowns of upper molars, LMC=distance between crowns of lower molars, LMR=distance between roots of lower molars, UCR=distance between roots of upper canines, UCC=distance between crowns of upper canines, LCC=distance between crowns of lower canines and LCR=distance between roots of lower canines.

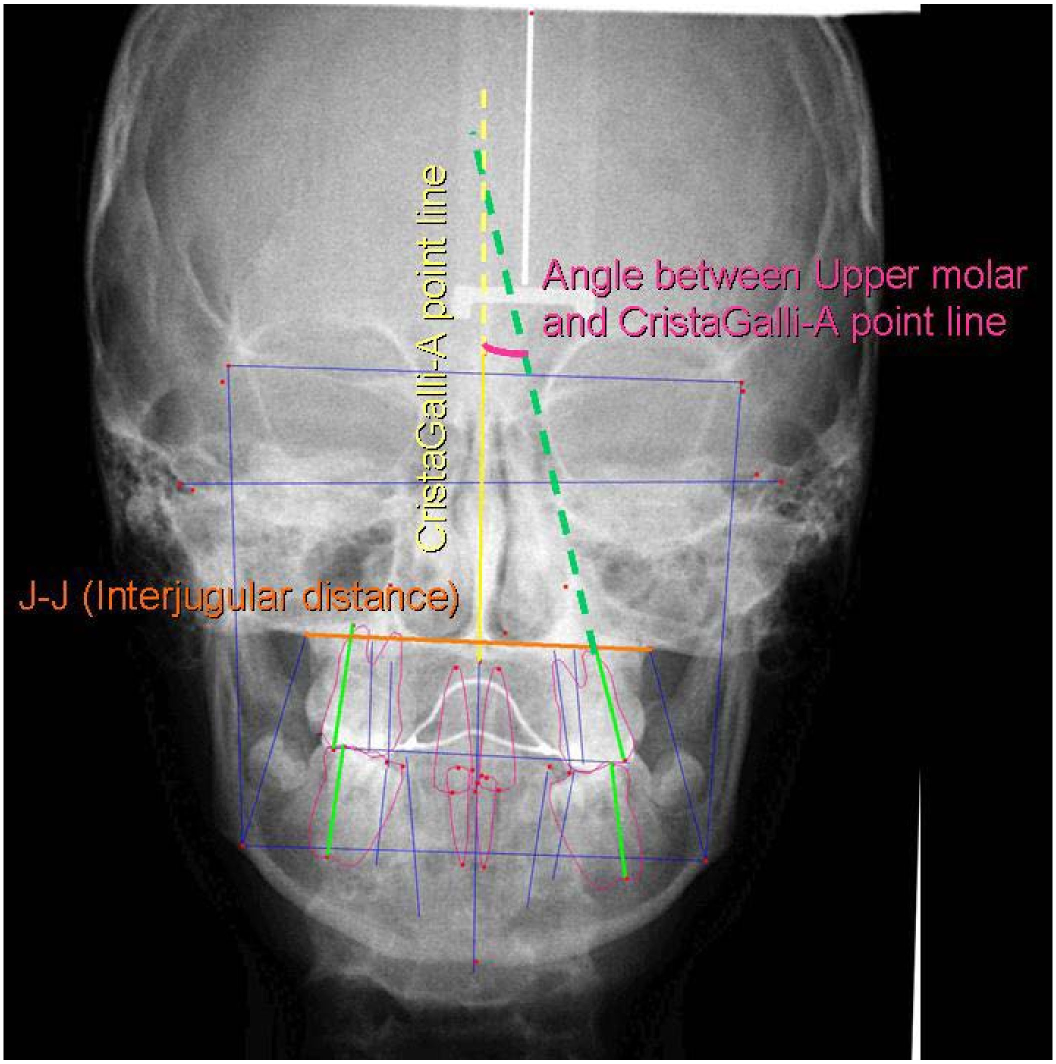

Figure 1-2- Interjugular distance; First molar angulation= the angle between each first molar and the line that connects "Crista galli" to "A-point".

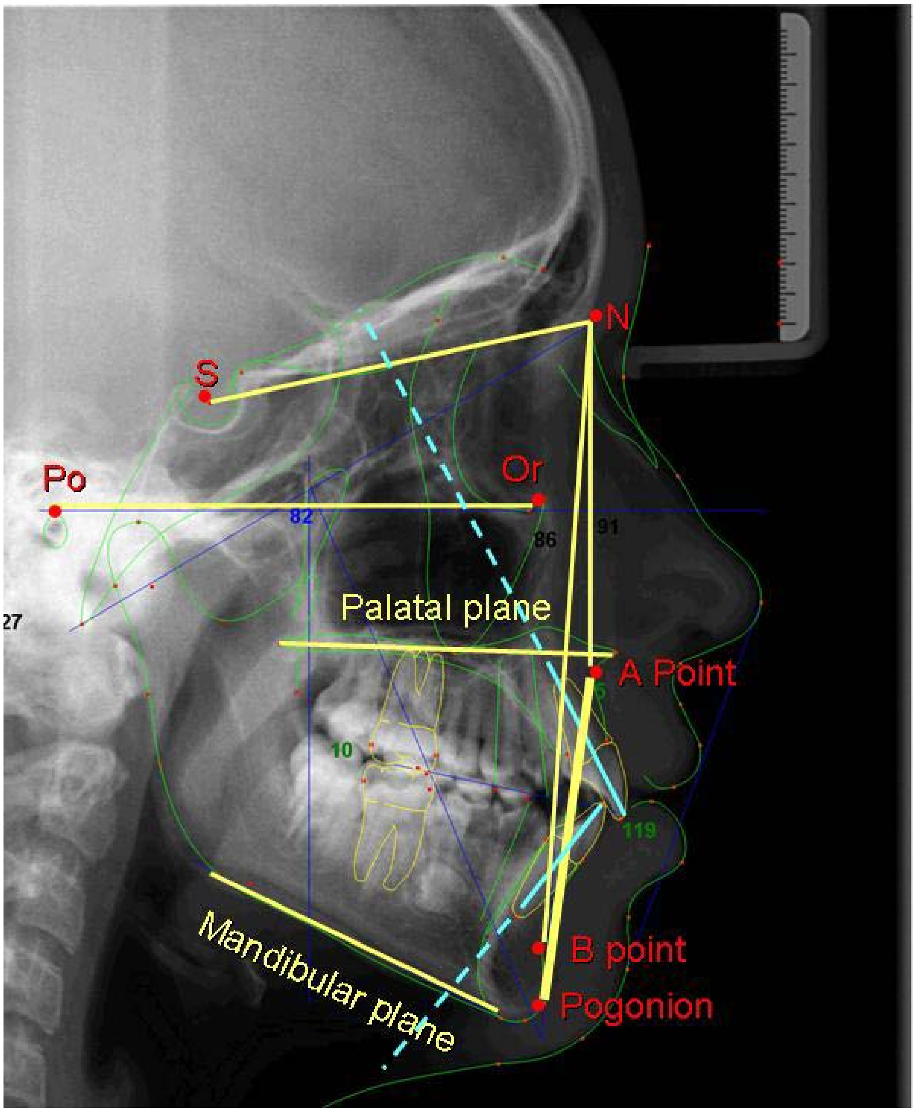

Figure 1-3-Angles and distances studied to determine changes in incisors positions.

1.4 Research hypotheses

Hypothesis 1. Transverse changes (i.e. changes in distances between either crowns or roots of upper and lower first molars and canines) in patients treated with Damon SL system and archwire protocols are similar to those of untreated individuals of Broadbent-Bolton growth templates.

Hypothesis 2. Changes of maxillary base in patients treated with Damon SL system are similar to those of untreated individuals of Broadbent-Bolton growth templates.

Hypothesis 3. Labiolingual Inclination of upper and lower incisors in patients treated with Damon SL system is similar to that of untreated individuals.

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2 CHAPTER 2. Cephalometric assessment of dental and skeletal changes following treatment with passive SL Damon brackets

2.1 Keywords

Self-ligating (SL) brackets, distance between roots of upper molars (UMR), distance between crowns of upper molars (UMC), distance between crowns of lower molars (LMC), distance between roots of lower molars (LMR), distance between roots of upper canines (UCR), distance between crowns of upper canines (UCC), distance between crowns of lower canines (LCC), distance between roots of lower canines (LCR), three dimensional (3D), two dimensional (2D).

2.2 Introduction

According to Rinchuse and Miles (2007) (1), considering the advancements made in orthodontics, the future of orthodontics will probably revolve around three main areas: three-dimensional (3D) imaging replacing two-dimensional (2D) cephalometry, self-ligating (SL) brackets and microimplants as endosseous anchorage. Due to conflicting and scarce reports in the literature, it is still debatable whether or not SL brackets induce posterior expansion. On the other hand, most studies have done their investigations using dental models as opposed to dental x-rays, thereby investigating only the crown distances and not the root distances. By combining the conventional two-dimensional x-rays and studying the distances between both crowns and roots of first molars and canines, we can determine if arch width increases following treatment with SL brackets. Therefore, in this thesis, we are focusing on evaluating the skeletal and dental effects of one of the self-ligating (SL) orthodontic bracket systems (Damon system) using a three-dimensional cephalomteric computer software (3DCeph) in both maxilla and mandible.

2.3 Material and methods

2.3.1 Sample size and inclusion criteria

Approval for this study has been obtained from Health Research Ethics Board, University of Alberta Edmonton, Canada (approval number 6734, 2008). Records of 20 patients who had already finished orthodontic treatment with Damon self-ligating brackets with the same clinician (T.D.C.) were collected based on the following inclusion criteria: having been treated for teeth mal-alignment and having finished treatment with a non-extraction approach using the Damon appliance and mechanics and use of no other appliances in conjunction with the Damon appliance. Pre-treatment crowding values ranged from -14 to +10 millimeters for the included subjects with minus sign (-) and plus sign (+) indicating crowding and spacing, respectively. Subjects, the majority of whom were Caucasians, consisted of all types of Angle molar relationships: Class I (45%), Class II (both subdivisions) (40%) and Class III (15%). As for skeletal relationship, 55% were Class I, 25% were Class II and 20% were Class III. The research subjects' ages ranged from 10 to 16 years of age at baseline (T1) and from 12 to 18 at post-treatment (T2).

2.3.2 Records

Records included pre-treatment (T1) and post-treatment (T2) digital radiographs (including two-dimensional Lateral cephalogram and Posterior-anterior (Frontal) cephalogram).

2.3.3 Tracing the images

Lateral view:

Lateral images were traced according to Rickets comprehensive analysis (2) with the ruler set to 10 millimeters in Dolphin Imaging software, version 11 (Chatsworth, California). Each Lateral image was then aligned on the Frankfort plane. Additional structures namely, cusp tips and root apexes of upper and lower cuspids and first bicuspids were added to the analysis manually.

Identified structures include:

Landmark	**Description**
Ruler point 1	A point on the scanned lateral cephalometric radiograph's ruler.
Ruler point 2	A point at 10 mm distance from ruler Point 1.
A point	Deepest point of the curve of the maxilla, between

	anterior nasal spine (ANS) and the incisor tooth.
Anatomical Gnathion	Midpoint between the most anterior and inferior point on the bony chin.
ANS	The tip of the anterior nasal spine.
Articulare	Intersection of posterior border of the neck of the condyle with base of sphenoid bone.
B Point	Most posterior point in the concavity along the anterior border of the symphysis.
Basion	Most inferior posterior point of the occipital bone at the anterior margin of the occipital foramen.
Clinoidale	Posterior point of the roof of orbit, where it meets anterior of sella turcica.
Condylion	Most posterior superior point of the condyle.
DC Point	Center of the neck of the condyle on the Nasion-Basion line.
Distal L6	Distal surface of the lower first molar, perpendicular to

	the occlusal plane.
Distal U6	Distal surface of the upper first molar, perpendicular to the occlusal plane.
Gonion	The most convex point along the inferior border of the Ramus
4 points of the Inferior alveolar canal	Inferior anterior, inferior posterior, superior anterior, superior posterior
Key ridge	Zygomaxillare: The most inferior point of the zygomatic ridge
L1 Labial gingival border	Labial cemento-enamel junction (CEJ) of the lower central incisor.
L1 Lingual gingival border	Lingual cemento-enamel junction (CEJ) of the lower central incisor.
L1 Root	Root apex of the lower central incisor.
L1 Tip	Tip of the lower central incisor.

L6 occlusal	Point on the occlusal surface crown of the lower first molar.
Lower lip	Most anterior point on the curve of the lower lip.
Menton	Most inferior point of the symphysis.
Mesial L6	Mesial surface of the lower first molar, perpendicular to the occlusal plane.
Mesial U6	Mesial surface of the upper first molar, perpendicular to the occlusal plane.
Mid ramus (R1)	Most concave point on the interior of the ramus.
Roof of orbit	Most superior point of the roof of the orbit.
Nasion	Intersection of the internasal suture with the nasofrontal suture in the midsagittal plane.
Orbitale	Lowest point of the floor of orbit; most inferior point of the external border of the orbital cavity.

PNS	Tip of the posterior nasal spine.
Pogonion	Most anterior point on the mid-sagittal symphysis.
Porion	Highest point of the ear canal; most superior point of the external auditory meatus.
PT point	Intersection of the inferior border of the foramen rotundum with the posterior wall of the pterygomaxillary fissure.
R2	Most convex point on the exterior border of the ramus along the vertical.
R4	Most superior border along the bottom of the ramus.
Ramus point	Most posterior point up the border of the ramus.
Sella	Center of the pituitary fossa of the sphenoid bone.
Sigmoid notch (R3)	Most inferior border along the top of the ramus.

ST Pogonion	Point on the anterior curve of soft tissue chin.
Supra orbitale	Most anterior point of the intersection of the shadow of the root of the orbit and its lateral contour.
Temporale	Point where the anterior wall of the temporale meets the anterior extension of the sphenoid bone.
Tip of nose	Pronasale. Point of the anterior curve of the nose.
U1 root	Root apex of the upper central incisor.
U1 tip	Incisal tip of the upper central incisor.
U6 occlusal	Point on the occlusal surface crown of the upper first molar.

Table 2-1-Landmarks of the Lateral view

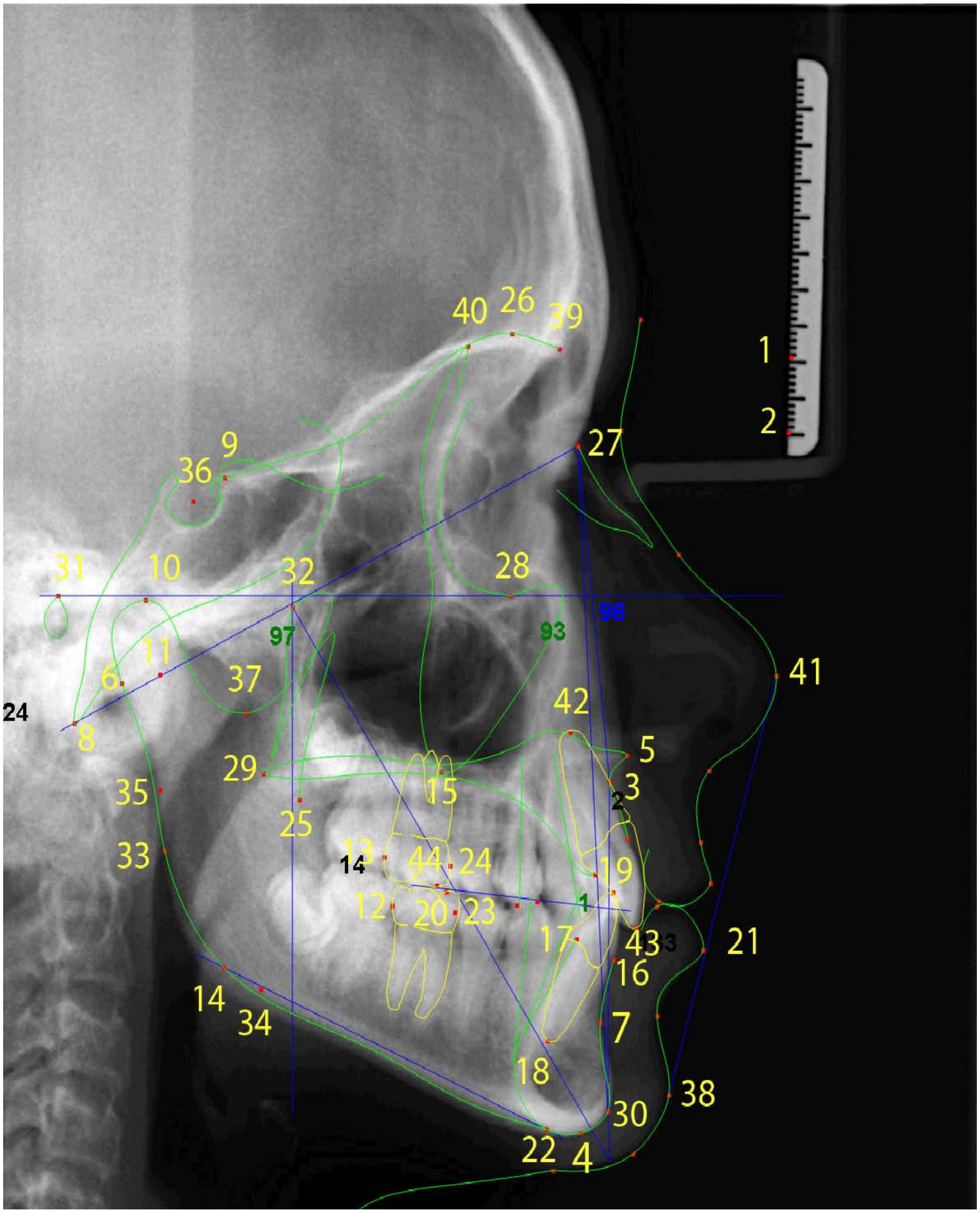


Figure 2-1-Landmarks of the Lateral view: 1) Ruler point 1. 2) Ruler point 2. 3) A point. 4) Anatomical Gnathion. 5) ANS. 6) Articulare. 7) B Point. 8) Basion. 9) Clinoidale. 10) Condylion. 11) DC Point. 12) Distal L6. 13) Distal U6. 14) Gonion. 15) Key ridge. 16) L1 Labial Gingival border. 17) L1 Lingual gingival border. 18) L1 root. 19) L1 tip. 20) L6 occlusal. 21) Lower lip. 22) Menton. 23) Mesial L6. 24) Mesial U6. 25) Mid ramus (R1). 26) Roof of orbit. 27) Nasion. 28) Orbitale. 29) PNS.30) Pogonion. 31) Porion. 32) PT point. 33) R2. 34) R4. 35) Ramus point. 36) Sella. 37) Sigmoid notch (R3). 38) ST Pogonion. 39) Supra orbitale . 40) Temporale. 41) Tip of nose. 42) U1 root. 43) U1 tip. 44) U6 occlusal

The lateral image is then aligned in Dolphin Imaging according to the Frankfort plane.

Frontal view:

Frontal images are traced according to Grummons (3), Grummons simplified frontal, Ricketts Simplified, Slick/Good and Standard analyses with the ruler set to 50 millimeters in Dolphin Imaging. Additional structures namely, cusp tips and root apexes of upper and lower cuspids and first bicuspids are manually added to the analysis.

Identified structures include:

Landmark	**Description**
Ruler point 1	A point on the ruler of the scanned cephalometric radiograph
Ruler point 2	A point at 50 mm distance from ruler point 1.
A point	Deepest point of the curve of the maxilla between the anterior nasal spine and the dental alveolus.
Antegonial notch R (AG)	Highest point in the antegonial notch on the patient's right side.

Antegonial notch L (GA)	Highest point in the antegonial notch on the patient's left side.
Condylion, Left	Most superior point of the condylar head of the patient's left side.
Condylion, Right	Most superior point of the condylar head on the patient's right side.
Crista galli	Most superior point on the Crista galli.
Jugular process, L	Intersection of the zygomatic buttress and outline of the tuberosity on the patient's left side.
Jugular process, R	Intersection of the zygomatic buttress and outline of the tuberosity on the patient's right side.
Lateral wall of nasal cavity, L	Most lateral and widest aspect of the bottom of the nose on patient's left side.
Lateral wall of nasal cavity, R	Most lateral and widest aspect of the bottom of the nose on patient's right side.
Latero-orbitale R	Most lateral point on the orbital rim on patient's right

	side.
Latero-orbitale L	Most lateral point on the orbital rim on patient’s left side.
L1 Mesial, L	Mesial tooth surface of the mandibular incisor on the patient’s left side.
L1 Mesial, R	Mesial tooth surface of the mandibular incisor on the patient’s right side.
L1 Tip, L	Mandibular incisal tip on the patient’s left side.
L1 Tip, R	Mandibular incisal tip on the patient’s right side.
L3 Tip, L	Tip of the mandibular cuspid on the patient’s left side.
L3 Tip, R	Tip of the mandibular cuspid on the patient’s right side.
L6 Buccal, L	Most buccal point of the mandibular first molar on the patient’s left side.
L6 Buccal, R	Most buccal point of the mandibular first molar on the

	patient's right side.
L6 Root, L	Root apex of left mandibular molar
L6 Root, R	Root apex of right mandibular molar
Menton	Most inferior point on the border of the mandible, directly inferior to mental protuberance.
U1 Mesial, L	Mesial tooth surface of the maxillary incisor on the patient's left side.
U1 Mesial, R	Mesial tooth surface of the maxillary incisor on the patient's right side.
U1 Tip, L	Maxillary incisal tip on the patient's left side.
U1 Tip, R	Maxillary incisal tip on the patient's right side.
U3 Tip, L	Tip of the maxillary cuspid on the patient's left side.
U3 Tip, R	Tip of the maxillary cuspid on the patient's right side.
U6 Buccal, L	Most buccal point of the maxillary first molar on the patient's left side.
U6 Buccal, R	Most buccal point of the maxillary first molar on the

	patient's right side.
U6 Root, L	(Mesio) Buccal root apex of left maxillary first molar
U6 Root, R	(Mesio) Buccal root apex of right maxillary first molar
Zygomatic arch, R	The center of the root of the right zygomatic arch, midpoint
Zygomatic arch, L	The center of the root of the left zygomatic arch, midpoint
Fronto Zygomatic Suture L (ZL, ZA)	Zygomatic-frontal suture, intersecting the orbit on the patient's left side.
Fronto Zygomatic Suture R (ZR, AZ)	Zygomatic-frontal suture, intersecting the orbit on the patient's right side.

Table 2-2-Landmarks of the frontal view

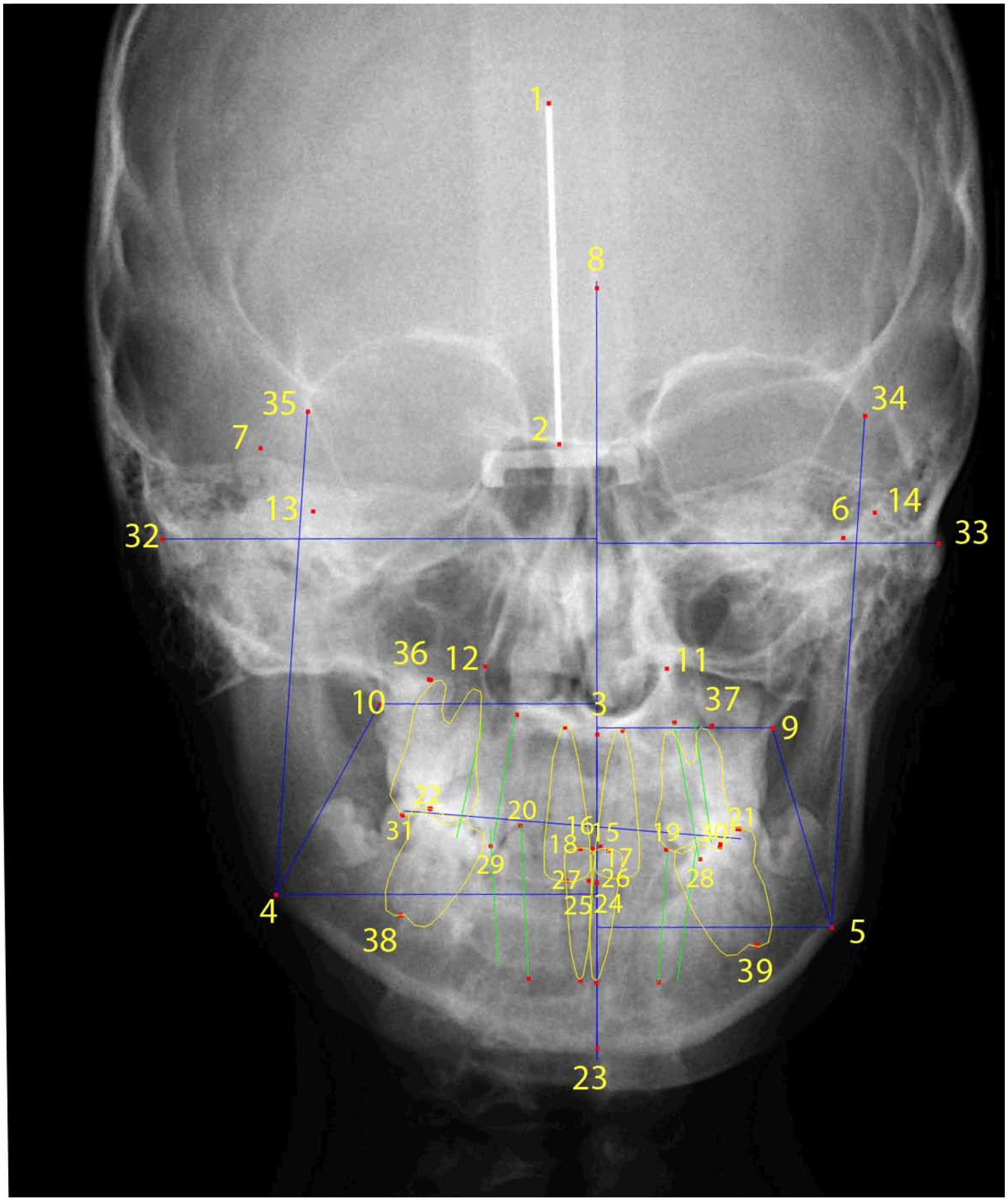


Figure 2-2-Landmarks of the Frontal view: 1) Ruler point 1. 2) Ruler point 2. 3) A point. 4) Antegonial notch R (AG). 5) Antegonial notch L (GA). 6) Condylion, Left. 7) Condylion, Right. 8) Crista Galli. 9) Jugular Process, L. 10) Jugular Process, R. 11) Lateral wall of Nasal cavity, L. 12) Lateral wall of Nasal cavity, R. 13) Latero-orbitale R. 14) Latero-orbitale L. 15) L1 Mesial, L. 16) L1 Mesial, R. 17) L1 Tip, L. 18) L1 Tip, R. 19) L3 Tip, L. 20) L3 Tip, R. 21) L6 Buccal, L. 22) L6 Buccal, R. 23) Menton. 24) U1 Mesial, L. 25) U1 Mesial, R. 26) U1 Tip, L. 27) U1 Tip, R. 28) U3 Tip, L. 29) U3 Tip, R. 30) U6 Buccal, L. 31) U6 Buccal, R .32) Zygomatic arch, R. 33) Zygomatic arch, L. 34) Fronto Zygomatic Suture L (ZL, ZA). 35) Fronto Zygomatic Suture R (ZR, AZ) 36) U6 Root apex, R. 37) U6 Root apex, L. 38) L6 Root apex, R. 39) L6 Root apex, L.

Both lateral and frontal traced images were printed 1:1 to make sure that their magnification factor was the same. To check for this equality of magnification, rulers of the printed images were measured and compared. The images were then saved as JPEG files; they were then converted into 1:1 ratio high quality PDF files for better quality of the images and easier visualization of the landmarks; PDF files were then opened in Photoshop CS3; Lateral and Frontal images of every patient at each time-point (either T1 or T2) were aligned along the Frankfort plane and cropped to the same size; the images were then saved as BMP (bitmap) files (RGB color, 24 bit) to be later imported into the 3D software.

2.3.4 3DCeph program

3DCeph is a windows based application. For this project, the application was run on Windows Vista. According to the software's manual (4), the program is compatible with Windows 95 and later versions. 3DCeph is composed of two separate modules. The first module, 3DCeph2000, creates two-dimensional (2D) sketches, whereas the second module, 3D-Aligner2000, converts the 2D sketches into a three-dimensional (3D) sketch and also generates three-dimensional measurements.

When the 3DCeph application opens, the user is prompted to choose whether a computer mouse or a digitizer is going to be used to identify the landmarks on the 3D program screen. In this project, we used the computer mouse and not a digitizer. Then a window opens which indicates which two views of the patient will be combined and converted to a 3D image. For our study, we used the combination of Lateral and Frontal views. However, any combination of the Lateral, Frontal and the Basilar images may be used.

Upon choosing or confirming the above-mentioned combination, a window opens which requires for the user to introduce a new patient by providing the patient's demographic data. Once the patient's details are provided, the screen tabs become active. The screen can be switched between the two selected views (i.e. Lateral and Frontal in this study). For each view, a Bitmap digital image (the previously traced x-ray) is loaded into the program. Then with the use of either the digitizer or the computer mouse, which was the choice of this study, the landmarks illustrated in the following table are identified on the previously traced images. Upon identification of all landmarks, one of the images is supposed to be calibrated by identifying two points 10 millimeters (mm) apart along a straight line, either horizontal or vertical. Since the magnification of both views, Frontal and Lateral, are the same, calibrating one image is sufficient. For this study, the Lateral image was calibrated using the previously identified ruler points which were 10 mm apart. The user should also locate a focal point on each view for the purpose of superimposition of the two images. The focal point for the Lateral view is the Porion point, whereas the focal point of the Frontal view is the intersection of the line which connects the two zygomatic processes and the midsagittal plane. Upon completion of these steps, a two-dimensional wire-shaped diagram is created for each view (i.e. Lateral and Frontal in our study). These wire-shaped diagrams plus an analysis file (.ana) and a patient file (.pat) are saved to be used in the second module of the 3D software, namely 3D-Aligner.

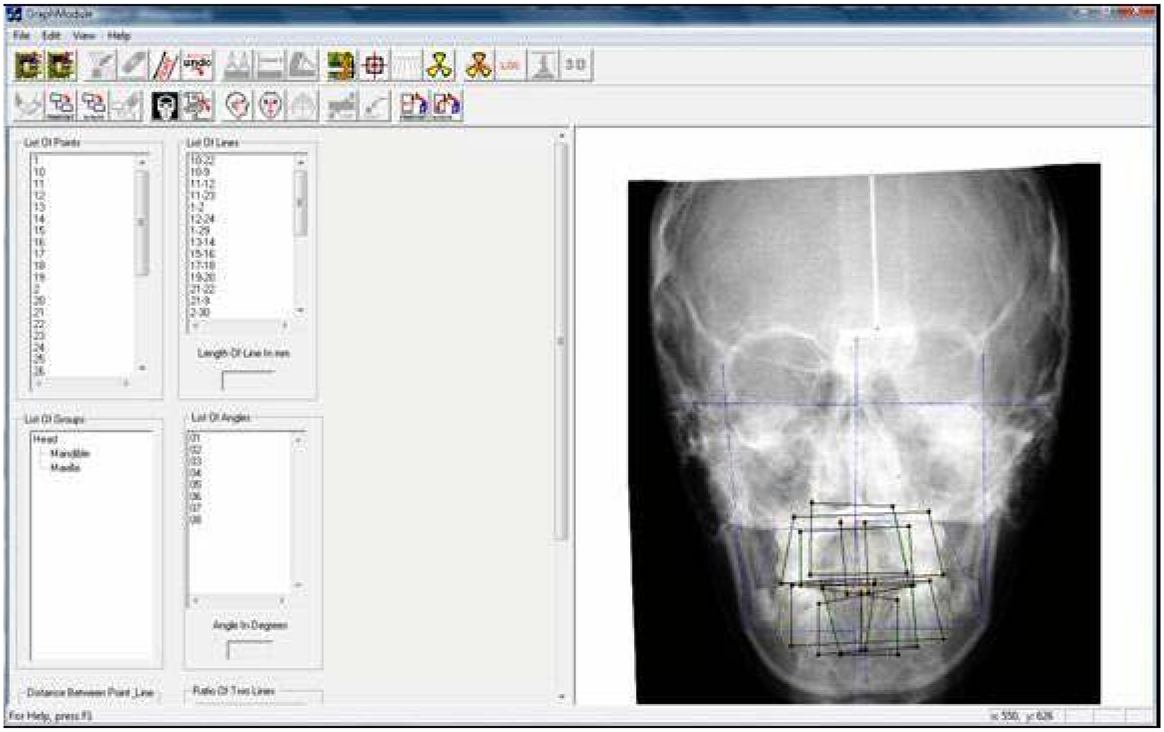


Figure 2-3-3DCeph2000: Frontal view

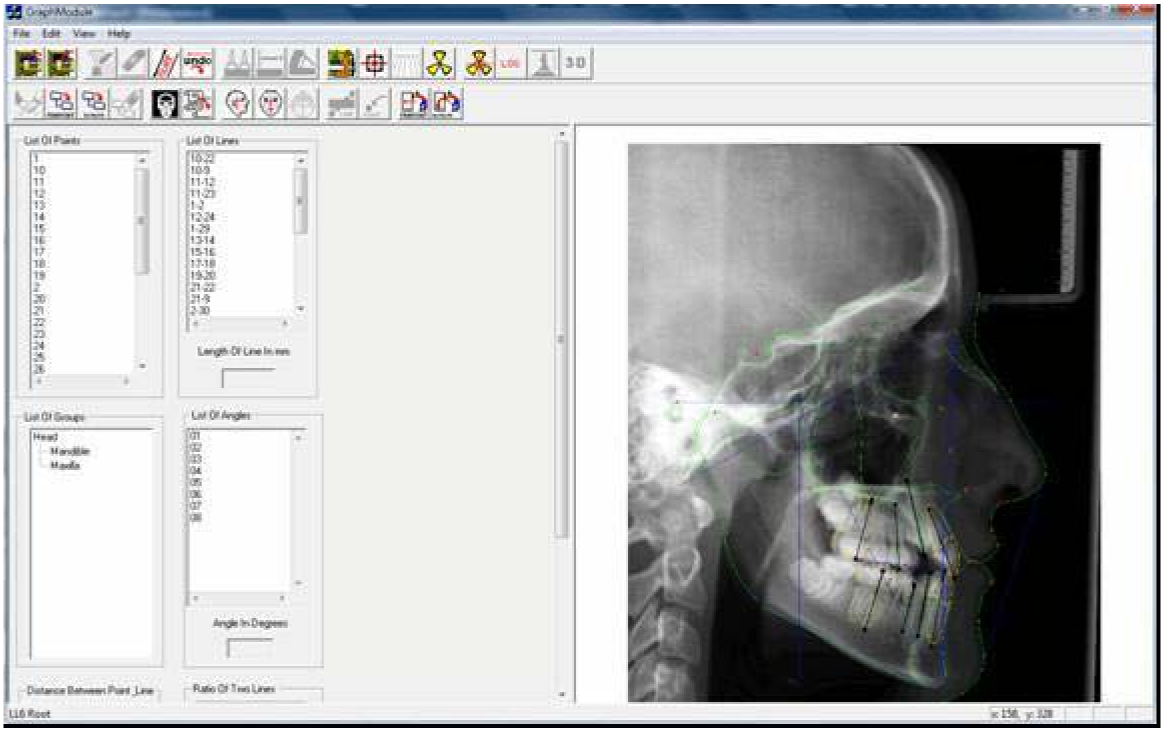


Figure 2-4-3DCeph2000: Lateral view

In 3D-Aligner, a patient file (.pat) which has previously been created by 3DCeph 2000 is opened. Upon opening the patient file, the 2D wire shaped diagrams will be displayed on the screen. The Lateral view is displayed in the lower left box, whereas the Frontal view is displayed in the lower right box. If there was also a Basilar view, which was not the case in our study, the Basilar view would have been displayed in the upper left box on the screen. In order to create an accurate 3D wire shaped diagram, the various landmarks of the two (or three) views of a patient need to be aligned. In 3D-Aligner this can be done either manually or automatically. In the automatic alignment, which was used for this project, the program takes the average of the two points in order to align the views. After selecting all the available landmarks and having them aligned, the 3D wire shaped diagram (frame) is created upon clicking the designated tab. This 3D frame is displayed in the upper right box [Figure 2.5]. Then two types of log, namely Patient Log and 3D Log are created. The Patient Log contains patient's details, the 2D measurements on each view and description of each measurement; whereas the 3D Log reports the 3D measurements. All linear measurements are reported in millimeters, while the angles are reported in degrees. These linear and angular measurements are listed in the following table. Both logs can be saved as text file (.log), whereas the 3D frame and the patient file are saved as Bitmap (.bmp) and patient (.pat) files respectively.

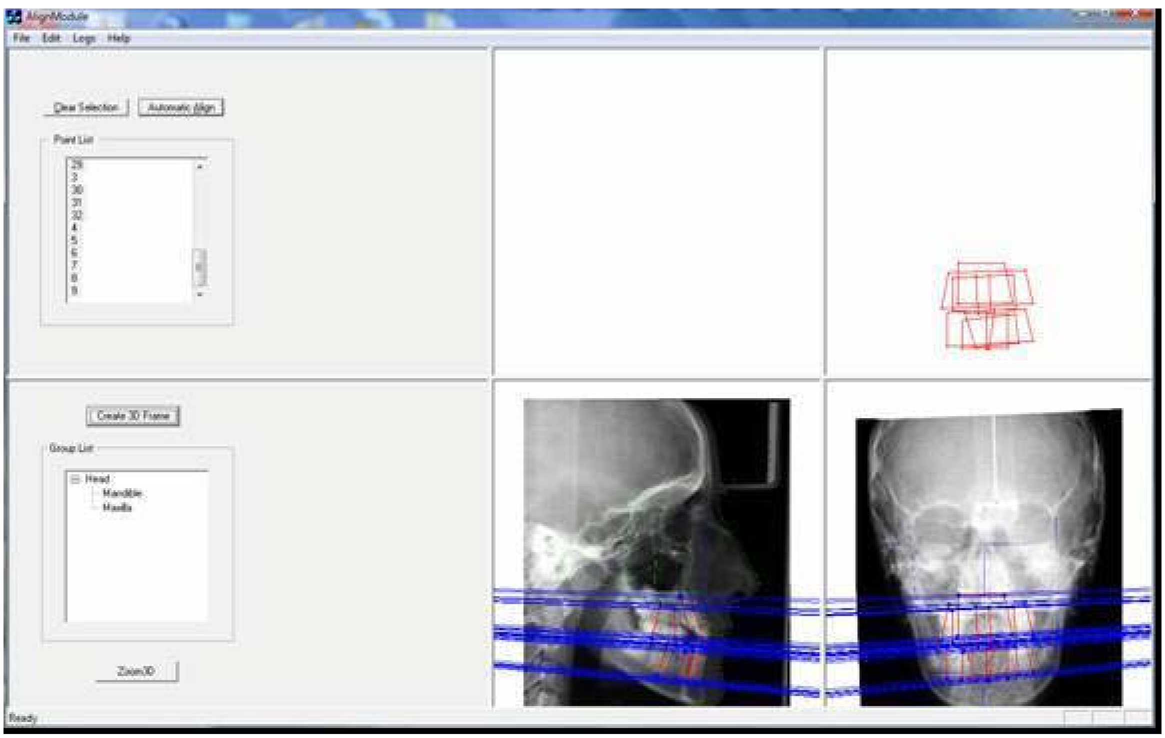
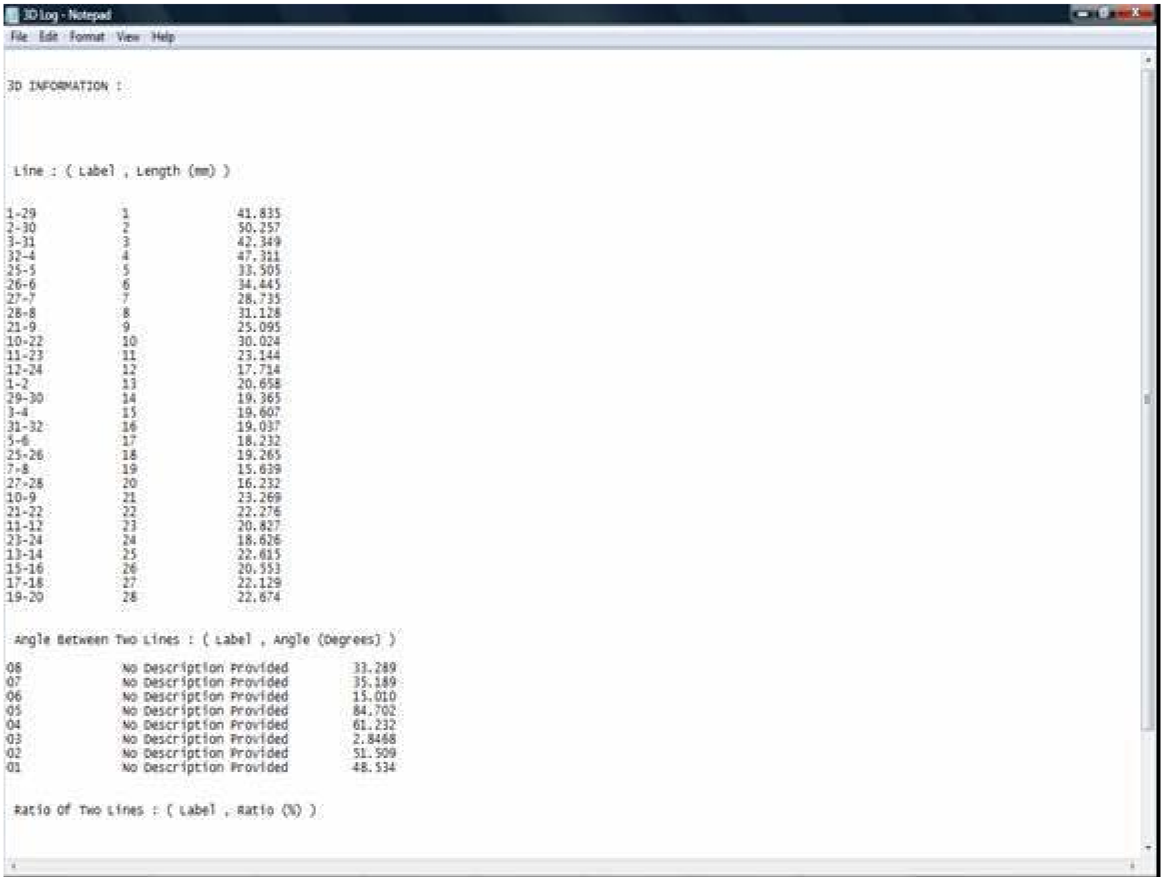


Figure 2-5- 3DAlign2000: 3Dframe(in red) ; Aligned 2D views



3D Log - Notepad

File Edit Format View Help

3D INFORMATION :

Line : (Label , Length (mm))

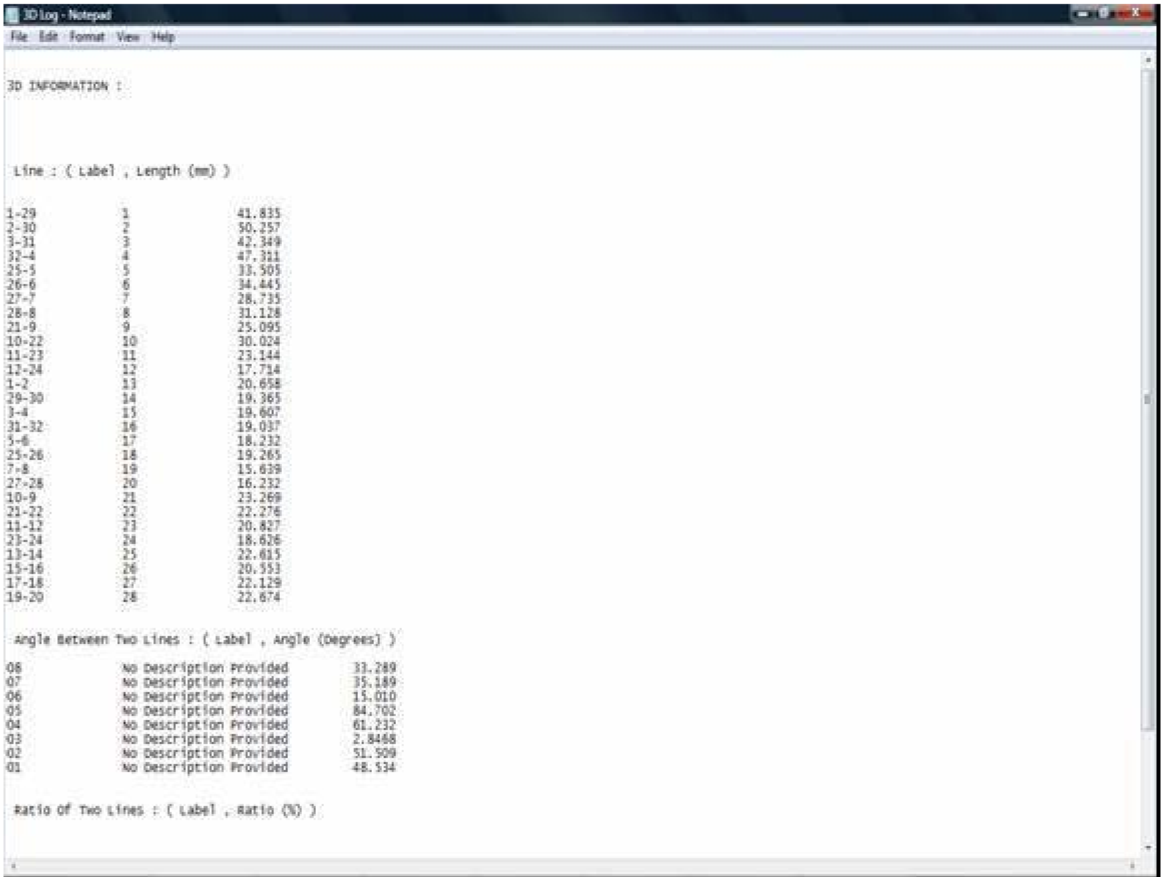
1-29	1	41.835
2-30	2	50.257
3-31	3	42.349
32-4	4	47.311
25-5	5	33.505
26-6	6	34.445
27-7	7	28.735
28-8	8	31.128
21-9	9	25.095
10-22	10	30.024
11-23	11	23.144
12-24	12	17.714
1-2	13	20.658
29-30	14	19.365
3-4	15	19.607
31-32	16	19.037
5-6	17	18.232
25-26	18	19.265
7-8	19	15.639
27-28	20	16.232
10-9	21	23.269
21-22	22	22.276
11-12	23	20.827
23-24	24	18.626
13-14	25	22.615
15-16	26	20.553
17-18	27	22.129
19-20	28	22.674

Angle Between Two Lines : (Label , Angle (Degrees))

08	No Description Provided	33.289
07	No Description Provided	35.189
06	No Description Provided	15.010
05	No Description Provided	84.702
04	No Description Provided	61.232
03	No Description Provided	2.8468
02	No Description Provided	51.509
01	No Description Provided	48.534

Ratio Of Two Lines : (Label , Ratio (%))

Figure 2-6- 3DAlign: Patient log



3D INFORMATION :

Line : (Label , Length (mm))

1-29	1	41.835
2-30	2	50.257
3-31	3	42.349
32-4	4	47.311
25-5	5	33.505
26-6	6	34.445
27-7	7	28.735
28-8	8	31.128
21-9	9	25.095
10-22	10	30.024
11-23	11	23.144
12-24	12	17.714
1-2	13	20.658
29-30	14	19.365
3-4	15	19.607
31-32	16	19.037
5-6	17	18.232
25-26	18	19.265
7-8	19	15.639
27-28	20	16.232
10-9	21	23.269
21-22	22	22.276
11-12	23	20.827
23-24	24	18.626
13-14	25	22.615
15-16	26	20.553
17-18	27	22.129
19-20	28	22.674

Angle Between Two Lines : (Label , Angle (Degrees))

08	No Description Provided	33.289
07	No Description Provided	35.189
06	No Description Provided	15.010
05	No Description Provided	84.702
04	No Description Provided	61.232
03	No Description Provided	2.8468
02	No Description Provided	51.509
01	No Description Provided	48.534

Ratio Of Two Lines : (Label , Ratio (%))

Figure 2-7- 3DAlign: 3Dlog

Description of points in 3DCeph
01 : UR6 Root
02 : UR6 Crown
03 : LR6 Crown
04 : LR6 Root
05 : UR4 Root
06 : UR4 Crown

07 : LR4 Crown
08 : LR4 Root
09 : UR3 Root
10 : UR3 Crown
11 : LR3 Crown
12 : LR3 Root
13 : UR1 Root
14 : UR1 Crown
15 : LR1 Crown
16 : LR1 Root
17 : UL1 Root
18 : UL1 Crown
19 : LL1 Crown
20 : LL1 Root
21 : UL3 Root
22 : UL3 Crown
23 : LL3 Crown
24 : LL3 Root
25 : UL4 Root
26 : UL4 Crown
27 : LL4 Crown
28 : LL4 Root
29 : UL6 Root

30 : UL6 Crown
31 : LL6 Crown
32 : LL6 Root

Table 2-3-Points in 3DCeph

Description of Lines in 3DCeph	
Line's number and the points it connects	**Description**
Line 01 : 01-29	Inter upper molar distance (Root)
Line 02 : 02-30	Inter upper molar distance (Crown)
Line 03 : 03-31	Inter lower molar distance (Crown)
Line 04 : 04-32	Inter lower molar distance (Root)
Line 09 : 09-21	Inter upper canine distance (Root)
Line 10 : 10-22	Inter upper canine distance (Crown)
Line 11 : 11-23	Inter lower canine distance (Crown)
Line 12 : 12-24	Inter lower canine distance (Root)

Table 2-4-Lines in 3DCeph

More information about 3DCeph can be found in the 3DCeph user manual, written by the programmer, Dr. Budi Kusnoto (4).

2.3.5 Controls

Bolton templates (standards) (5) of ages 10 to 18 were used as controls. The process of converting the two-dimensional Bolton templates to three-dimensional images was similar to that of the treatment group, except for the fact that Bolton standards did not need to be traced in Dolphin Imaging, converted to PDF and printed in 1:1. Instead, both frontal and lateral Bolton templates for each age were scanned into Dolphin Imaging and saved in JPEG format. The JPEG images were directly opened in Photoshop to be aligned and cropped, unlike records of the treatment group which were converted into high-quality PDF files first. The resulting BMP images were then imported into 3DCeph to be processed like the records of our treatment group.

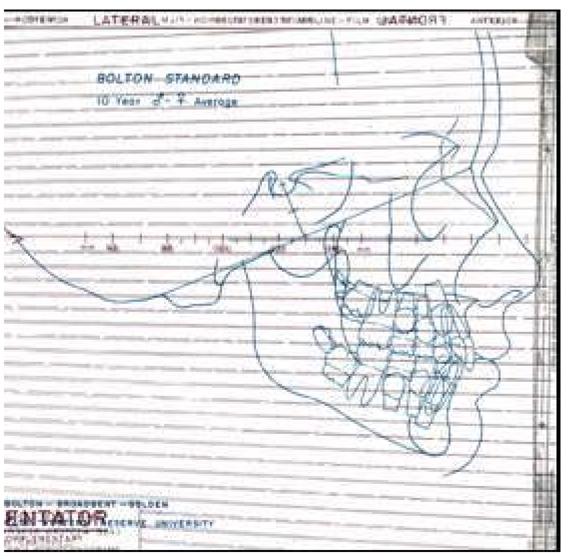


Figure 2-8-Bolton templates: Lateral

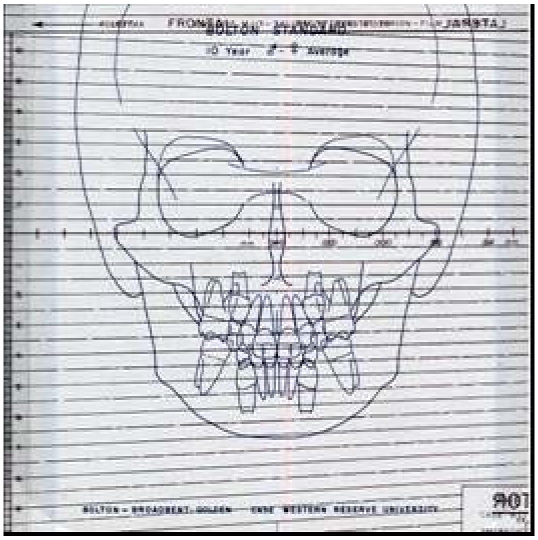


Figure 2-9-Bolton templates: Frontal

Bolton templates did not need to be traced in Dolphin Imaging, printed in 1:1 and converted into PDF files for the following reasons:

1. They were already in the form of a template and not an x-ray, therefore there was no need to trace them in Dolphin Imaging to create teeth templates.

2. They were scanned at a high resolution (300 dpi) so they did not need to be converted into high-quality PDF files for better quality.

3. They all had the same magnification factor and therefore they did not need to be printed in 1:1 for their rulers to be measured and compared.

It is note-worthy that both lateral and frontal views of Bolton templates have rulers with 5 mm increments on them. Like the treatment group, the ruler on the lateral view was used for the purpose of calibration. Also, the estimated Porion on the lateral view of the Bolton templates, which coincides with number 90 mm on the ruler, was used as the focal point on this view (6). As for the frontal view, the intersection of the line connecting the zygomatic processes and the midsagittal plane was used to locate the focal point.

Here are images of Bolton templates imported into 3DCeph system:

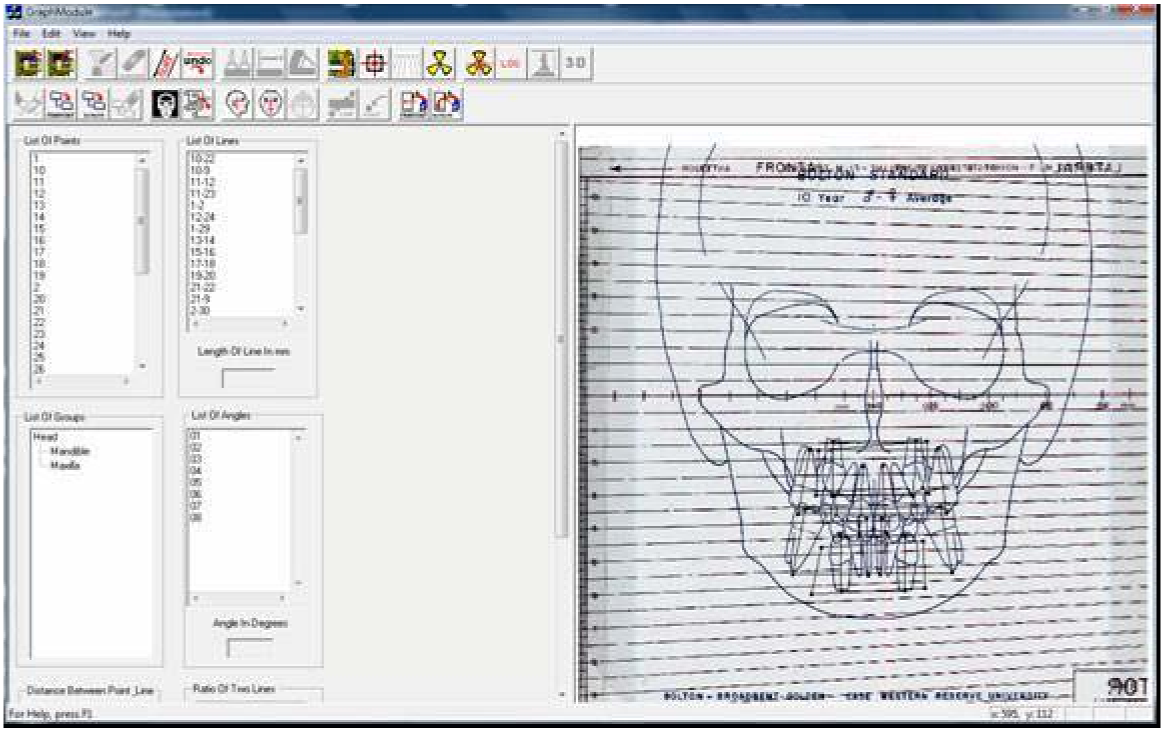


Figure 2-10-3DCeph: Frontal view (Bolton templates)

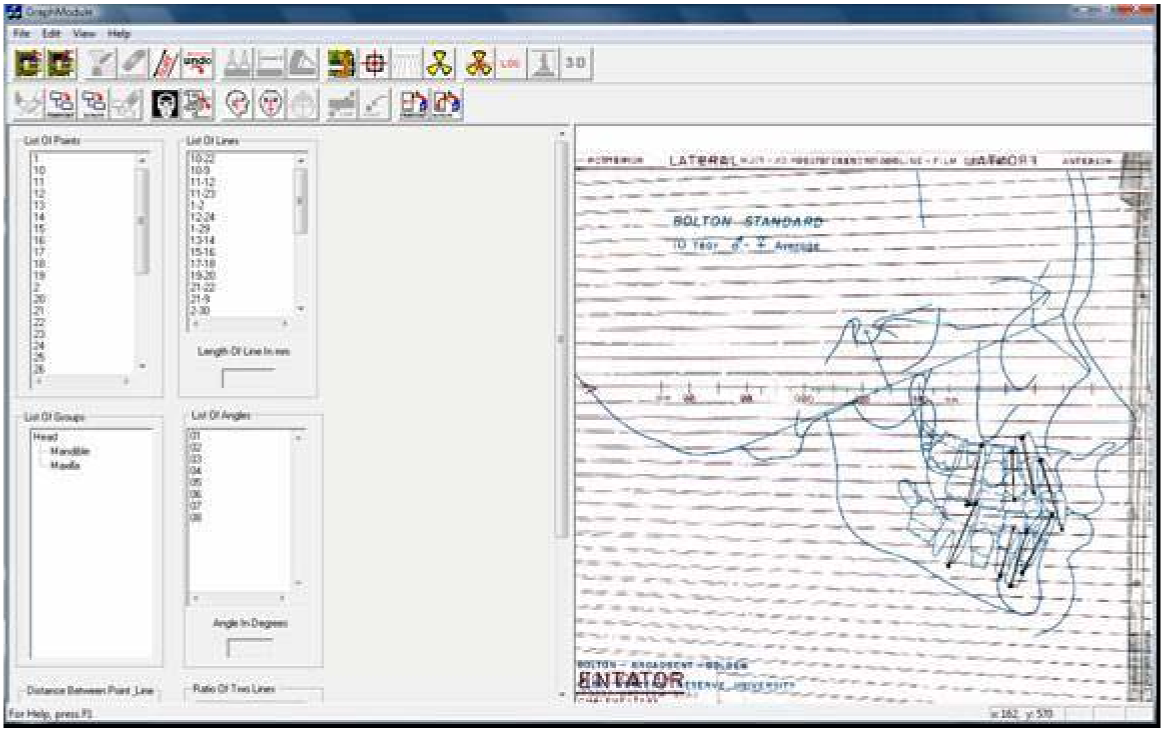


Figure 2-11- 3DCeph: Lateral view (Bolton templates)

Once BMP images of Bolton templates were imported into 3DCeph2000, like records of the Damon treated group, they were traced and calibrated; the calibrated traced images were imported into 3D-Aligner; the 3D frame, patient log and 3D log were created and saved.

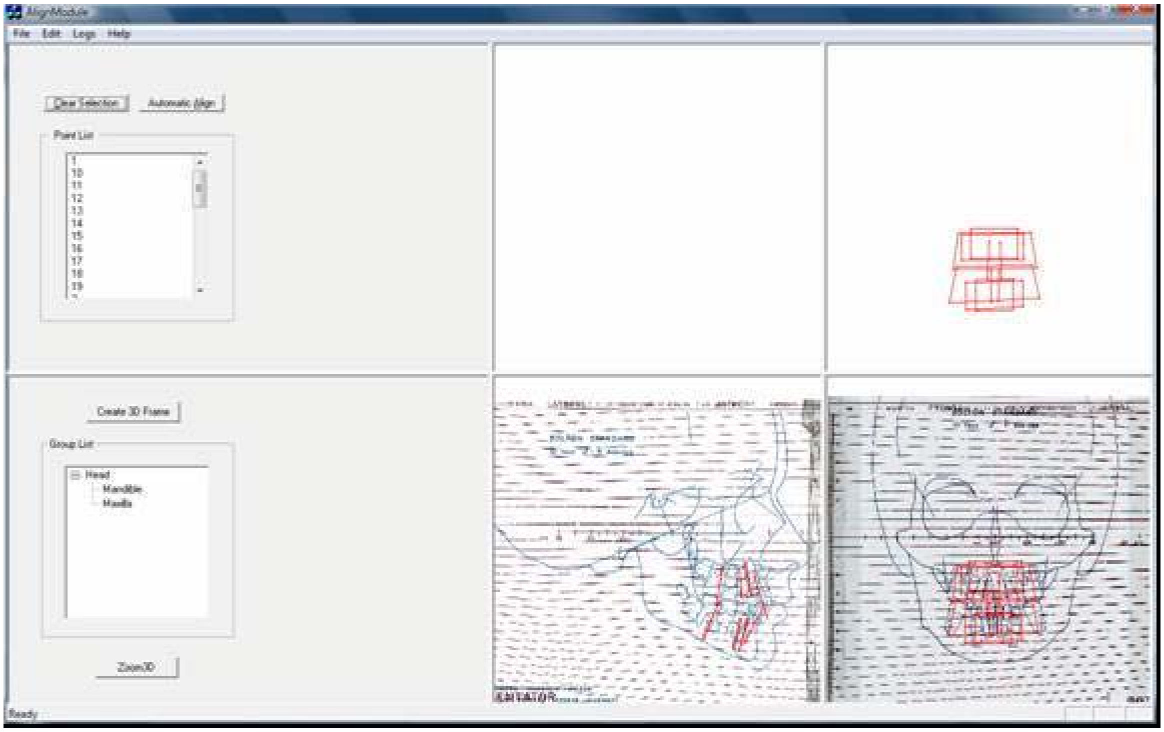


Figure 2-12-3DAlign: 3D frame; aligned 2D images (Bolton templates)

We calculated the difference between each measurement at T1 (baseline) and T2 (post-treatment) for each subject of the treatment group and then compared this difference (increase) with the difference (increase) of corresponding templates to determine if this increase is larger than what would normally occur with growth, as it is the case with Bolton templates.

2.3.6 Reliability testing

To check for intra-examiner reliability (reproducibility), one examiner (S.E.) traced and measured records of randomly selected subjects from each group (4 from treatment group and 5 from control group) three times with an interval of at least two weeks in between. To check for inter-examiner reliability, records of these subjects were also traced by a second examiner (TEB).

To check for the above-mentioned reliabilities, the intra-class correlation coefficient (ICC) was calculated for the following measurements:

Measurement	Description
FMA (MP-FH) (°)	The angle between the mandibular plane (Gonion-Menton) and Frankfort horizontal plane (Porion-Orbitale).
Po-Or (mm)	The distance between Porion and Orbitale.
MMo|FH (mm)	Mesial molar relationship: the distance of the lines drawn perpendicular to the Frankfort line from mesial points of first upper and lower molars.
S-N (mm)	The distance between Sella and Nasion.
AGM (L) (mm)	The distance between left Antegonion and Midsagittal Reference plane.
AGM (R) (mm)	The distance between right Antegonion and Midsagittal Reference plane.
LMC	The distance between mesiobuccal cusps of lower permanent first molars.
UMC	The distance between mesiobuccal cusps of upper permanent first molars.
LCC	The distance between cusp tips of lower permanent cuspids.
UCC	The distance between cusp tips of upper permanent cuspids.

LMR	The distance between mesiobuccal root apices of lower permanent first molars.
UMR	The distance between mesiobuccal root apices of upper permanent first molars.
LCR	The distance between root apices of lower permanent cuspids.
UCR	The distance between root apices of upper permanent cuspids.

Table 2-5-Reliability measurements

It should be noted that since Bolton templates were directly traced in the 3D program, which only provides dental measurements, therefore in the control group, only the dental distances, and not the first six items of the above table, were measured and investigated.

The correlation coefficient was large for all the measurements; therefore there was no statistically significant difference between the repeated measurements. The ICC for inter-rater reliability lied between 0.71 and 0.99, whereas the ICC for intra-rater reliability lied between 0.75 and 0.99. ICC's for all variables can be found in tables A1.1 and A1.2 in Appendix 1.

ICC (Intra-Class Correlation Coefficient)	
Inter-examiner	$.71 \leq ICC \leq .99$
Intra-examiner	$.75 \leq ICC \leq .99$

Table 2-6-ICC (Intra-class correlation coefficient) values

2.3.7 Statistical analysis

2.3.7.1Three-dimensional data

2.3.7.1.1 Transverse dimensions (arch width)

Nonparametric test (Mann-Whitney U) was used on the retrieved data to compare changes of intermolar and inter-canine distances between the two groups. MANOVA was not performed as assumptions (normality, equal variance and perfect linear relationship) were not met for this model. The alpha was set at 0.05, meaning that differences were considered significant at $P < 0.05$. The SPSS software (version 14.0 ; SPSS Inc) was used for statistical procedures.

2.3.7.1.2 Effect of pre-treatment crowding on transverse change

Samples of the treatment (Damon) group were divided into the following three categories:

- Category 0= No crowding: Initial crowding≤0
- Category 1=Mild crowding: 0<Initial crowding≤5
- Category 2= Moderate crowding: Initial crowding>5

Due to unequal variance between the three categories, small sample size and not having a normally distributed data, Nonparametric test (Kruskall-Wallis test) was used on the retrieved data to compare transverse changes in the treatment group with regard to initial crowding. Data were analyzed using the SPSS software (version 14.0; SPSS Inc) with 0.05 value chosen for the alpha.

2.3.7.2 Two-dimensional data

2.3.7.2.1 Interjugular distances

2.3.7.2.2 Angles made between first molars and Crista galli-A Point line

2.3.7.2.3 Incisors position

Because of unequal variances of the two groups, nonparametric test (Mann-Whitney U) was used on the retrieved data to compare changes of interjugular distance (JJ), molar angulation and incisor inclination between the two groups. The data were analyzed with the SPSS software (version 14.0; SPSS Inc) with the alpha set at 0.05. As for incisor position, although assumptions (normality, equal variance and perfect linear relationship) were not fully met for MANOVA, it was still run and its results confirmed the results of nonparametric test (Mann-Whitney U).

2.3.7.3 Correlation between two-dimensional and three-dimensional data

Paired t-test was used to compare results of two-dimensional and three-dimensional analyses for changes of intermolar and inter-canine distances in Damon treated group. Assumptions for normality and equal variance were met for this statistical model. The SPSS software (version 14.0 ; SPSS Inc) was used and alpha was set at 0.05.

2.4 Results

2.4.1 Three-dimensional data

2.4.1.1Transverse dimensions (arch width)

According to nonparametric tests (Mann-Whitney U), differences in changes of the upper intermolar distances (roots) and lower intercanine distances (roots) were statistically significant ($P<.001$, $P= .001$) However, there were no statistically significant differences in changes of the other transverse dimensions ($P>0.006$). It is noteworthy that although our alpha is set at 0.05, due to the large number of comparisons made, it would be more cautious to do the Bonferroni correction for our alpha, meaning that we divide it by the number of comparisons made (alpha/8=0.006).

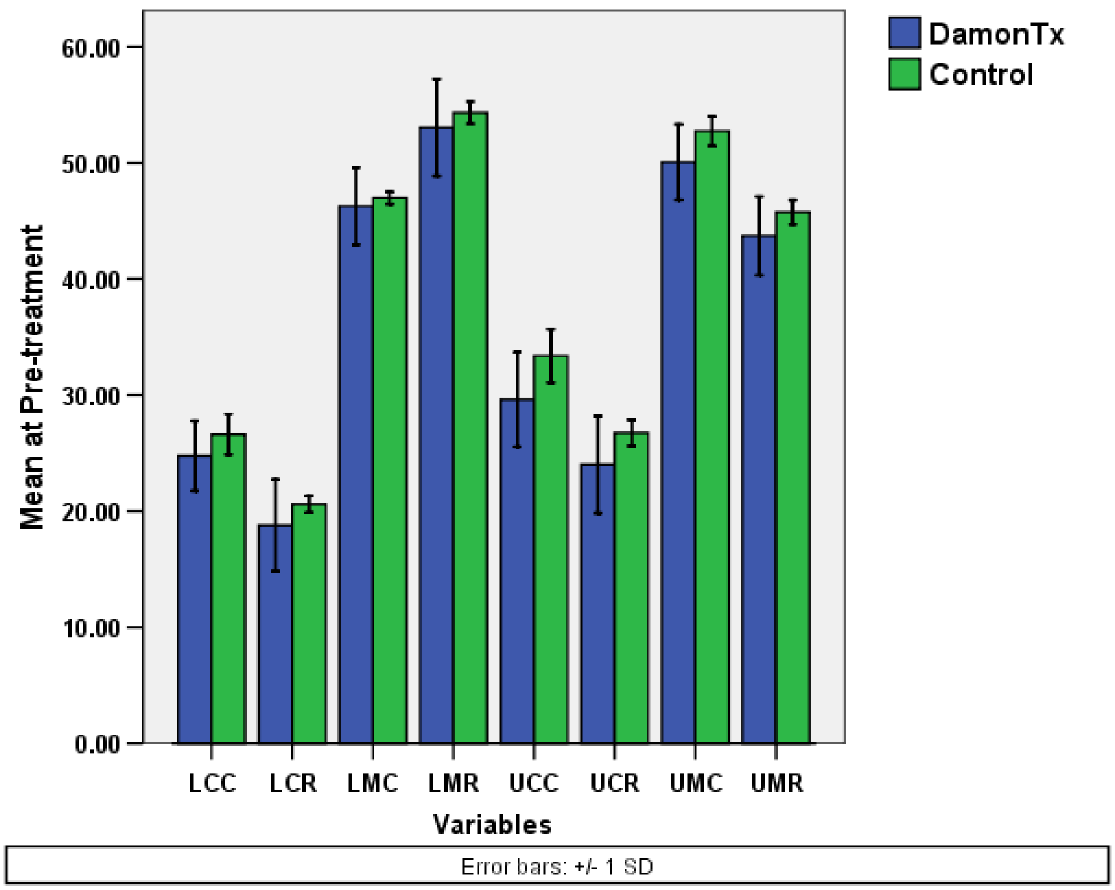


Figure 2-13-Pre-treatment transverse dimensions

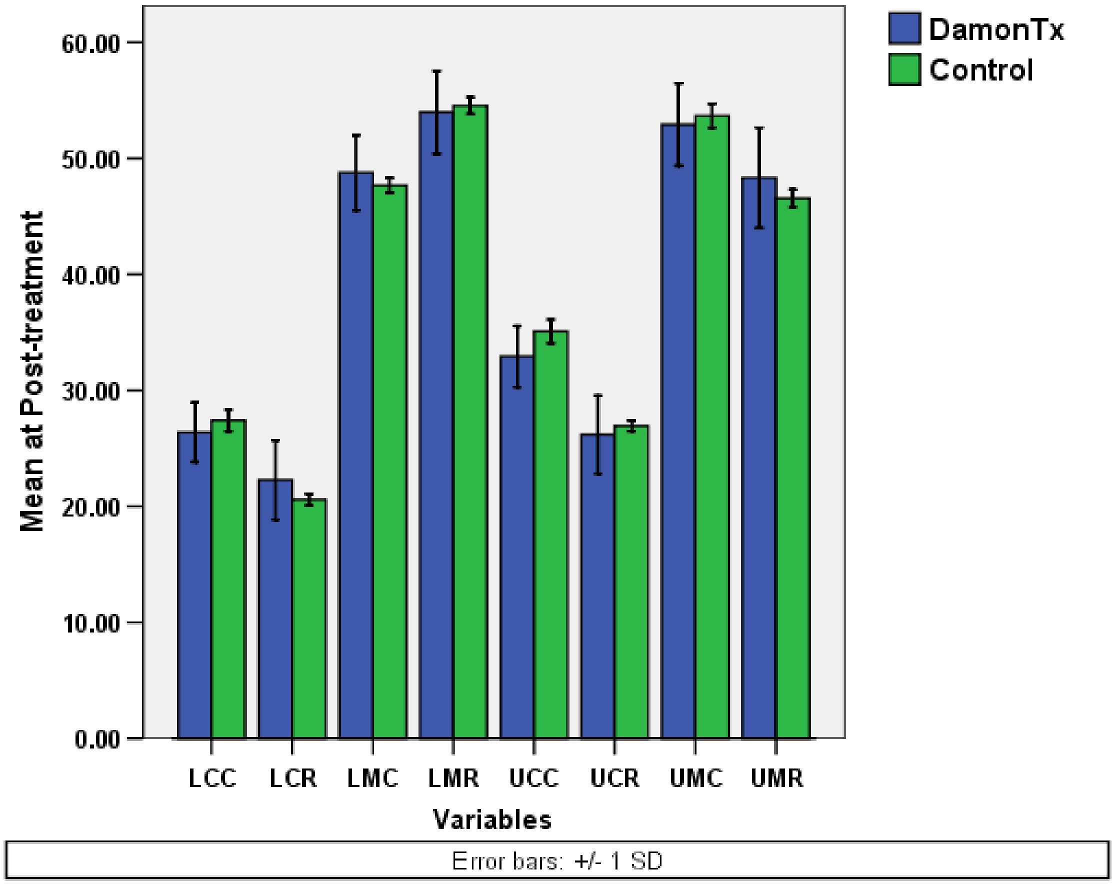


Figure 2-14-Post-treatment transverse dimensions

Measurement	Treatment group Change	Control group Change	P-value
UMR (Upper Molar Root)	4.6±4.2	0.8±1.5	.000*
UMC (Upper Molar Crown)	2.8±2.9	0.9±1.6	.028
LMC (Lower Molar Crown)	2.5±3.2	0.7±1.6	.091
LMR (Lower Molar Root)	0.9±4.4	0.2±1.6	.758
UCR (Upper Canine Root)	2.2±4.0	0.2±1.6	.114
UCC (Upper Canine Crown)	3.3±4.0	1.7±1.6	.174
LCC (Lower Canine Crown)	1.6±3.1	0.8±1.6	.445
LCR (Lower Canine Root)	3.5±3.1	-0.01±1.6	.001*

Table 2-7-Comparison of changes of Upper (U) and lower (L) intermolar (M) and intercanine (C) distances between crowns (C) and roots (R) between the two groups (according to Mann-Whitney test).

*significant (P-value< 0.006)

Measurement	Treatment group			Control group			P
	Initial	**Final**	**Change**	**Initial**	**Final**	**Change**	
	Mean± SD	**Mean± SD**	**Mean± SD**	**Mean± SD**	**Mean± SD**	**Mean± SD**	
UMR(mm)	43.72±3.40	48.31±4.32	4.59±4.2	45.75±1.04	46.55±0.75	0.80±1.5	.000*
UMC(mm)	50.07±3.25	52.91±3.55	2.84±2.9	52.74±1.28	53.67±1.03	0.93±1.6	.028
LMC(mm)	46.27±3.33	48.76±3.23	2.48±3.2	46.99±0.51	47.66±0.63	0.67±1.6	.091
LMR(mm)	53.04±4.18	53.97±3.56	0.93±4.4	54.34±0.95	54.54±0.72	0.20±1.6	.758
UCR(mm)	24.00±4.16	26.19±3.34	2.19±4.0	26.75±1.11	26.94±0.45	0.18±1.6	.114
UCC(mm)	29.62±4.07	32.92±2.62	3.29±4.0	33.37±2.31	35.09±1.01	1.71±1.6	.174
LCC(mm)	24.77±3.00	26.37±2.55	1.60±3.1	26.64±1.74	27.40±0.92	0.76±1.6	.445
LCR(mm)	18.79±3.95	22.28±3.40	3.49±3.1	20.59±0.70	20.57±0.49	-0.01±1.6	.001*

Table 2-8-Within group comparison: Upper (U) and lower (L) intermolar (M) and intercanine (C) distances between crowns (C) and roots (R) in millimetres (mm).

2.4.1.2Effect of pre-treatment crowding on transverse changes

We compared the transverse changes of the treatment group with regard to pre-treatment crowding to determine if pre-treatment crowding has an impact on transverse changes. To do so, samples of the treatment (Damon) group were divided into the following categories:

- Category 0= No crowding: Pre-treatment crowding≤ 0 (Maxilla: n=5; Mandible: n=8)
- Category 1= Mild crowding: 0< Pre-treatment crowding ≤ 5 (Maxilla: n=9; Mandible: n=8)
- Category 2= Moderate crowding: Pre-treatment crowding > 5 (Maxilla: n=6; Mandible: n=4)

Pre-treatment values for crowding did not affect transverse changes (P> 0.006) in either maxilla or mandible. (Tables and figures below) Again, due to the large number of comparisons the Bonferroni correction was made for our alpha, meaning that we divided it by the number of comparisons made (Alpha/8=0.006).

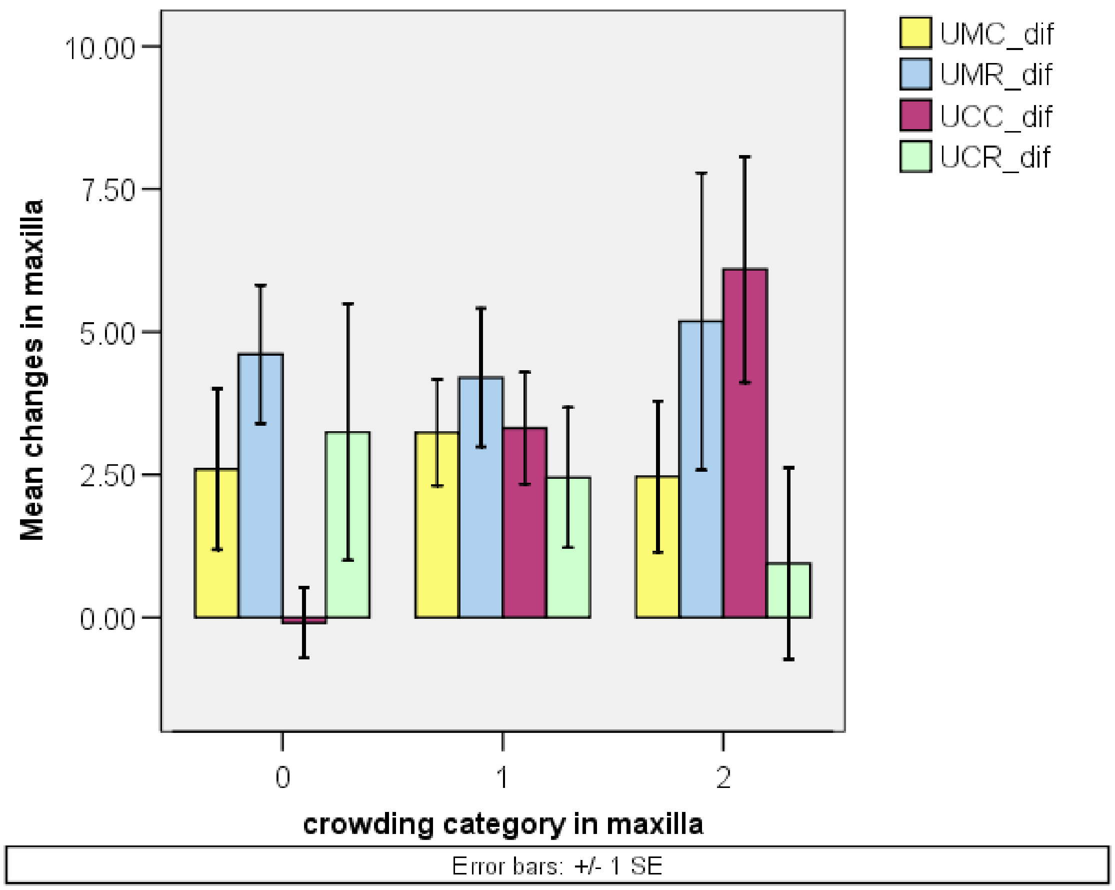


Figure 2-15- Pre-treatment crowding in maxilla and changes of transverse dimensions.

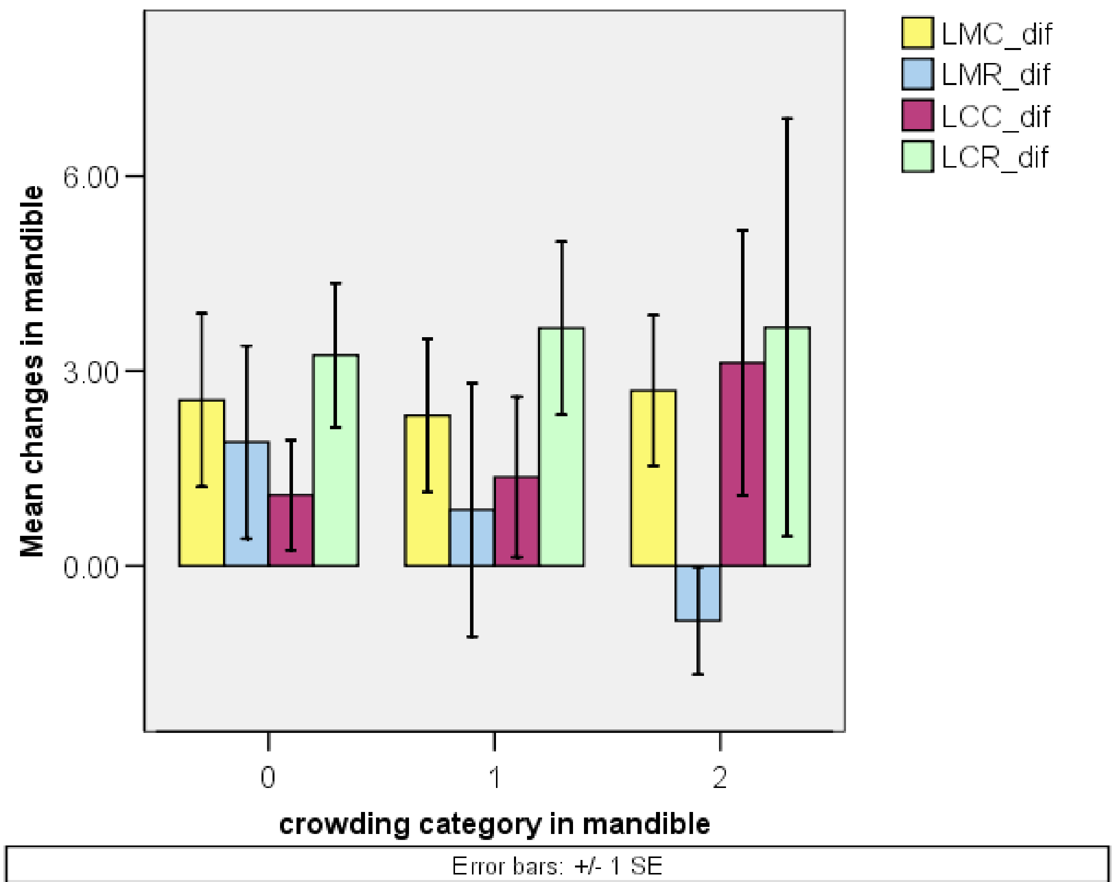


Figure 2-16-Pre-treatment crowding in mandible and changes of transverse dimensions.

Measurements	Crowding Category			P-value
	No crowding	Mild crowding (≤5mm)	Moderate Crowding (>5mm)	
	Mean± SD	Mean± SD	Mean± SD	
UMC changes	2.59±3.15	3.23± 2.78	2.46± 3.23	.714
UMR changes	4.60± 2.70	4.19± 3.63	5.18± 6.37	.809
UCC changes	-0.09± 1.37	3.31± 2.92	6.09± 4.84	.024
UCR changes	3.24± 5.02	2.44± 3.67	0.94 ± 4.09	.585
LMC changes	2.55± 3.77	2.31± 3.34	2.69± 2.32	.931
LMR changes	1.90± 4.20	0.85± 5.52	-0.84± 1.65	.509
LCC changes	1.08± 2.40	1.36± 3.49	3.12± 4.08	.563
LCR changes	3.24± 3.14	3.65± 3.77	3.66± 6.43	.979

Table 2-9-Transverse changes and pre-treatment crowding.

2.4.2 Two-dimensional data

2.4.2.1Interjugular distance

According to Mann-Whitney U statistical test, changes of interjugular distance in the treatment group were not significantly different from those of the control group (P> 0.05). Therefore, width of maxillary base did not significantly increase in the treatment group compared to the control group.

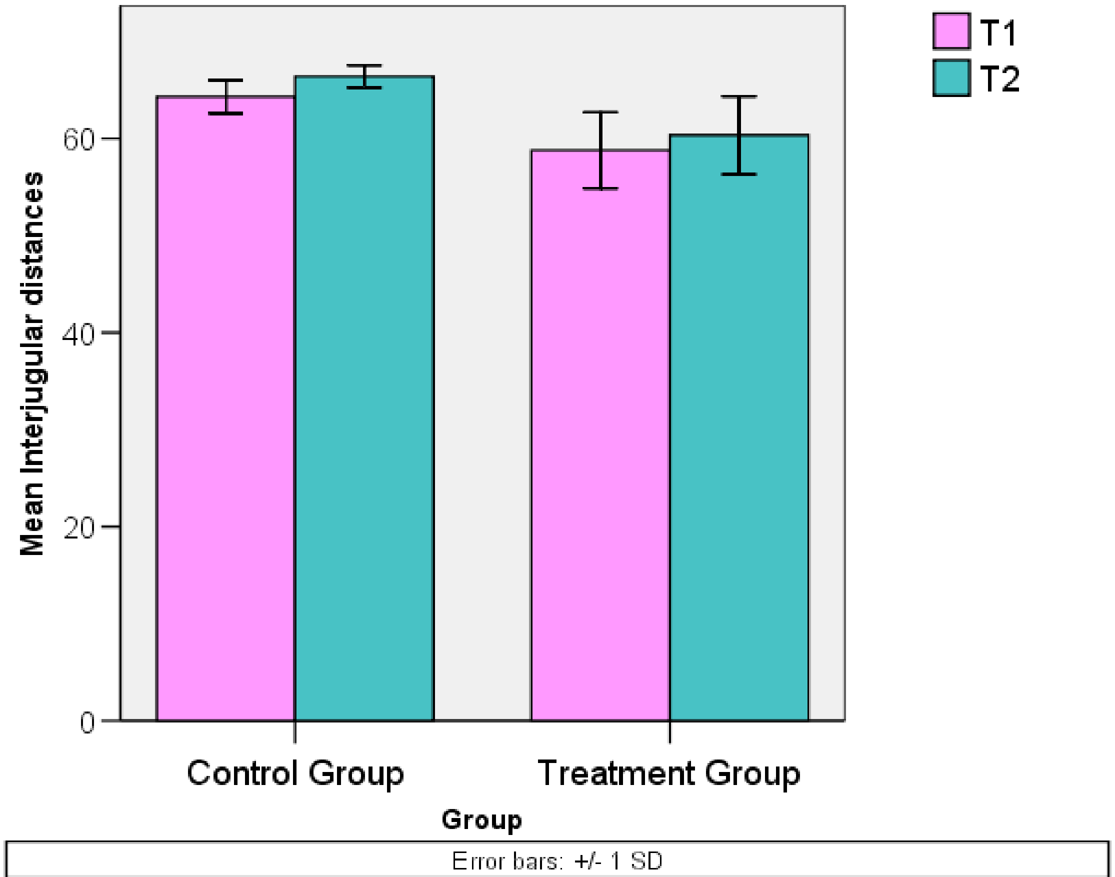


Figure 2-17-Interjugular distance

	Treatment Group			Control Group			P
	Initial	Final	Change	Initial	Final	Change	
	Mean± SD	Mean± SD	Mean± SD	Mean± SD	Mean± SD	Mean± SD	
J-J	58.79±3.91	60.34±4.02	1.55±4.69	64.32±1.69	66.40±1.16	2.09±1.46	.081

Table 2-10-Interjugular changes

2.4.2.2Angles made between first molars and Crista galli-A Point line

According to nonparametric statistical test (Mann-Whitney U), in the treatment group, angles made between first molars with Crista galli-A point line did not show any significant changes compared to the control group (P> 0.05). Therefore, it seems that in the treatment group first molars did not tip more than they did in the control group.

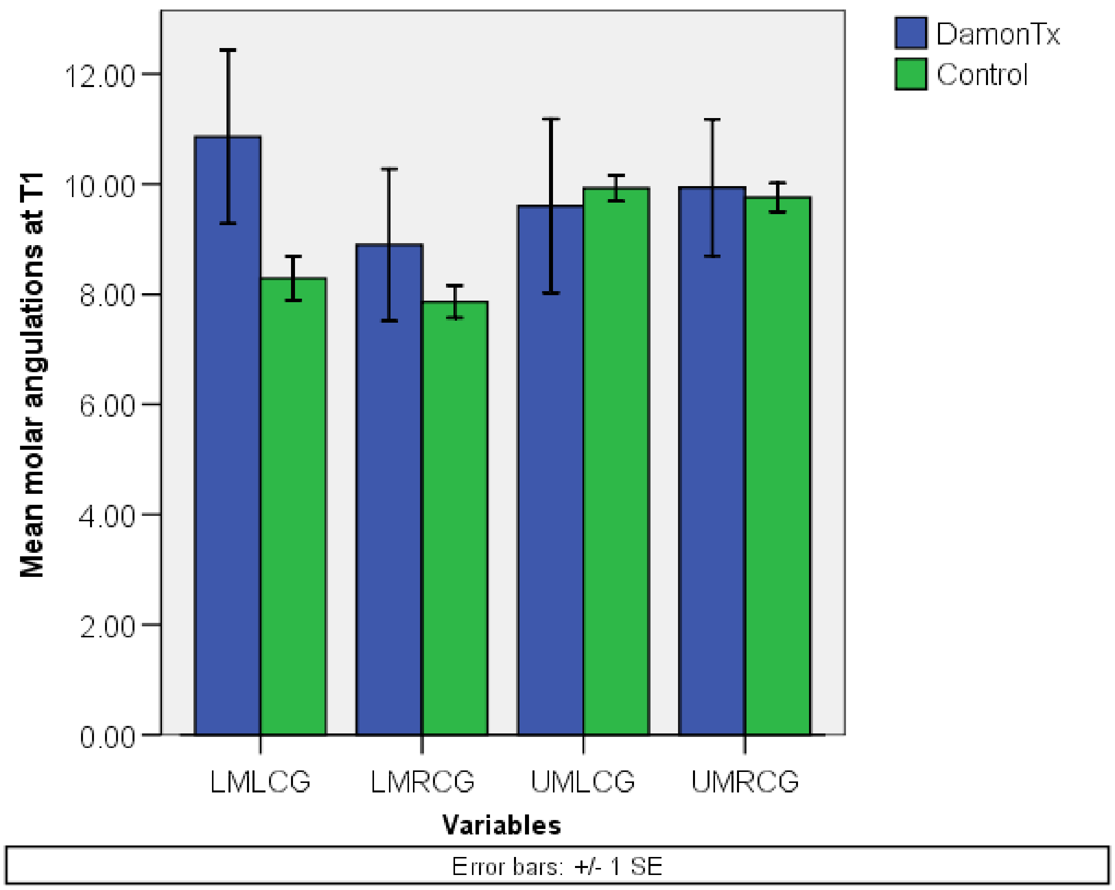


Figure 2-18-Molar angulation values at pre-treatment

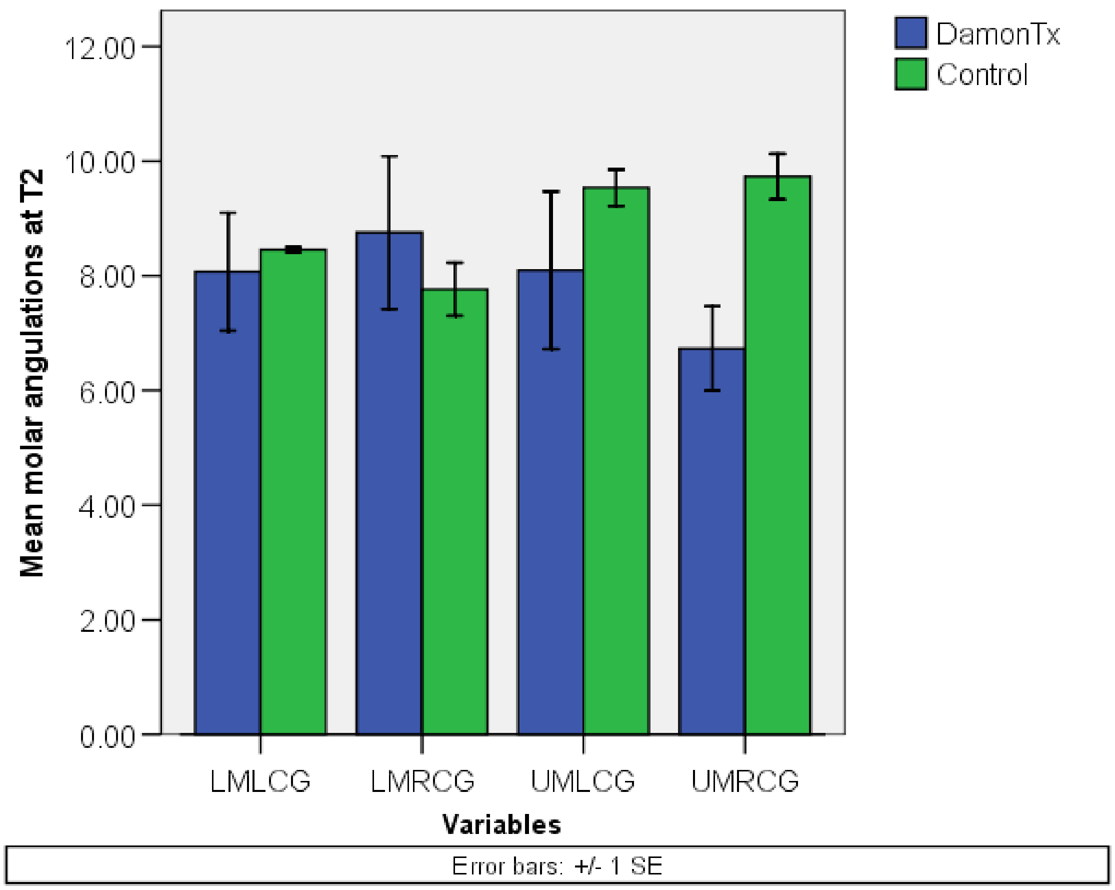


Figure 2-19-Molar angulation values at post-treatment

Measurement	Treatment Group			Control Group			P
	Initial	Final	Change	Initial	Final	Change	
	Mean±SD	Mean±SD	Mean±SD	Mean±SD	Mean±SD	Mean±SD	
UM(R)-CG1	9.94±5.54	6.73±3.30	-3.21±5.74	9.76±1.17	9.73±1.78	-0.03±2.15	.157
UM(L)-CG1	9.61±7.06	8.10±6.15	-1.51±6.55	9.93±1.06	9.54±1.42	-0.39±2.03	.253
LM(R)-CG1	8.90±6.18	8.76±5.96	-0.14±6.30	7.87±1.30	7.77±2.07	-0.10±2.76	.383
LM(L)-CG1	10.86±7.06	8.07±4.59	-2.79±8.26	8.29±1.79	8.46±0.21	0.17±1.89	.314

Table 2-11-First molar angulations

2.4.2.3Incisor positions

According to both nonparametric statistical test (Mann-Whitney U) and MANOVA, in the treatment group, angles made between upper incisors with *Frankfort horizontal plane*, *Sella-Nasion line*, *Nasion-A point line*, *A point- Pogonion line* and *Palatal plane* all showed a significantly larger increase compared to the control group (P< 0.05), whereas changes of the distance between upper incisors with *Nasion-A point line* and *A point-Pogonion line*, were not significantly different from the control group (P> 0.05). Since the angles increased, but the distances did not, therefore, it seems that in the treatment group, lingual root torque of the upper incisors has been increased more than that of the control group.

As for the mandible, the angles made between the lower incisors with *Nasion-B point line*, *A point-Pogonion line* and the *mandibular plane* all showed a significant increase compared to the control group (P< 0.05). The distances between lower incisors with *A point-Pogonion line* and *Nasion-B point line* both showed significant increases compared to the control group as well (P< 0.05). Since both angles and distances were increased, therefore in the treatment group, lower incisors proclination was larger than that of the control group. Changes of distance between *Sella* and *Nasion* were not significantly different between the two groups (P> 0.05). Therefore, growth of anterior cranial base length was similar in both groups. It should be noted that although we did a large number of comparisons here, there is no point in doing the Bonferroni correction for the alpha as our significant p-values are smaller than alpha either with or without the Bonferroni correction.

Pre-treatment:

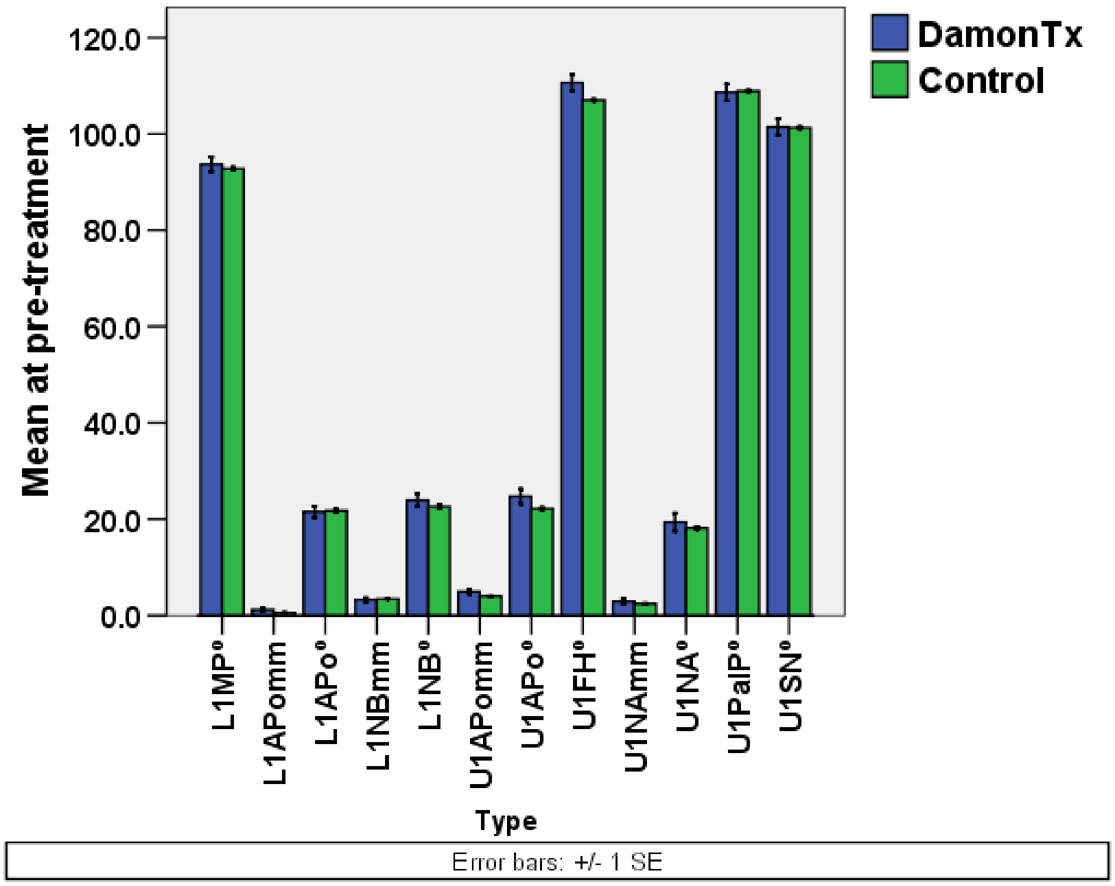


Figure 2-20-Incisors' positions at pre-treatment

Post-treatment:

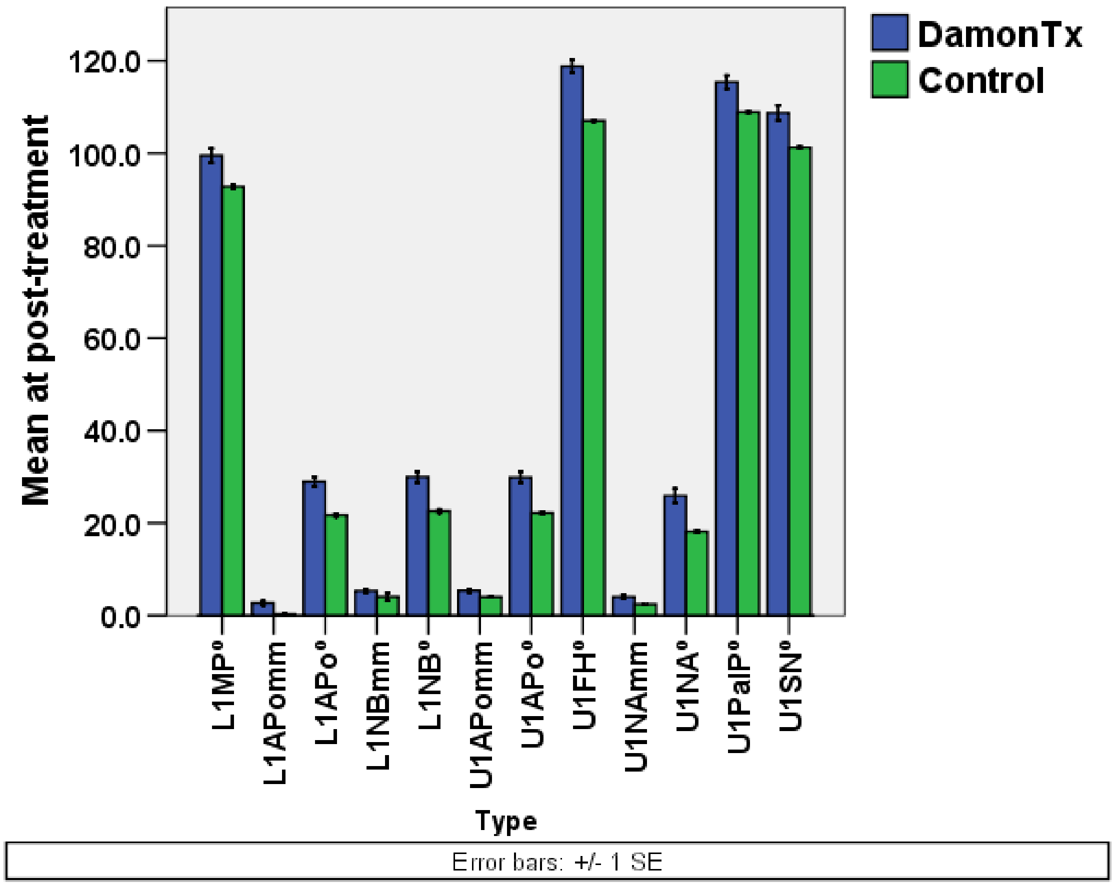


Figure 2-21-Incisors' positions at post-treatment

Measurement	Treatment Group			Control Group			P
	Initial	Final	Change	Initial	Final	Change	
	Mean± SD	Mean± SD	Mean±SD	Mean± SD	Mean± SD	Mean±SD	
L1MPº	93.71±6.77	99.50±7.01	5.80±6.89	92.77±1.55	93.09±1.80	0.32±2.94	.006*
L1APomm	1.24±1.80	2.71±1.89	1.48±1.69	0.61±0.24	0.39±0.49	0-.23±0.52	.001*
L1APoº	21.53±5.19	28.94±4.64	7.42±7.09	21.74±1.65	22.47±1.09	0.73±2.28	.000*
L1NBmm	3.28±1.96	5.31±1.62	2.04±1.69	3.42±0.33	3.20±0.41	-0.23±0.61	.000*
L1NBº	23.92±6.08	29.97±5.25	6.05±6.84	22.58±1.70	22.50±1.58	-0.08±2.85	.002*
U1APomm	4.92±1.97	5.38±1.80	0.46±1.90	3.99±0.34	3.69±0.48	-0.30±0.42	.076
U1APoº	24.75±6.84	29.87±5.42	5.12±5.38	22.19±1.31	20.86±1.45	-1.33±0.93	.000*
U1FHº	110.64±7.85	118.82±5.96	8.18±6.54	107.03±0.85	107.46±1.23	0.44±1.54	.000*
U1NAmm	2.91±2.56	4.02±2.21	1.12±2.45	2.45±0.48	2.56±0.59	0.12±0.81	.121
U1NAº	19.37±8.45	25.90±6.88	6.53±6.74	18.18±1.39	18.10±1.27	-0.08±1.82	.001*
U1PalPº	108.63±7.74	115.37±6.51	6.74±5.89	108.91±0.97	109.73±0.70	0.83±1.49	.000*
U1SNº	101.44±7.69	108.74±7.37	7.30±6.49	101.29±0.92	101.63±0.81	0.35±1.12	.000*
SN	66.29±3.87	67.07±3.63	0.38±2.50	70.69±1.25	72.11±1.10	1.43±0.95	.149

Table 2-12-Changes of incisors positions;* significant (P-value<0.05*)*

2.4.3 Correlation between two-dimensional and three-dimensional data

Paired t-test showed no statistically significant differences between dental measurements made using two and three dimensional analyses in the Damon treated group (P> 0.05), therefore, the measurements of the two analyses were in agreement.

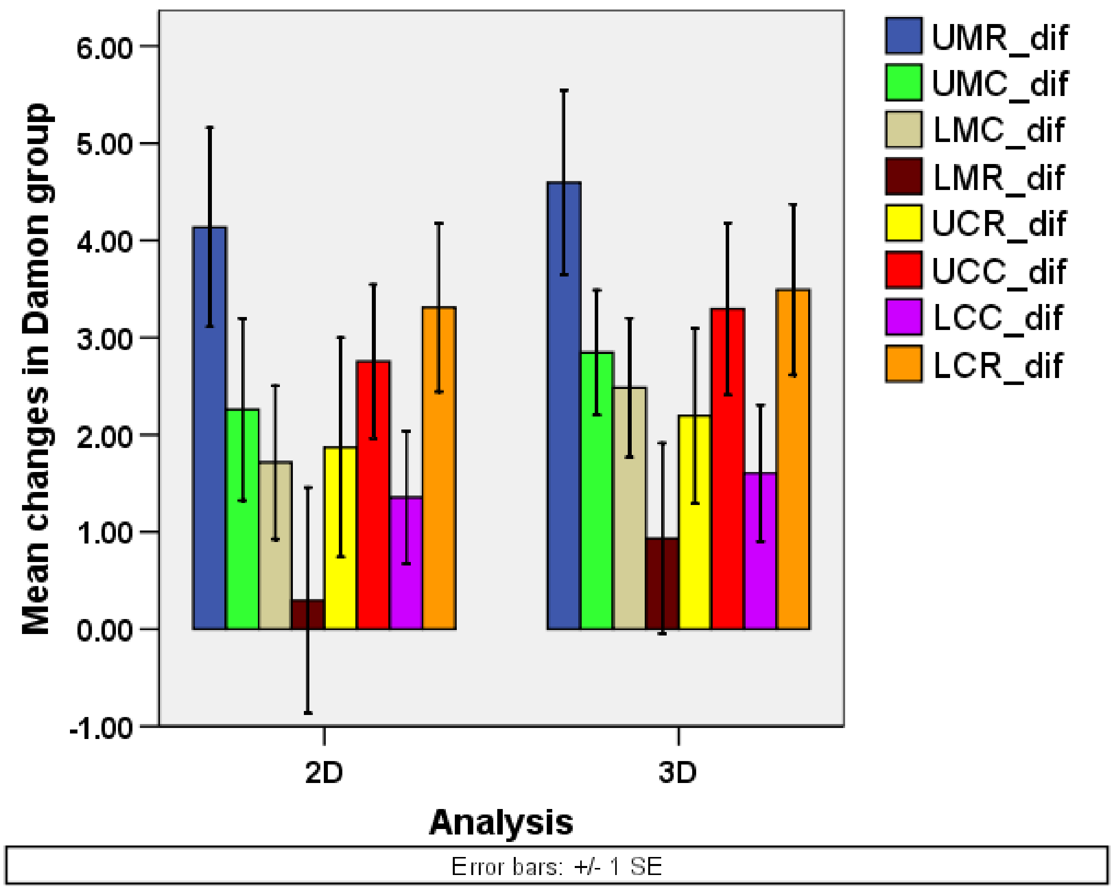


Figure 2-22-2D and 3D measurements of changes of transverse dimensions in Damon patients.

Analysis	Variables							
	UMR_dif	**UMC_dif**	**LMC_dif**	**LMR_dif**	**UCR_dif**	**UCC_dif**	**LCC_dif**	**LCR_dif**
2D	4.14±4.58	2.26±4.18	1.72±3.53	0.30±5.20	1.87±5.05	2.76±3.53	1.36±3.06	3.31±3.88
3D	4.60±4.24	2.85±2.87	2.48±3.20	0.93±4.39	2.20±4.03	3.30±3.96	1.61±3.14	3.49±3.93
P	.573	.502	.373	.505	.511	.292	.603	.626

Table 2-13-2D and 3D measurements of changes of transverse dimensions in Damon patients.

2.4.4 Measurements on dental models

To be compared to measurements made on the x-rays, Intermolar distances were measured on available dental models of five patients (3 sets of plaster models and 2 pairs of Orthocad models). These samples were selected based on availability of dental models. Measurements of the models and the X-rays and the differences between these two sets of measurements are illustrated in the following tables and figures. No statistical tests were run though, due to the small number of samples.

Patients	T1				T2			
	UMC		LMC		UMC		LMC	
	XRay	Model	XRay	Model	XRay	Model	XRay	Model
1	54.79	52.00	53.68	50.00	57.42	57.00	53.66	51.50
2	50.02	49.50	42.19	42.50	54.21	52.00	48.31	46.00
3	49.69	47.00	46.26	43.00	48.43	49.50	45.31	44.00
4	53.16	52.90	47.92	47.30	52.63	54.70	49.68	48.30
5	48.22	50.30	46.73	44.70	55.84	54.20	49.97	46.30

Table 2-14-Measurements on dental models and X-Rays of 5 samples of the Damon group

	Models Mean± SD	X-Rays Mean± SD	Difference between the 2 groups Mean± SD
UMC1	50.3±2.3	51.2±2.7	0.8±2.0
LMC1	45.5±3.1	47.4±4.1	1.9±1.7
UMC2	53.5±2.8	53.7±3.4	0.2±1.8
LMC2	47.2±2.8	49.4±3.0	2.2±1.0

Table 2-15-Means of measurements in models and X-rays

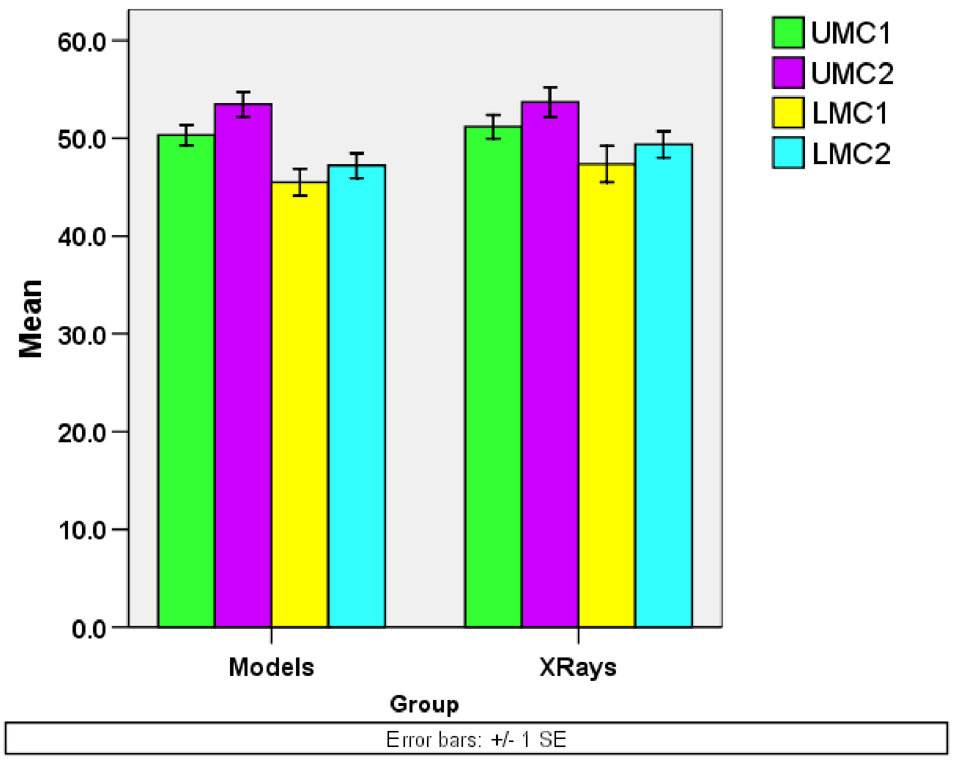


Figure 2-23-Measurements in models and X-rays of 5 Damon patients

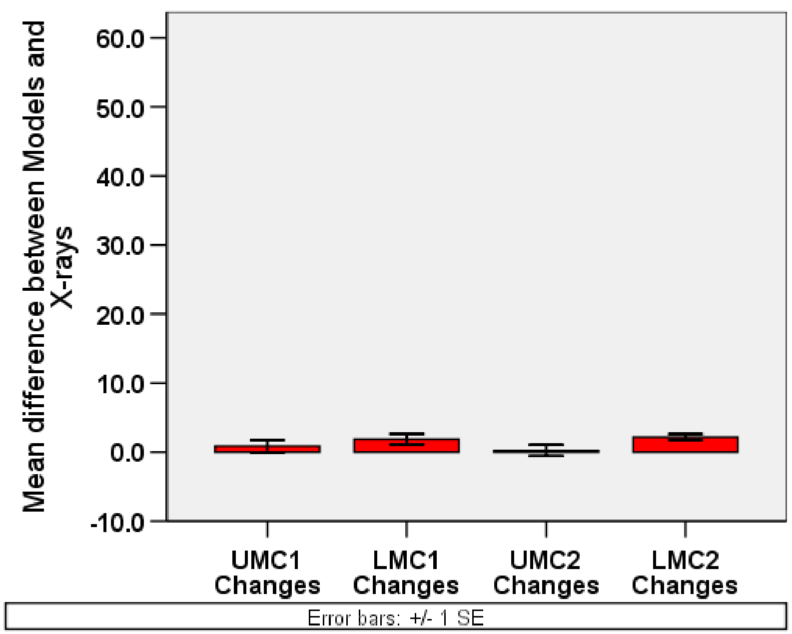


Figure 2-24-Differences of the measurements between X-Rays and Models for each variable

2.5 Discussion

Orthodontic treatment with the Damon system using its suggested archwire sequence protocols is reported to show arch width increases (7), but the evidence regarding this claim is limited and somewhat contrasting. Over the past few years, transverse changes with Damon self-ligating system have been compared with those of conventional brackets with the use of dental models (8-10). The present study however was intended to compare these changes with those of untreated population to determine if Damon system in fact results in significant increase of the arch width. Furthermore, our study used a three-dimensional analysis of patients' radiographs to investigate root movements in addition to crown movements. Only non-extraction cases were included in the study so that expansion would not be compromised by movement of the teeth into the extraction spaces.

Changes of intermolar and intercanine distances (between crowns) were not significantly different between the two groups. Neither were changes in lower intermolar distance (roots) and upper intercanine distance (roots). Changes of distances between roots of upper molars and the distance between roots of lower canines, however, showed statistically significant differences between the two groups. The distance between roots of upper molars changed 4.59 millimetres (mm) on average in Damon group as opposed to 0.8 mm (on average) in the control group; the difference between the two groups can be considered clinically significant (3.79 mm). As for the distance between roots of lower canines, the average change was +3.49 and -0.01 mm in Damon and control groups respectively; this difference too can be considered clinically significant. This significant buccal movement of the roots has different clinical implications for upper molars and lower canines. With upper molars, it suggests a bodily movement as opposed to a tipping movement, whereas with lower canines it can help with retention and stability of treatment results in the long term.

Furthermore, in the treatment group, since the angles made between the maxillary incisor and the reference lines increased, but the distances did not, therefore, it seems that lingual movement of root apex of the upper incisors occurred rather than forward movement of the incisal tip. On the other hand, as for the mandibular incisors, both angles and distances between the lower incisors and the reference lines increased, therefore we can conclude that the incisal tip of the mandibular incisors moved forward in the treatment group. Therefore, orthodontic treatment with the Damon system resulted in statistically greater proclination of mandibular incisors and lingual root torque of maxillary incisors. Free play of archwire in the ligature-free brackets may be an explanation for this proclination and/or torque.

In this study, it appears that teeth alignment in subjects of the treatment group was accomplished by intermolar and/or intercanine width increase along with either proclination of mandibular incisors or lingual root torque of maxillary incisors. Incisor advancement, molar expansion and inter-canine expansion have all been shown to increase the arch perimeter (11) which in turn results in alignment of teeth and alleviation of crowding. There were cases in which lower intercanine and/or intermolar distances for crowns decreased at post-treatment; however in these cases either proclination of lower incisors helped correct the crowding or the width decrease helped close the pre-treatment spacing. There were also cases for which upper intercanine and/or intermolar distances for crowns decreased at post-treatment; however in these cases either proclination of upper incisors or lingual root torque helped relieve the crowding or the width decrease helped close the pre-treatment spacing. Also, in some instances, intermolar width decrease was compensated for by intercanine width increase and vice versa.

Comparison with literature should be made with caution, because unlike the present study all of the above-mentioned related studies compared Damon system with conventional brackets and not untreated controls. Having said that, our findings are in complete agreement with those of Scott et al (2008) who found lower intermolar and intercanine changes to be similar with both Damon and conventional ligation brackets (8). Our findings are also in agreement with those of Jiang's (2008), because although Jiang reported a statistically significant difference between the two groups for the distance between crowns of lower molars, the difference was not clinically significant (0.77 mm) (9). Our findings, however, are in partial agreement with those of Pandis et al (2007) as, unlike our study, Pandis reported changes in the distance between crowns of lower molars to be significantly different between the two groups (with a 1.5 mm difference). (10) It is possible that in our study, mandibular incisor proclination, which was significantly larger in the Damon group, compensated for the intermolar width changes which were not significantly different; whereas, in Pandis's study, changes of mandibular proclination were not different between the two groups, while intermolar changes were significantly different.

Fleming et al (2009) (12) studied mandibular transverse dimensions with another type of passive self-ligating bracket (SmartClip-3M Unitek). Findings of that study are in agreement with the present study as it reported no differences between intercanine increases in SL bracket and conventional bracket groups. Although the intermolar width increase was reported to be statistically greater than the conventional group, however as the authors themselves admit, the clinical significance of this difference (0.9 mm) is debatable.

In the present study, buccal (or lingual) tipping of first molars in the treatment group was not significantly different from the control group. This may suggest that molar movements were bodily and not related to bucco-lingual tipping of the crowns. As for maxillary skeletal expansion, orthodontic treatment with the Damon system did not result in statistically greater increase in the distance between the right and left jugal processes compared to the control group. This expected finding in this group of patients treated with the Damon system suggests that Damon system did not result in maxillary base expansion. It was also revealed that pre-treatment values for crowding did not affect transverse changes in either maxilla or mandible. However, future studies regarding this outcome are encouraged as our sample size after further classification into three crowding categories was way too small for us to be able to rely on this result.

Retrospective studies have been criticized by researchers for being potentially biased and/or confounded (10). Although this has been a retrospective study, bias was minimized by using records of patients treated by a single practitioner thereby eliminating inter-operative variability. Also, our inclusion criteria only allowed inclusion of subjects who had not received any additional type of intervention such as functional appliances thereby minimizing confounding factors which could have led to distorted results.

However, the results of this study should be considered with caution due to a small sample size and the fact that our control group consisted of matching average Bolton templates as opposed to actual individual samples. Although Bolton templates are rather old and were generated by periodic examination of a specific ethnic population (Caucasians), we used them as our control group as these templates are part of one of the largest longitudinal studies to this date and they have been previously used (13) for comparative studies. Furthermore, since we did not either take a random sample or randomly assign the treatment to the subjects, inferences should be made cautiously. Future studies with larger sample sizes, random allocation of treatment and use of a randomly taken sample are suggested.

This study also generated 3D measurements for Bolton templates (5) of ages 10-18. (Appendix 1) Since these measurements were obtained from 3D frames, which were created by combining lateral and frontal templates of each age, they may be more accurate than 2D measurements which are made using only the frontal template.

2.6 Conclusion

Our findings suggest that transverse changes (i.e. changes in distances between crowns of upper and lower first molars and canines) which result from orthodontic treatment with Damon passive SL system are similar to those of untreated individuals. However, changes of upper intermolar distances (roots) and lower intercanine distances (roots) are larger compared to untreated individuals. Our results also showed that lingual torque of roots of maxillary incisors and proclination of mandibular incisors are larger than those of untreated individuals. Not surprisingly, width of maxillary base does not appear to increase as a result of treatment with Damon system. As detected in 3D reconstructive measurements tool, our findings also suggest that Damon treatment does not result in tipping of molar crowns. Furthermore, arch width changes do not seem to be affected by pre-treatment crowding values. Overall, according to our findings, teeth alignment with Damon system appears to be accomplished with a combination of arch width changes and incisor proclination or lingual root torque.

Future studies:

Other outcomes of orthodontic treatment with Damon system such as changes of airway size and tongue space can be studied in future studies to determine if Damon treatment has a significant effect on these variables. There are also several other aspects of SL brackets which are yet to be investigated such as: rate of alignment (14-17), bracket failure (18, 19), chair-side time savings (15, 20), operator's level of convenience, appointment intervals, patient's discomfort (16, 21) and/or satisfaction level. Also, maybe a larger sample size with random allocation of treatment to the subjects and also random selection of the samples can be studied with 3DCeph with different malocclusions (Class II and Class III malocclusions). Furthermore, it is recommended to select samples using more strict inclusion criteria with regard to age, crowding values, Angle malocclusion classification and treatment duration.

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3 Appendix 1

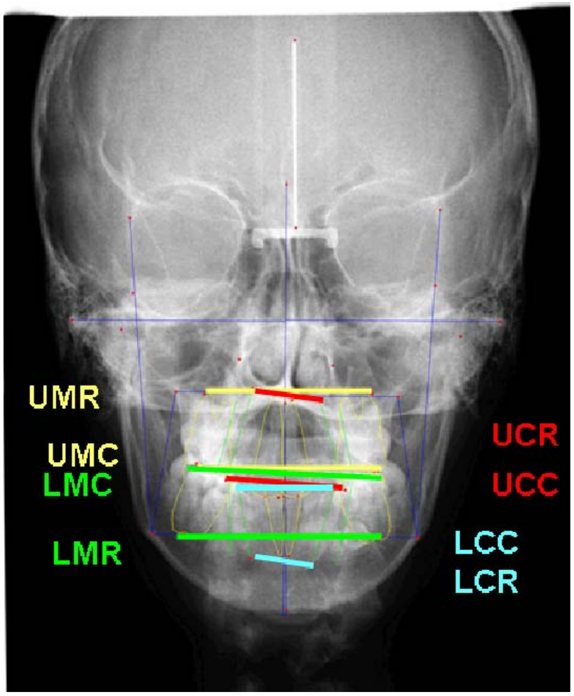

Figure A1. 1- Transverse measurements made and compared between the two groups: LMC: The distance between mesiobuccal cusps of lower permanent first molars. UMC: The distance between mesiobuccal cusps of upper permanent first molars. LCC: The distance between cusp tips of lower permanent cuspids. UCC: The distance between cusp tips of upper permanent cuspids. LMR: The distance between mesiobuccal roots of lower permanent first molars. UMR: The distance between mesiobuccal roots of upper permanent first molars. LCC: The distance between roots of lower permanent cuspids. UCC: The distance between roots of upper permanent cuspids.

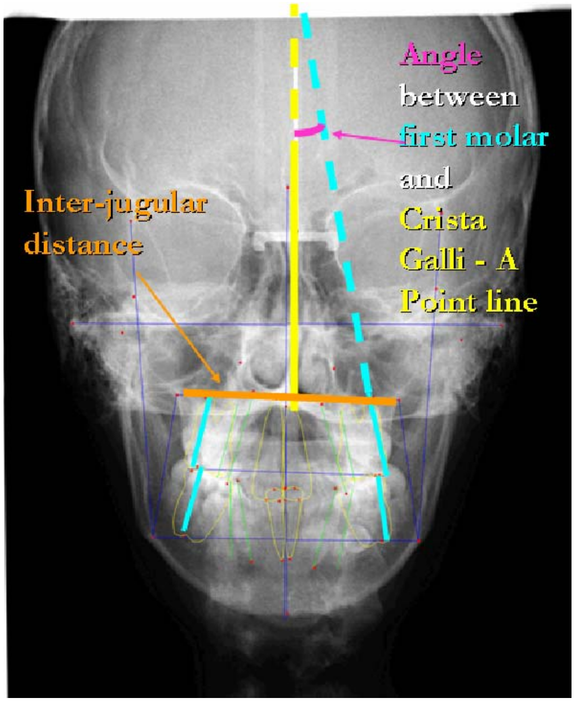

Figure A1. 2- Molar angulation and maxillary base width (JJ).

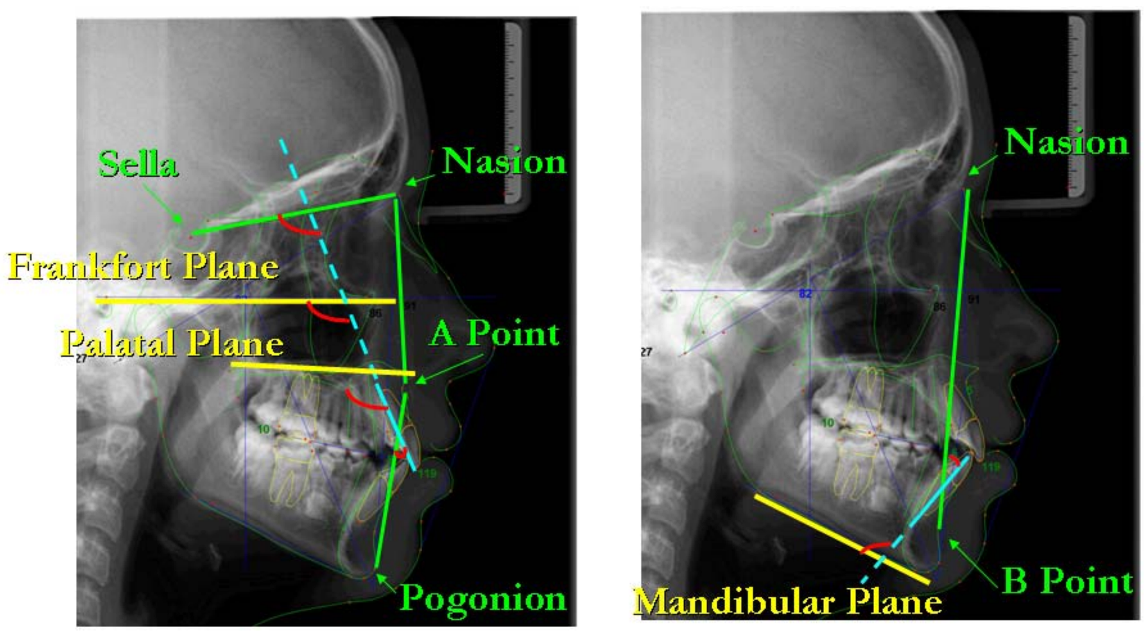

Figure A1. 3-Angles and distances measured for evaluation of incisors positions.

Variable	Control group	
	Inter-examiner reliability	Intra-examiner reliability
UMR	.867	.960
UMC	.889	.965
LMC	.800	.885
LMR	.771	.857
UCR	.790	.781
UCC	.951	.990
LCC	.707	.943
LCR	.922	.893

Table A1. 1-Intra-class correlation coefficient (ICC) for the control group.

Variable	Damon group	
	Inter-examiner reliability	Intra-examiner reliability
LMC1	.983	.962
UMC1	.990	.996
LCC1	.915	.997
UCC1	.887	.999
UMR1	.938	.957
LMR1	.976	.939
UCR1	.967	.985
LCR1	.771	.857
JJ1	.938	.984
UMR-CG1	.978	.921
UML-CG1	.998	.980
LMR-CG1	.994	.908
LML-CG1	.992	.934
FMA(MP-FH)1	.992	.995
Po-Or1	.894	.833
MMo1	.992	.986
S-N1	.910	.834
AGML1	.951	.997
AGMR1	.706	.993
LMC2	.846	.993
UMC2	.833	.980
LCC2	.989	.996
UCC2	.798	.975

UMR2	.982	.990
LMR2	.759	.977
UCR2	.827	.917
LCR2	.986	.972
JJ2	.897	.983
UMR-CG2	.729	.748
UML-CG2	.981	.962
LMR-CG2	.992	.990
LML-CG2	.925	.844
FMA(MP-FH)2	.987	.991
Po-Or2	.859	.975
MMo2	.937	.989
S-N2	.823	.889
AGML2	.955	.992
AGMR2	.786	.930

Table A1. 2-Intra-class correlation coefficient (ICC) for Damon group.

Control Group					
Variables	**Templates**				
	11 yr	**14 yr**	**15 yr**	**16 yr**	**17 yr**
UMR-A	44.83	46.84	47.04	47.41	45.09
UMR-B	45.38	49.00	47.61	47.99	45.09
UMC-A	52.03	52.60	54.24	55.42	52.06
UMC-B	53.14	53.74	53.14	55.42	51.53
LMC-A	46.49	48.01	48.17	47.42	45.62
LMC-B	47.60	47.24	47.05	47.45	44.02
LMR-A	54.81	53.77	54.85	55.44	52.61
LMR-B	55.35	55.53	55.38	56.01	53.69
UCR-A	27.11	26.85	27.11	26.85	25.23
UCR-B	26.01	27.16	26.57	25.71	24.17
UCC-A	30.44	33.74	35.43	35.99	34.89
UCC-B	31.01	35.54	34.88	36.59	35.43
LCC-A	24.91	26.87	27.13	28.58	25.23
LCC-B	24.37	31.13	26.08	28.04	25.23
LCR-A	21.04	20.57	19.93	21.14	19.86
LCR-B	20.47	20.70	19.41	21.14	19.87

Table A1. 3-Inter-rater reliability measurements for Control Group. A: first examiner; B: Second examiner.

Control Group					
Variables	Templates				
	11 yr	14 yr	15 yr	16 yr	17 yr
UMR-a	44.83	46.84	47.04	47.41	45.09
UMR-b	43.77	46.86	47.05	47.41	45.09
UMR-c	44.28	47.41	47.05	47.42	46.49
UMC-a	52.03	52.60	54.24	55.42	52.06
UMC-b	51.51	52.58	53.70	55.41	51.52
UMC-c	52.59	52.60	53.69	55.43	53.13
LMC-a	46.49	48.01	48.17	47.42	45.62
LMC-b	45.96	47.43	47.05	47.41	46.18
LMC-c	46.51	47.44	47.60	48.57	46.50
LMR-a	54.81	53.77	54.85	55.44	52.61
LMR-b	54.79	53.77	54.83	55.45	52.63
LMR-c	54.81	53.77	54.83	55.48	54.81
UCR-a	27.11	26.85	27.11	26.85	25.23
UCR-b	27.72	26.85	26.57	26.85	25.23
UCR-c	27.11	26.87	26.01	26.28	26.56
UCC-a	30.44	33.74	35.43	35.99	34.89
UCC-b	29.93	34.32	34.88	36.00	34.89
UCC-c	30.44	33.75	35.42	36.58	35.99
LCC-a	24.91	26.87	27.13	28.58	25.23
LCC-b	24.91	26.86	27.72	28.57	26.30
LCC-c	24.35	27.42	26.57	28.00	27.13
LCR-a	21.04	20.57	19.93	21.14	19.86
LCR-b	21.59	20.00	19.93	21.14	19.86
LCR-c	21.59	20.03	19.95	21.14	21.04

Table A1. 4-Intra-rater reliability measurements for Control group. a: first measurements; b: second measurements; c: third measurements.

Damon Group				
Variables	Patients			
	1	2	3	4
LMC1-A	48.1	40.0	49.9	45.5
LMC1-B	50.0	38.9	51.1	46.1
UMC1-A	52.2	43.0	51.2	56.4
UMC1-B	51.3	41.6	50.5	55.1
LCC1-A	18.5	21.4	22.3	25.6

LCC1-B	18.8	23.2	20.2	24.4
UCC1-A	22.8	23.2	30.4	34.1
UCC1-B	23.6	22.0	27.4	29.1
UMR1-A	44.5	38.9	43.5	41.1
UMR1-B	43.7	38.5	43.4	43.3
LMR1-A	56.4	51.0	62.8	57.0
LMR1-B	56.2	47.9	63.9	55.8
UCR1-A	29.1	17.8	20.6	19.7
UCR1-B	28.0	17.0	18.2	17.1
LCR1-A	26.0	19.4	25.9	24.0
LCR1-B	23.2	21.9	25.2	25.3
JJ1-A	57.2	49.9	61.4	56.7
JJ1-B	54.2	47.5	60.0	59.8
UMRCG1-A	11.4	12.0	13.8	19.2
UMRCG1-B	11.1	11.4	11.8	20.2
UMLCG1-A	11.9	2.3	10.1	22.2
UMLCG1-B	11.7	1.1	11.0	22.6
LMRCG1-A	8.1	17.8	17.7	12.8
LMRCG1-B	8.0	18.6	17.2	11.7
LMLCG1-A	5.4	15.0	22.5	21.9
LMLCG1-B	7.1	14.9	20.6	22.9
LMC2-A	49.1	44.4	48.9	51.0
LMC2-B	47.7	41.8	46.2	48.3
UMC2-A	52.4	48.0	54.2	54.6
UMC2-B	51.6	47.1	52.2	50.8
LCC2-A	26.9	23.5	28.8	27.5
LCC2-B	26.5	23.6	29.7	27.7
UCC2-A	33.7	29.2	37.7	33.6
UCC2-B	34.4	31.4	34.3	33.9
UMR2-A	48.0	43.9	56.3	47.4
UMR2-B	47.5	43.2	54.4	45.7
LMR2-A	49.7	54.7	54.5	58.9
LMR2-B	51.1	51.7	52.6	55.0
UCR2-A	23.2	24.6	24.8	23.2
UCR2-B	21.5	24.2	26.2	23.2
LCR2-A	21.2	21.9	24.8	29.9
LCR2-B	21.0	23.6	24.3	30.2
JJ2-A	60.6	57.9	64.5	58.2
JJ2-B	58.4	56.3	62.1	57.3
UMRCG2-A	3.7	6.3	4.1	7.8
UMRCG2-B	5.6	7.5	6.3	7.5
UMLCG2-A	7.9	5.2	1.8	16.8

UMLCG2-B	5.6	3.1	0.4	15.5
LMRCG2-A	1.6	23.9	8.8	19.3
LMRCG2-B	3.7	26.7	8.3	20.0
LMLCG2-A	3.3	8.3	7.6	11.9
LMLCG2-B	5.1	6.1	9.0	11.1
mmo1-A	1.5	1.9	1.8	-4.5
mmo1-B	.9	1.1	1.5	-4.9
FMA1-A	19.9	23.5	11.1	19.6
FMA1-B	20.1	24.9	12.3	20.1
PoOr1-A	73.8	73.1	74.7	73.7
PoOr1-B	73.4	72.1	75.4	73.5
SN1-A	63.1	61.4	63.6	65.7
SN1-B	61.2	59.9	64.8	66.0
AGML1-A	42.7	37.3	38.0	38.0
AGML1-B	41.6	36.1	36.5	38.1
AGMR1-A	36.6	35.4	37.0	38.9
AGMR1-B	36.7	33.3	35.7	36.6
mmo2-A	-.7	-3.5	-1.4	-2.5
mmo2-B	-.5	-3.2	-.5	-3.5
FMA2-A	21.3	19.7	12.0	22.6
FMA2-B	20.7	21.1	13.3	22.5
PoOr2-A	80.7	74.9	76.5	70.7
PoOr2-B	77.1	70.3	75.2	68.0
SN2-A	67.8	62.1	64.2	67.5
SN2-B	65.8	62.0	63.8	64.4
AGML2-A	38.1	42.6	38.4	41.0
AGML2-B	38	42	37	40
AGMR2-A	39.4	35.2	36.6	39.0
AGMR2-B	37.2	33.8	37.2	37.0

Table A1. 5-Inter-rater reliability measurements for Damon group. A: first examiner; B: second examiner.

Damon Group				
Variables	**Patients**			
	1	**2**	**3**	**4**
UMR1-a	45.2	39.3	43.1	39.8
UMR1-b	44.5	38.9	43.5	41.1
UMR1-c	45.2	39.6	40.6	39.9
UMC1-a	51.6	41.0	50.7	55.4
UMC1-b	52.2	43.0	51.2	56.4

UMC1-c	51.6	41.0	50.9	55.4
LMC1-a	46.5	41.4	47.1	47.0
LMC1-b	48.1	40.0	49.9	45.5
LMC1-c	46.5	41.4	47.4	47.0
LMR1-a	53.7	53.3	59.6	54.9
LMR1-b	56.4	51.0	62.8	57.0
LMR1-c	53.7	53.6	59.9	56.4
UCR1-a	29.7	20.0	19.0	22.1
UCR1-b	29.1	17.8	20.6	19.7
UCR1-c	30	20	18	20
UCC1-a	22.8	23.1	29.4	33.8
UCC1-b	22.8	23.2	30.4	34.1
UCC1-c	22.8	23.6	29.4	33.8
LCC1-a	19.1	21.4	21.7	26.2
LCC1-b	18.5	21.4	22.3	25.6
LCC1-c	19.1	21.4	21.7	26.2
LCR1-a	24.3	21.6	22.7	23.8
LCR1-b	26	19	26	24
LCR1-c	24.7	20.7	22.2	24.6
JJ1-a	57.2	52.7	61.2	56.1
JJ1-b	57.2	49.9	61.4	56.7
JJ1-c	57.2	52.7	61.9	55.5
UMRCG1-a	6.2	7.8	8.6	18.4
UMRCG1-b	11.4	12.0	13.8	19.2
UMRCG1-c	5.4	7.8	11.1	18.2
UMLCG1-a	10.8	2.8	12.1	23.2
UMLCG1-b	11.9	2.3	10.1	22.2
UMLCG1-c	10.9	3.9	17.6	23.3
LMRCG1-a	14.4	23.5	20.4	7.7
LMRCG1-b	8.1	17.8	17.7	12.8
LMRCG1-c	14.2	25.3	19.4	7.9
LMLCG1-a	3.6	26.3	17.1	17.7
LMLCG1-b	5.4	15.0	22.5	21.9
LMLCG1-c	3.6	25.7	20.1	22.4
UMR2-a	46.8	43.8	54.7	45.3
UMR2-b	48	44	56	47
UMR2-c	46.8	45.3	55.8	46.3
UMC2-a	53	48	54	52
UMC2-b	52.4	48.0	54.2	54.6
UMC2-c	53	48	54	53
LMC2-a	50.3	44.4	48.6	50.6
LMC2-b	49.1	44.4	48.9	51.0
LMC2-c	50.3	44.4	48.6	50.3

LMR2-a	51.1	52.4	52.2	59.3
LMR2-b	49.7	54.7	54.5	58.9
LMR2-c	51.1	53.6	53.2	58.9
UCR2-a	25.3	24.5	24.1	23.1
UCR2-b	23.2	24.6	24.8	23.2
UCR2-c	24.5	24.7	24.1	24.8
UCC2-a	34	30	35	34
UCC2-b	33.7	29.2	37.7	33.6
UCC2-c	34	30	36	34
LCC2-a	27.2	23.5	29.2	28.1
LCC2-b	26.9	23.5	28.8	27.5
LCC2-c	27.2	23.8	29.2	28.1
LCR2-a	19.9	22.1	24.5	27.2
LCR2-b	21.2	21.9	24.8	29.9
LCR2-c	22.4	21.8	25.7	28.4
JJ2-a	60.6	57.9	62.6	58.4
JJ2-b	60.6	57.9	64.5	58.2
JJ2-c	60.6	57.9	62.6	58.2
UMRCG2-a	6.4	7.7	1.1	7.0
UMRCG2-b	3.7	6.3	4.1	7.8
UMRCG2-c	6.5	6.9	5.0	6.0
UMLCG2-a	9.8	3.2	1.4	12.3
UMLCG2-b	7.9	5.2	1.8	16.8
UMLCG2-c	10.6	0.8	2.7	12.2
LMRCG2-a	2.2	21.5	6.0	17.3
LMRCG2-b	1.6	23.9	8.8	19.3
LMRCG2-c	1.3	21.5	4.2	15.6
LMLCG2-a	4	3.4	5	12.3
LMLCG2-b	3.3	8.3	7.6	11.9
LMLCG2-c	4.8	9.3	11.5	11.8
mmo1-a	1.3	1.9	-0.3	-5.0
mmo1-b	1.5	1.9	1.8	-4.5
mmo1-c	1.3	2.0	-0.3	-4.6
FMA1-a	18.6	23.4	10.2	18.4
FMA1-b	19.9	23.5	11.1	19.6
FMA1-c	18.8	24.6	11.1	19.6
PoOr1-a	73.4	73.3	73.9	72.7
PoOr1-b	73.8	73.1	74.7	73.7
PoOr1-c	74.1	73.7	74.8	73.1
SN1-a	64.9	63.3	62.7	65.7
SN1-b	63.1	61.4	63.6	65.7
SN1-c	63.7	64.4	63.7	66.8
AGML1-a	42.7	37.3	38.7	38.2

AGML1-b	42.7	37.3	38.0	38.0
AGML1-c	42.7	37.3	38.7	38.2
AGMR1-a	36.6	35.6	36.3	38.9
AGMR1-b	36.6	35.4	37.0	38.9
AGMR1-c	36.6	35.6	36.3	38.9
mmo2-a	-0.8	-3.6	-1.2	-2.5
mmo2-b	-0.7	-3.5	-1.4	-2.5
mmo2-c	-0.8	-3.4	-1.2	-1.8
FMA2-a	21	20	13	24
FMA2-b	21.3	19.7	12.0	22.6
FMA2-c	21.9	19.5	13.6	24.9
PoOr2-a	79.6	77.2	78.3	68.0
PoOr2-b	80.7	74.9	76.5	70.7
PoOr2-c	80.2	76.2	78.1	71.2
SN2-a	68.2	64.6	66.8	65.8
SN2-b	67.8	62.1	64.2	67.5
SN2-c	66.7	62.7	65.6	67.9
AGML2-a	38.3	43.0	38.1	42.2
AGML2-b	38.1	42.6	38.4	41.0
AGML2-c	38.3	43.0	38.1	42.2
AGMR2-a	39.8	37.6	36.9	40.2
AGMR2-b	39.4	35.2	36.6	39.0
AGMR2-c	39.8	37.6	36.9	40.2

Table A1. 6-Intra-rater reliability measurements for Damon group. a: first measurement; b:second measurement; c:third measurement.

Test Statistics[b]

	UMR_dif	UMC_dif	LMC_dif	LMR_dif	UCR_dif	UCC_dif	LCC_dif	LCR_dif
Mann-Whitney U	68.000	119.000	137.000	188.500	141.000	149.000	171.000	77.000
Wilcoxon W	278.000	329.000	347.000	398.500	351.000	359.000	381.000	287.000
Z	-3.574	-2.193	-1.706	-.311	-1.597	-1.381	-.786	-3.330
Asymp. Sig. (2-tailed)	.000	.028	.088	.756	.110	.167	.432	.001
Exact Sig. [2*(1-tailed Sig.)]	.000[a]	.028[a]	.091[a]	.758[a]	.114[a]	.174[a]	.445[a]	.001[a]

a. Not corrected for ties.

b. Grouping Variable: Tx Group

Table A1. 7-Non-Parametric tests: between group comparisons of mean intermolar (UMR, UMC, LMC, and LMR) and intercanine (UCR, UCC, LCC, and LCR) changes.

Test Statistics[a,b]

	LMC_dif	LMR_dif	LCC_dif	LCR_dif	UMC_dif	UMR_dif	UCC_dif	UCR_dif
Chi-Square	6.740	.673	6.902	3.442	.188	4.227	1.552	.608
df	2	2	2	2	2	2	2	2
Asymp. Sig.	.034	.714	.032	.179	.910	.121	.460	.738

a. Kruskal Wallis Test

b. Grouping Variable: Angle Cl

Table A1. 8-Non-Parametric test: Mean variable changes according to pre-treatment crowding values in Damon group.

Test Statistics[b]

	JJ_dif
Mann-Whitney U	135.000
Wilcoxon W	345.000
Z	-1.761
Asymp. Sig. (2-tailed)	.078
Exact Sig. [2*(1-tailed Sig.)]	.081[a]

a. Not corrected for ties.

b. Grouping Variable: TxGroup

Table A1. 9-Non-Parametric tests: Between group comparison of changes of interjugular distance (JJ).

Test Statistics[b]

	UMRCG_dif	UMLCG_dif	LMRCG_dif	LMLCG_dif
Mann-Whitney U	147.000	157.000	167.000	162.000
Wilcoxon W	357.000	367.000	377.000	372.000
Z	-1.435	-1.165	-.894	-1.030
Asymp. Sig. (2-tailed)	.151	.244	.371	.303
Exact Sig. [2*(1-tailed Sig.)]	.157[a]	.253[a]	.383[a]	.314[a]

a. Not corrected for ties.

b. Grouping Variable: TxGroup

Table A1. 10-Non-Parametric tests: Between group comparisons of changes of molar angulations (UMRCG, UMLCG, LMRCG and LMLCG)

Test Statistics[b]

	U1 FH_ dif	U1 SN_ dif	U1 NAmm_ dif	U1 NAº_ dif	U1 APomm _dif	U1 APoº_ dif	U1 PPlan_ dif	L1 NBmm_ dif	L1 NBº_ dif	U1 PalPº_ dif	L1 APomm _dif	L1to APoº_ dif	SN_ dif
Mann-Whitney U	65.00	75.50	142.500	81.00	134.50	42.000	66.500	40.000	87.00	99.000	81.500	73.500	146.0
Wilcoxon W	275.0	285.5	352.500	291.0	344.50	252.0	276.50	250.000	297.0	309.00	291.500	283.50	356.0
Z	-3.66	-3.37	-1.559	-3.22	-1.777	-4.283	-3.615	-4.341	-3.06	-2.735	-3.212	-3.425	-1.46
Asymp. Sig. (2-tailed)	.000	.001	.119	.001	.076	.000	.000	.000	.002	.006	.001	.001	.143
Exact Sig. [2*(1-tailed Sig.)]	.000[a]	.000[a]	.121[a]	.001[a]	.076[a]	.000[a]	.000[a]	.000[a]	.002[a]	.006[a]	.001[a]	.000[a]	.149[a]

a. Not corrected for ties.

b. Grouping Variable: TxGroup

Table A1. 11-Non-Parametric tests: Between group comparisons of changes of incisor positions (U1FHº, U1SNº, U1NAmm, U1NAº, U1APomm, U1APoº, U1PalatalPlaneº, L1NBmm, L1NBº, IMPAL1MPº, L1APomm, L1toAPoº) and SN.

Measurements (mm) / Age(years)	10	11	12	13	14	15	16	17	18
UMR	44.28	44.83	44.83	45.94	46.84	47.04	47.41	45.09	45.93
UMC	51.47	52.03	52.58	52.06	52.60	54.24	55.42	52.06	53.69
LMC	46.50	46.49	46.50	47.06	48.01	48.17	47.42	45.62	47.62
LMR	55.41	54.81	54.83	53.17	53.77	54.85	55.44	52.61	54.83
UCR	28.78	27.11	27.67	25.45	26.85	27.11	26.85	25.23	27.12
UCC	28.23	30.44	33.21	34.33	33.74	35.43	35.99	34.89	35.99
LCC	22.70	24.91	26.01	27.70	26.87	27.13	28.58	25.23	28.24
LCR	22.14	21.04	20.48	19.95	20.57	19.93	21.14	19.86	21.06

Table A1. 12- 3D measurements for Bolton standards (templates) ages 10-18.

4 Appendix 2: Summary of Instructions to use for 3DCeph

A) Preparation of images:

First step is to prepare the images so that they can be used in 3DCeph software. Posterior-Anterior (PA or Frontal) and Lateral cephalograms have to be digitized.

In Dolphin Imaging, using the “File” menu, choose “Open Patient Charts” and select your patient. Then open the records for your patient by choosing the appropriate time point. Digitize the Lateral view in Dolphin Imaging using “Ricketts Comprehensive” analysis. Use “ruler” as the calibration tool. Add canine’s cusp tip and apex as “custom structures”. Using “reorient” icon, align the x-ray on the Frankfort plane. Then save the digitization. Digitize the Frontal view in Dolphin Imaging using all available analyses. Use “ruler” as calibration tool. By using “save settings” option, the digitization setting can be saved. Missing structures such as canines are added as “custom structures”.

Enable “landmark markers” and print both digitized lateral and frontal views in 1:1. Compare the rulers for equality on the printed views to make sure that magnification factor has been the same for both views. Once you make sure of equality of rulers lengths on both views, convert both images into high quality PDF files using the PDF creator and save the PDF files.

Open the PDF files (both Lateral and Frontal at the same time) in Photoshop. Note that image magnification in Photoshop has to be the same for both views. Align both Lateral and Frontal views on the Frankfort plane while opening them together. Make sure that the 2 points representing the rulers should be existent.

“Crop” the two views using the same size and magnification and save them as Bitmap files (BMP, windows 24 bit) in RGB color mode.

B) *3D Ceph* software:

1) First module: 3DCeph 2000:

Open 3DCeph.exe. program. Using the “File” menu, click on “new patient”. Choose “mouse” as the digitizer. Once prompted to choose an analysis, open “Damon .ana” file from data folder in 3DCeph as the analysis file. In the template that opens up, define the patient’s name and information. Load the BMP digitized lateral image and digitize it again in 3DCeph. In a similar manner, load the BMP digitized frontal view and digitize it again. Using “Create Focal Point” tab, define the focal point in each view: focal point in the Lateral view is the ear rod (coincides with Porion), whereas in the Frontal view it is midway between the ear rods on the midsagittal plane. Using the “Calibrate” tab, calibrate the two (Frontal and Lateral) views. To calibrate, define two points 10 millimeters apart from each other along the ruler on either view. Once calibration is done, save the generated patient file in .pat format to be imported into the next module.

2) Second module: 3D-Aligner 2000:

Open the 3D-Aligner program. Using the “File” menu, choose “Open patient” and select the patient file (.pat file) from the previous module. In the “Point List”, select all the points and align them all by clicking the “Automatic align” tab. Then click the “Create 3D Frame” tab to generate the three-dimensional wire (sketch). Using the “Logs” menu, choose “3D-log” and then click on “Create” to generate the three-dimensional measurements. You can save this log as a text file (.txt file).