Comparison of Skeletal and Dental Changes Obtained from a Tooth-Borne Maxillary Expansion Appliance Compared to the Damon System Assessed Through a Digital Volumetric Imaging

by

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A thesis submitted in partial fulfillment of requirements for the degree of

Master of Science

Medical Sciences-Orthodontics

University of Alberta

Abstract

Introduction: The purpose of this thesis was to evaluate and compare dental and skeletal changes associated with the Damon and Rapid Maxillary Expander (RME) expansion over 6 months using a Cone-Beam Computed Tomography (CBCT).

Methods: A sample of 82 patients were randomly allocated to either Group A or B (41 patients in each group). Patients in Group A received orthodontic treatment using the Damon system (self-ligating brackets). Patients in Group B received treatment using the Hyrax (a type of RME) appliance for 6 months, and then non self-ligating brackets were used to complete the orthodontic treatment. CBCT images were taken two times (baseline and six months into treatment). The AVIZO software was used to locate 18 landmarks (dental and skeletal) on sagittal, axial, and coronal slices of CBCT images.

Results: Comparison between two groups showed that transverse movement of maxillary first molars and premolars were much greater in the Hyrax group. The lateral movements of posterior teeth were associated with buccal tipping of crowns. No clinically significant difference in the vertical or antero-posterior direction between two groups was noted. Alveolar bone next to root apex of maxillary first premolar and molar teeth showed clinically significant lateral movement in the Hyrax group only.

Conclusion: Comparison between two groups showed significantly greater transverse expansion of the first molar and first premolars with buccal tipping in the RME group. No significant changes were noted in any skeletal landmarks except alveolar bone next to

root apex of maxillary first premolar and molar teeth, suggesting a possible bone apposition following teeth movement

Preface

This thesis is an original work by Hye Jin Nam. This project was approved by the University of Alberta Ethics Board (Pro00013379) under the name " Comparison of Skeletal and Dental Changes Obtained from a traditional Tooth-Borne Maxillary Expansion Appliance Compared to the Damon System Assessed Through Digital Volumetric Imaging" on April 21th, 2010.

No part of this thesis has been previously published. The systematic review on "Dental and Skeletal Changes Associated with the Damon System Philosophical Approach" has been accepted and pending for the publication in International Journal of Orthodontics.

Acknowledgements

I wish to express my sincere thanks to my supervisor, Dr. Manuel Lagravère-Vich for all the support and guidance through 3 years of education at University of Alberta. Also, I would like to thank Dr. Carlos Flores-Mir for his support on systematic review, and Dr. Giseon Heo and Dr. Paul Major for their overall support on development of the thesis project.

This thesis would not have been possible without the help of my husband and my parents. Last, I would like to thank our God for giving me the strength to finish this study.

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Chapter 1 Introduction

Problem Statement

Deficiencies in the transverse dimension of dental arches are commonly seen in patients with malocclusion. Studies have shown that maxillary interpremolar and intermolar widths are significantly narrower in class II or III malocclusion patients in comparison to normal occlusion group. [1,2] Traditional treatment of narrow maxillary arches in growing patients involves a Rapid Maxillary Expansion (RME) with separation of the midpalatal suture. Hyrax is one of the most commonly used RME appliances, that has a screw device positioned across a palatal vault, which is activated daily until the desired maxillary expansion is achieved. [3] However, previous studies have revealed that this appliance is associated with some negative dental side effects such as tipping of molars, gingival recession and relapse of dental expansion. [4]

The Damon appliance (Ormco, Orange, California) is one of the self-ligating bracket systems that has been increasingly used by orthodontists for widening of maxillary arch. [5] Their philosophy is based on "light biologically-sensible forces" of the bracket system that allows predictable expansion without negative side effects seen in RME devices. In addition, the company claims many superior functions over conventional bracket systems such as shorter treatment time, reduced pain experience, and better aesthetic outcomes. [6] While the Damon system is heavily marketed to both orthodontists and the public, many of their improved clinical performances are not based on high quality scientific evidence. Currently, there is only one peer-reviewed article (non-English) that compares dental and skeletal changes between the Damon and traditional RME treatment.[7] This study has a small sample size (19 patients total), and the analysis was based on a 2-dimensional image, which often does not provide accurate measurement of craniofacial changes.[7] Given the extent of the claims that is associated with this appliance and their heavy marketing to the public, the need for the unbiased randomized clinical trial on the Damon system is timely.

Furthermore, majority of currently available studies on expansion were done using 2-dimensional imaging techniques such as a Cephalometric radiograph and Posterior-anterior radiograph. A systematic Review on the Damon system revealed that only one study used a CBCT to analyze the changes in transverse dimension between the Damon and other bracket system.[8] With the advance of 3D-imaging techniques and increasing availability in many offices, the need for 3-dimensional analysis of skeletal and dental changes are warranted.

Research Objectives/Questions

The objective of the present study is to compare the 3D skeletal and dental changes associated with the Damon and RME expansion in comprehensive orthodontic treatment.

Primary questions:

1) *Are there any 3D craniofacial landmark position differences between the Damon and Hyrax expansion treatment groups at 6 months?*

Secondary questions:

2) *Are there any 3 D craniofacial landmark position differences over 6 months of treatment regardless of appliance types?*

Hypothesis

Primary questions:

- H_0: *The mean change of X, Y, and Z craniofacial landmark coordinates over 6 months in Damon group is not different from the mean change of X, Y, and Z coordinates over 6 months in Hyrax group.*
- H_a: *The mean change of X, Y, and Z craniofacial landmark coordinates over 6 months in Damon group is different from the mean change of X, Y, and Z coordinates over 6 months in Hyrax group.*

Secondary questions:

- H_0: *Within each treatment group (the Hyrax and Damon System), there is no mean difference in X, Y, and Z craniofacial landmark coordinates of all craniofacial landmarks over 6 months treatment.*
- H_a: *Within each treatment group (the Hyrax and Damon System), there is mean difference in X, Y, and Z craniofacial landmark coordinates of all craniofacial landmarks over 6 months treatment.*

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Chapter 2 Review of Literatures

2.1 Systematic Review: *Dental and Skeletal Changes Associated With the Damon System Philosophical Approach*

1. Introduction

Any tooth movement has dynamic effects on bone and soft tissue structures surrounding it. With increased force levels, an avascular area in the PDL, also known as a hyalinized area, can slow down the tooth movement, and also may increase the risk of root resorption and the amount of pain due to chemicals released from the ischemic area. If continuous excessive orthodontic force is applied to teeth, it can occlude and cut off blood supply to the periodontal ligament (PDL), resulting in necrosis of the compressed area. Therefore, use of light continuous forces are suggested to be critical in achieving desired movements in orthodontics while minimizing the unwanted side effects.[1]

The Damon appliance system (Ormco, Orange, California) is one of the many self-ligating bracket systems that have been increasingly used by orthodontists. This philosophical approach claims to have many benefits over conventional bracket systems, including less force applied on the teeth, reduced amount of pain experienced by patients, and higher treatment efficiency.[2,3] The Damon bracket is advertised as "a nearly friction-free" system.[2] Compared to the conventional bracket and the use of ligating ties, it has been claimed that a passive self-ligating bracket, like the Damon one, allows a wire to slide through the brackets with a lower resistance to sliding resulting in faster levelling and alignment of teeth.[2,3] The proponents of this philosophical approach use of the term "optimal force zone" which implies that the force applied to teeth should generate an optimal pressure to allow uninterrupted vascular supply to the tooth and its surrounding system.[2,3]

In addition to suggested benefits listed above, this philosophy argues that the light force produced by the system allows the connective tissue and alveolar bone to follow tooth movement similar to a Frankel appliance effect. The acrylic shield of a Frankel appliance extends into the vestibule, causing outward pull on connective tissue, and this tension is subsequently transmitted to periosteal fibers of alveolar bone. Similarly, a significant widening of maxillary arch can be achieved with the low and continuous force of the Damon System. However, the exact cellular mechanism describing the net apposition of bone in the direction of the line of applied force could not found. Next, the applied force is so light that the pressure from lips can minimize unwanted tipping of incisors during alignment stage. These two claims suggest that the need for extraction is reduced when using the Damon System as additional arch perimeter through transverse expansion can be safely gained.[2]

The Damon's proposed benefits are heavily marketed to both orthodontists and patients without high quality evidence. Currently, there is no systemic review on the potential benefits of the Damon System over more traditional orthodontic bracket/archwire system management. In 2011, a critical review on the Damon system[4] was published. Acknowledging their limited search strategy, they concluded that other than a possible reduced chair-side time for orthodontists, many of its claims such as lower pain experience, higher efficiency of treatment, and better stability after expansion were not clearly supported by the available literature.

This review will focus on one of many benefits suggested by proponents of the Damon system, which is that a stable clinically meaningful expansion can be done negating the need for rapid palatal expansion appliances. If this claim is true, it may allow orthodontists to attain maxillary expansion without some of the negative associated side effects commonly seen in the rapid expansion appliance such as a tipping movement of posterior teeth.

2. Materials and Methods

2.1. Protocol and Registration

The PROSPERO website was accessed on March 17, 2017, and no systemic review on the Damon system was registered. A proposal for the systematic review was registered on November 2nd, 2018 (registration #: CRD42017059758).

2.2. Eligibility Criteria

The PICO model was used to formulate the research questions:

<u>Population:</u> Patients with any type of malocclusion with maxillary arch crowding,

<u>Intervention:</u> Orthodontic treatment following the Damon system philosophy,

<u>Comparison:</u> Orthodontic treatment using any conventional bracket/archwire system or any type of maxillary expansion appliance,

<u>Outcome:</u> Maxillary dental and skeletal transverse changes.

There was no restriction on publication year, length of follow-up, and treatment duration. The exclusion criteria included editorials, review articles, studies that focus on efficiency and speed of treatment, dental changes in mandibular arch, biomechanical properties of brackets, and pain related to the Damon system.

2.3. Search Strategy

Two independent researchers completed an electronic search in four major databases. Cochrane, PubMed, and EMBASE databases were accessed on October 5th, 2018. Additionally, a partial grey literature was completed by reading the title/abstract of the first 100 hits on Google Beta Scholar database. The keywords used for the electronic search were (Damon and [bracket or brackets or appliance or system or braces]). The detailed search strategy is outlined in the appendix 2.1.

2.4. Study Selection

In each database result, titles were screened first and then abstracts were reviewed in each article. Details of the selection process are listed in Figure 2.1. Randomized controlled trials, prospective and retrospective controlled clinical trials were included in this systematic review.

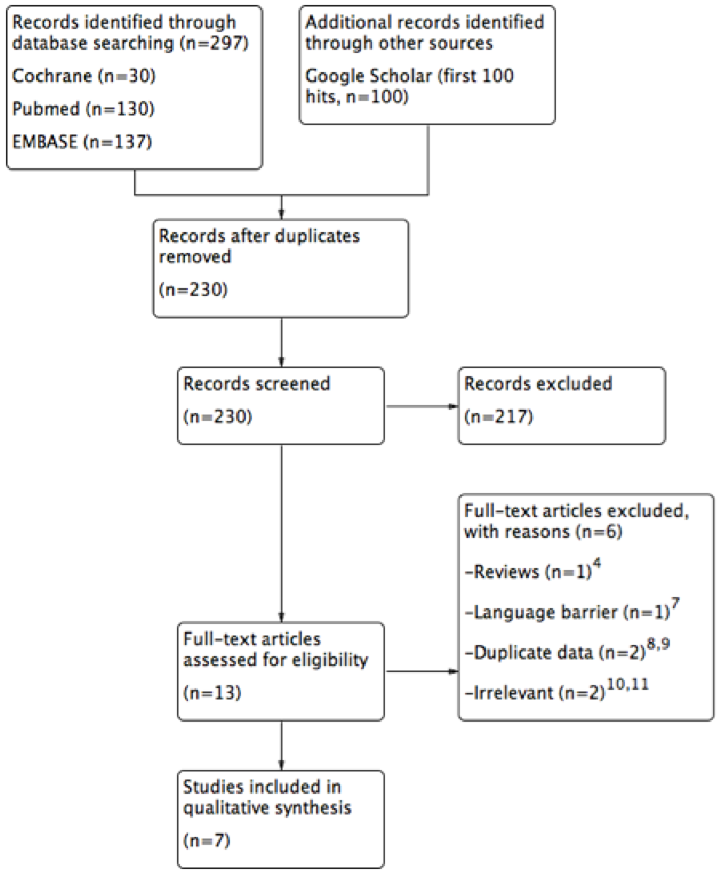

Figure 2.1. PRISMA Flow Chart for Literature Search

2.5. Data Collection Process and Data items

For each article, the following data were extracted: publication year, study design, number of intervention groups, sample description, malocclusion characteristics, records used for analysis, and significant clinical findings. In the case of uncertainty, the author of the article was contacted for clarification.

2.6. Risk of Bias Assessment

The quality assessment of individual studies was done using two different tools. The Cochrane RTCs was used for randomized controlled studies, which is divided into a selection, performance, detection, attrition, reporting, and other bias.[5] The MINORS was used for both prospective and retrospective cohort studies.[6]

2.7. Summary Measures

Only qualitative analysis of dental and skeletal changes was possible. Due to the methodological differences and heterogeneity between the included studies a meta-analysis was not considered.

3. Results

3.1. Literature search

The detailed study selection process is shown in Figure 2.1. Out of 397 total published articles, 167 duplicate articles were removed. From the remaining 230 articles, 217 were later excluded after reading the abstract. During the second selection stage, eligibility assessments were done by reading the full-text of the remaining 13 articles. At this stage 6 articles[4,7-11] were excluded due to reasons stated in the flow chart. Hence the final number of included articles was 7.

3.2. Description of studies

3.2.1. Methods for analysis.

Table 2.1 summarizes characteristics of each study. Out of 7 included studies, only 1 study used 3-dimensional imaging (CBCT) for the analysis. All other studies used 2-dimensional imaging such as a lateral cephalometric radiograph and/or a posteroanterior cephalometric radiograph.

The majority of studies compared the Damon (self-ligating bracket) system to various types of conventional (non-self-ligating bracket) system as a comparison group. Only Atik and Ciger[11] used a quad helix for a few months before a full bonding appointment with conventional brackets as comparison group. Out of 7 included studies, 3 studies[12-14] used Ormco Damon archwires for all patients. The remaining 4 studies[15-18] used Ormco Damon archwires for the Damon treatment group and various different companies' archwires for the comparison group.

3.2.2. Changes in transverse dimension in each treatment group.

All studies showed an increase in maxillary transverse dimension in each treatment group except for one study. (Table 2.2) The majority of studies found an increase in maxillary intercanine, interfirst premolar, intersecond premolar, and intermolar distance after the treatment in all treatment groups. Only Shook et al. group found no statistical difference in intercanine and intermolar distance in any of the treatment groups.[15] In addition, Catteneo et al., using a cone-beam computed tomography (CBCT), found that the transverse expansion was achieved by tipping movement of posterior teeth in either group.[16] Buccal bone remodeling was also measured using a coronal cross-section generated from the CBCT. Both the Damon and In-Ovation bracket system treatment groups showed a decrease in the buccal bone thickness after the treatment.[16] According to GRADE, the overall quality of evidence supporting this outcome is moderate (Table 2.3).

3.2.3. Changes in inclination of anterior teeth.

4 out of 7 included studies compared the axial inclination of anterior teeth before and after the treatment. (Table 2.2) The majority of studies showed a proclination of maxillary incisor teeth after the treatment in all treatment groups.[12-14] Only one study found a greater maxillary incisor proclination in a Damon treatment group.[17] According to GRADE, the overall quality of evidence supporting this outcome is low. (Table 2.3)

3.2.4. Comparison between the treatment groups.

Majority of studies concluded that there is no significant difference in the final transverse dimension between the Damon and the conventional bracket system. (Table 2.4) Yet, there were some minor differences between included studies. Atik and Ciger found a greater increase in maxillary molar inclination in the Damon treatment group.[12] Also, Vajaria et el. found a greater increase in maxillary intermolar width after treatment in the Damon group.[17] However, all other measurements (maxillary intercanine, interfirst premolar, and intersecond premolar widths) showed no significant difference between groups.[17]

3.3. Risk of bias of included studies

3.3.1. Cochrane bias tool was used to analyze three randomized controlled trials (RCT) included in this study. (Figure 2.2) One study was assessed as a low risk of bias. Two other RCT studies were assessed as an unclear risk of bias since the detailed process of allocation was not clearly stated in the methods section.

3.3.2. MINORS was used to analyze prospective clinical trials and retrospective cohort studies included in this review. (Table 2.5) Two studies were assessed as a medium risk of bias. Two remaining studies were assessed as a high risk of bias mainly due to inadequate reporting of characteristics of treatment groups.

4. Discussion

The Damon system, one of the perceived leading self-ligating bracket systems, has been widely used by many orthodontists. Some clinicians may see less of a need for extraction with the Damon system because of its claim that a light force and a low friction mechanic allow a clinically stable arch expansion.[6]

Our systematic review revealed 7 articles suitable for the inclusion of the results in this paper. Based on the Cochrane RoB and MINORS tools, only 1 study had a low risk of bias, 2 studies presented a medium risk of bias, and the remaining 4 studies had either a high risk of bias or an unclear risk of bias. The most common sources of bias resulted from the inadequate description of the treatment group and/or from the inadequate randomization/blinding of the procedures.[12,16] Due to the nature of this clinical intervention, a perfect double blinded randomized clinical trial may be difficult to achieve. The bracket design and archwires can be easily identified amongst clinicians, and therefore, multiple blinding is unfeasible. It was decided to also include high quality prospective cohort studies in this review. This was with the idea of increasing the number of studies to synthesize and have conclusions based on more treated patients. The drawback is the risk of bias increases automatically under this approach. Because of that, findings from the included articles should be analyzed with caution.

The majority of studies showed that there was a significant increase in transverse dimension in each group after the completion of treatment. (Table 2.2) However, one study did not find a significant increase in maxillary intercanine and intermolar dimension in both treatment groups.[15] In contrast to other studies where most cases were finished with a rectangular stainless steel (SS) or TMA archwire, their Damon treatment cases were finished with copper Niti archwires.[15] Also, even in a conventional treatment group, their final few archwires were customized to the patient's existing arch shape.[15] In addition, all studies showed an increase in maxillary incisor proclination after the treatment. (Table 2.2) This finding is inconsistent with the "lip bumper" claim by the Damon group where a low pressure from the Damon archwire system and the resting lip pressure mitigate the tendency for incisor proclination.[19] Since all treatment groups had some level of initial crowding to start, the crowding was partially resolved by a proclination of incisors. However, one must note that none of the included studies reported or analyzed a torque prescription of each bracket system. When a full-size archwire is engaged in a bracket, a specific torque prescription can influence the final axial inclination of teeth regardless of treatment mechanics.

Next, the comparison between the Damon and the non-Damon system groups showed a similar finding. Majority of studies showed no significant difference in the final transverse dimension between the two treatment groups in their intercanine, interpremolar, and intermolar distances. (Table 2.4) Half of the included studies used the Damon arch form archwires for all patients while the rest of studies used archwires from different companies. Irrespective of different arch form shapes by various companies, all studies showed similar result. Yet, one study found that the intermolar distance was wider in the Damon group.[17] This could be attributed to the fact that their Damon group was finished with 0.019x0.025 SS or TMA standard Damon archwires while their conventional bracket group was finished with 0.016x0.022 SS archwires customized to the patient's original arch shape.[17]

The main claim of the Damon philosophy is that the light force on dentition will induce remodeling of the bone in the direction of tooth movement.[19] Despite its popular claim, there is only one study that investigated the thickness of bone after the treatment, and it failed to show any bone growth after the treatment based on the CBCT analysis.[16] Although CBCT is currently the gold standard for assessing the alveolar bone around the dentition, it has a few limitations. First, the size of voxel (resolution) and the partial volume average effect of CBCT can influence the accuracy in the measurement of alveolar bone thickness.[20,21] Furthermore, an immediate and post-retention study of an expansion appliance showed that the thickness of alveolar bone was reduced right after the treatment completion, but the thickness was increased after 6 months of retention period.[22] Thus, there is a need for a long-term post retention study to investigate the possible late bone remodeling process.[22]

Limitations

A few limitations existed in this review. The majority of included studies had a low to medium risk of bias. Although most studies had consistent findings across the studies, a definite clinical recommendation cannot be made due to a low number of high quality studies. Moreover, some studies did not report the level of maxillary arch crowding and/or constriction in the beginning of treatment. These two factors can influence the final stability/amount of expansion at the end of the treatment. Lastly, although interventions were done mainly in adolescent patients, the age range across all the studies combined was from 11 to 31 years old. Misawa-Kageyama et al. found that the alveolar bone remodeling activity is higher in younger age group.[23] Since the biological response from the orthodontic treatment can vary with age, further studies are required with more attention paid to the heterogeneity of treatment groups.

5. Conclusion

- There is not enough evidence to support the claim that the Damon system allows additional arch expansion with better tipping control than with traditional techniques.
- Regardless of different intervention methods in comparison groups, available limited evidence does not show clinical meaningful differences in the Damon dental transverse dimension when compared to other treatment approaches.

6. Acknowledgements

The author declares no conflicts of interest. No funding was received.

7. Figure Legend

Figure 1: PRISMA Flow Chart for Literature Search

Figure 2: Cochrane Bias Tool Summary Chart. The plus sign indicates a low risk of bias. The question mark indicates unclear risk of bias. The minus sign indicates a high risk of bias.

Table 2.1. Characteristics of included studies

Study group and year	Study design	Treatment group (A, B, vs C)	Sample (size and a mean age)	Records used for analysis	Malocclusion (MO) TYPE	Landmark used for analysis (unit in mm unless specified)	Treatment sequence (Archwire progression protocol)
Atik and Ciger 2014[12]	RCT	A: Quad helix and conventional B: Damon 3MX bracket	A: 17 patients (14.5±1.2 yrs) B: 16 patients (14.8±1.0 yrs)	Cephalometric, Posteroanterior radiographs, and dental casts	Moderate max/mand crowding, Class I MO with maxillary constriction	U1-SN°, U1-FH°, U1-NA°, U1-NA, IMPA°, FMIA°, L1-NB°, L1-NB, OJ, OB, UR6-OH°, UR6-OH, UL6-OH°, UL6-OH, JR-JL, UR6-UL6, intercanine width, inter-first premolar width, inter-second premolar width, intermolar width	Group A: Quad helix used until lingual cusps of max first molars contacts with buccal cusps of mand first molars. Then, a sequence of Ormco 0.014 Cu-NiTi, 0.018 Cu-NiTi, 0.014x0.025 Cu-NiTi, 0.017x0.025 Cu-NiTi, 0.017x0.025 SS, and 0.019x0.025 SS archwires were used. Group B: A sequence of Damon arch form 0.014 Cu-NiTi, 0.018 Cu-NiTi, 0.014x0.025 Cu-NiTi, 0.017x0.025 Cu-NiTi, 0.017x0.025 SS, and 0.019x0.025 SS archwires were used.
Atik et al. 2016[13]	Prospe-ctive Clinical Trial	A: Self-ligating (Nexus) B: Conventional C: Passive self-ligating bracket	A: 15 patients (14.4±1.5 yrs) B: 15 patients (14.4±1.6 yrs) C: 16 patients (14.8±1.0 yrs)	Cephalometric, Posteroanterior radiographs, and dental casts	Moderate max/mand crowding, Class I MO, non-extraction treatment	3-3, 4-4, 5-5, 6-6, UR6-ML, UR6-ML°, UL6-ML, UL6-ML°, UR6-UL6, U1-NA°, U1-NA, U1-SN°, U1-FH°, IMPA°, FMIA°, L1-NB°, L1-NB, OJ, OB	All groups were treated with a sequence of Damon arch form 0.014 Cu-NiTi, 0.018 Cu-NiTi, 0.014x0.025 Cu-NiTi, 0.017x0.025 Cu-NiTi, 0.017x0.025 SS, and 0.019x0.025 SS archwires.
Cattaneo et al. 2011[16]	RCT	A: Damon B: In-Ovation (active self-ligating brackets)	A: 21 patients (16.0±5.7 yrs) B: 20 patients (15.0±3.3 yrs)	Dental casts and CBCT	Class I, II, and mild Class III MO, non-extraction treatment	Width 13-23, Width 14-24, Width 15-25, Width 16-26, λ 1st prem°, λ 2nd prem°, Bone area R (mm^2), Bone area L (mm^2)	Group A: Archwire selection based on the Damon Work-book protocol Group B: Treatment protocol based on GAC recommendation
Fleming et al. 2013[14]	RCT	A: Damon Q B: In-Ovation C C: Ovation (conventional)	A: 32 patients (18.9±2.9 yrs) B: 32 patients (22.5±8.5 yrs) C: 32 patients (18.6±3.4 yrs)	Cephalometric radiographs and dental casts	Any type of MO with maxillary crowding <6mm, non-extraction treatment	Intercanine width, inter-first premolar width, inter-second premolar widths, intermolar width, maxillary incisor inclination°, maxillary molar inclination°	All groups were treated with a sequence of Damon arch form 0.013 Cu-NiTi, 0.014 Cu-NiTi, 0.014x0.025 Cu-NiTi, 0.018x0.025 Cu-NiTi, and 0.019x0.025 SS archwires.
Shook et al. 2014[15]	Retrospe-ctive study	A:Conventional B: Damon	A: 45 patients (15.0±3.5 yrs) B: 39 patients (15.3±4.1 yrs)	Digital models	Any type of MO, non-extraction treatment	Intercanine width, and intermolar width, IC:SW (%), IL:SW (%), BCC:TSA (%), BCL:TSA (%)	Group A: A sequence of 0.014 Cu-NiTi, 0.018 Cu-NiTi, 0.018x0.025 SS OrthoForm III Ovoid arch forms (3M Unitek) were customized to arch shape Group B: A sequence of Damon arch form 0.014 Cu-NiTi to 0.018x0.025 Cu-NiTi archwires were used
Tecco et al. 2009[18]	Prospe-ctive Clinical Trial	A:Conventional B: Self-ligating (Damon-3MX, Ormo)	A: 20 patients B: 20 patients Mean age 15.8 yrs (range 14 to 30 yrs)	Dental casts	Any type of MO with low mand plane angle, normal OB, mild crowding	Intercanine, Interfirst premolar, Intersecond premolar, Intermolar width	Group A: A sequence of 3M Unitek 0.016 Cu-NiTi followed by 0.019x0.025 Cu-NiTi (OrthoForm II), non-specified rectangular archwires were used Group B: A sequence of Ormco 0.014 Cu-NiTi, 0.016 Cu-NiTi, 0.016x0.025 Cu-NiTi, and non-specified rectangular archwires were used
Vajaria et al.	Retrospe-	A: Damon	A: 27 patients	Cephalometric	Class I MO with	U1-SN, U1-Apog, L1-MP, L1-	Group A: A sequence of Damon arch form 0.012 to

2011[17]	ctive study	B: Conventional	B: 16 patients A mean age not listed	radiographs and dental casts	maxillary constriction	Apog, Mand IC, Max IC, Mand 1PM, Max 1PM, Mand 2PM, Max 2PM, Max IM, Mand IM, L3 depth, L6 depth, U3 depth, U6 depth	0.014 Cu-NiTi, 0.016 Cu-NiTi, 0.014x0.025 Cu-NiTi, 0.018x0.025 Cu-NiTi, and 0.019x0.025 SS or TMA archwires were used. Group B: A sequence of Ormo 0.013 Cu-Niti, 0.014 Cu-Niti, Highland Metals 0.016 Cu-Niti, Oscar 0.016 SS, Rocky Mountain 0.016x0.022 SS archwires were customized to arch shape

Table 2.2. Qualitative and quantitative summary of the individual study results *(Skeletal and dental changes within the group)*

Study group and year	Treatment group (A, B, vs C)	Records time point	Main Statistically Significant Findings (Changes within the group from T_0-T_1)
Atik and Ciger 2014[12]	A: Quad helix and Conventional bracket B: Damon 3MX bracket	T_0: before tx T_1: after tx (13.2-15.3 months)	Group A Decrease in OJ (-1.05±1.37mm), Increase in intercanine (2.02±1.67mm), interfirst premolar (5.72±1.70mm), intersecond premolar (5.04±2.15mm), intermolar (3.83±1.57mm) widths Increase in max incisor proclination (U1-SN°: 1.95±4.64°) Group B Decrease in OJ (-1.16±1.77mm), Increase in intercanine (2.53±2.16mm), interfirst premolar (5.06±2.41mm), intersecond premolar (4.90±2.55mm), intermolar (3.43±1.80mm) widths Increase in max incisor proclination (U1-SN°: 3.68±3.64°)
Atik et al. 2016[13]	A: Self-ligating (Nexus) B: Conventional C: Passive self-ligating bracket (Damon)	T_0: before tx T_1: after tx (13.2-14.6 months)	Group A Increase in intercanine (2.03±1.33mm), interfirst premolar (4.03±1.53mm), intersecond premolar (3.52±1.21mm), intermolar (2.34±1.14mm) widths Increase in max incisor proclination (U1-SN°: 4.00±4.42°) Group B Increase in intercanine (2.02±0.95mm), interfirst premolar (4.05±1.75mm), intersecond premolar (3.23±0.94mm), intermolar (2.61±2.13mm) widths Increase in max incisor proclination (U1-SN°: 3.06±2.44°) Group C Increase in intercanine (2.53±2.16mm), interfirst premolar (5.07±2.41mm), intersecond premolar (4.9±2.55mm), intermolar (3.43±1.80mm) widths Increase in max incisor proclination (U1-SN°: 3.68±3.64°)
Cattaneo et al., 2011[16]	A: Damon B: In-Ovation (active self-ligating brackets)	T_0: before tx T_1: after tx (21.1-22.4 months)	Group A Increase in intercanine (1.4±1.7mm), interfirst premolar (4.3±1.6mm), intersecond premolar (4.0±1.9mm), intermolar (1.9±1.2mm) widths Increase in buccal inclination of first premolar (11.7±9.7°) Increase in buccal inclination of second premolar (13.5±8.1°) Group B Increase in intercanine (0.7±1.7mm), interfirst premolar (4.5±1.6mm), intersecond premolar (3.3±1.8mm), intermolar (1.3±1.3mm) widths Increase in buccal inclination of first premolar (11.8±12.4°) Increase in buccal inclination of second premolar (13.0±9.1°)
Fleming et al. 2013[14]	A: Damon Q B: In-Ovation C C: Ovation (conventional)	T_0: before tx T_1: after tx (Minimum of 8.5 months)	Group A Increase in intercanine (1.97±2.16mm), interfirst premolar (4.51±2.68mm), intersecond premolar (3.96±2.51mm), intermolar (1.22±2.26mm) widths Increase in max incisor proclination (1.12±3.88°) Group B Increase in intercanine (1.78±2.21mm), interfirst premolar (3.75±2.31mm), intersecond premolar (3.78±1.91mm), intermolar (1.82±1.59mm) widths Increase in max incisor proclination (3.25±6.89°) Group C Increase in intercanine (0.88±2.18mm), interfirst premolar (3.7±3.19mm), intersecond premolar (3.59±2.80mm), intermolar (1.41±2.08mm) widths Increase in max incisor proclination (2.84±5.68°)
Shook et al. 2014[15]	A:Conventional B: Damon	T_0: before tx T_1: after tx (Mean of 25.6 months)	Group A No significant difference in intercanine (0.10mm) and intermolar (0.53mm) width Group B No significant difference in intercanine (-0.29mm) and intermolar (0.86mm) width
Tecco et al. 2009[18]	A:Conventional B: Self-ligating (Damon-3MX, Ormo)	T_0: before tx T_1: 12 months into tx	Group A Increase in intercanine (2.6±2.4mm), interfirst premolar (4.3±2.1mm), intersecond premolar (4.1 ±2.1mm), intermolar (2.4±2.0mm) widths Group B Increase in intercanine (3.3±2.6mm), interfirst premolar (4.4±2.5mm), intersecond premolar (4.2 ±1.8mm), intermolar (2.3±1.5mm) widths
Vajaria et al. 2011[17]	A: Damon B: Conventional	T_0: before tx T_1: after tx (not specified)	Group A Increase in intercanine (1.74±3.44mm), interfirst premolar (2.87±3.03mm), intersecond premolar (2.77±3.19mm), intermolar (2.79±1.60mm) widths Increase in max incisor proclination (U1-SN°: 3.13±8.05°) Group B Increase in intercanine (1.72±2.72mm), interfirst premolar (3.44±1.80mm), intersecond premolar (2.87±2.41mm), intermolar (0.60±2.42mm) widths Increase in max incisor proclination (U1-SN°: 3.50±5.22°)

Table 2.3. GRADE's summary of findings for randomized controlled trials. Dental Changes Associated with the Damon System Compared to a Conventional Bracket System or an Expansion Appliance. A qualitative descriptive analysis of the results was performed; meta-analysis was not performed due to differences in methodology.

Population: Patients with any type of malocclusion with maxillary arch crowding,
Intervention: Orthodontic treatment following the Damon system philosophy,
Comparison: Orthodontic treatment using any conventional bracket/archwire system or any type of maxillary expansion appliance,
Outcome: Maxillary dental and skeletal changes.

Outcomes	Number of studies/ study design	Number of participants	Certainty of the evidence (GRADE)
Maxillary Intercanine Distance assessed with: Dental casts, PA ceph, CBCT follow up: mean 14.3 months	3 RCTs	67 in Damon group 101 in comparison group	⊕⊕⊕◯ MODERATE [a]
Maxillary Intermolar Distance assessed with: Dental casts, PA ceph, CBCT follow up: mean 14.3 months	3 RCTs	67 in Damon group 101 in comparison group	⊕⊕⊕◯ MODERATE [a]
Maxillary Incisor Proclination assessed with: Cephalometric Radiograph follow up: mean 10.9 months	2 RCTs	48 in Damon group 81 in comparison group	⊕⊕◯◯ LOW [a,b]

GRADE Working Group grades of evidence
High certainty: We are very confident that the true effect lies close to that of the estimate of the effect
Moderate certainty: We are moderately confident in the effect estimate: The true effect is likely to be close to the estimate of the effect, but there is a possibility that it is substantially different
Low certainty: Our confidence in the effect estimate is limited: The true effect may be substantially different from the estimate of the effect
Very low certainty: We have very little confidence in the effect estimate: The true effect is likely to be substantially different from the estimate of effect

Explanations
a. Need bigger sample size. Total number of participants is less than 400
b. One out of two studies have unclear risk of bias

Table 2.4. Summary of conclusions of the individual study results *(Skeletal and dental changes between the group)*

Study group and year	Treatment group (A, B, vs C)	Records time point	Statistically Significant Findings (Changes between the group from T_0-T_1)
Atik and Ciger 2014[12]	A: Quad helix and Conventional bracket B: Damon 3MX bracket	T_0: before tx T_1: after tx (13.2-15.3 months)	No difference between groups in transverse dimension Greater increase in max molar inclination in group B
Atik et al. 2016[13]	A: Self-ligating B: Conventional C: Passive self-ligating bracket	T_0: before tx T_1: after tx (13.2-14.6 months)	No difference between groups in transverse dimension
Cattaneo et al., 2011[16]	A: Damon B: In-Ovation (active self-ligating brackets)	T_0: before tx T_1: after tx (21.1-22.4 months)	No significant difference in inter-premolar bucco-lingual inclination between two groups Bone area decrease 20% in Damon, 14% in In-Ovation group
Fleming et al. 2013[14]	A: Damon Q B: In-Ovation C C: Ovation (conventional)	T_0: before tx T_1: after tx (Minimum of 8.5 months)	No significant difference in transverse dimension, incisal and molar inclination between three groups
Shook et al. 2014[15]	A:Conventional B: Damon	T_0: before tx T_1: after tx (Mean of 25.6 months)	No difference between groups in transverse dimension
Tecco et al. 2009[18]	A:Conventional B: Self-ligating (Damon-3MX, Ormo)	T_0: before tx T_1: 12 months into tx	No difference between groups in transverse dimension
Vajaria et al. 2011[17]	A: Damon B: Conventional	T_0: before tx T_1: after tx (not specified)	No difference between groups in transverse dimension Greater increase in maxillary intermolar width in group A

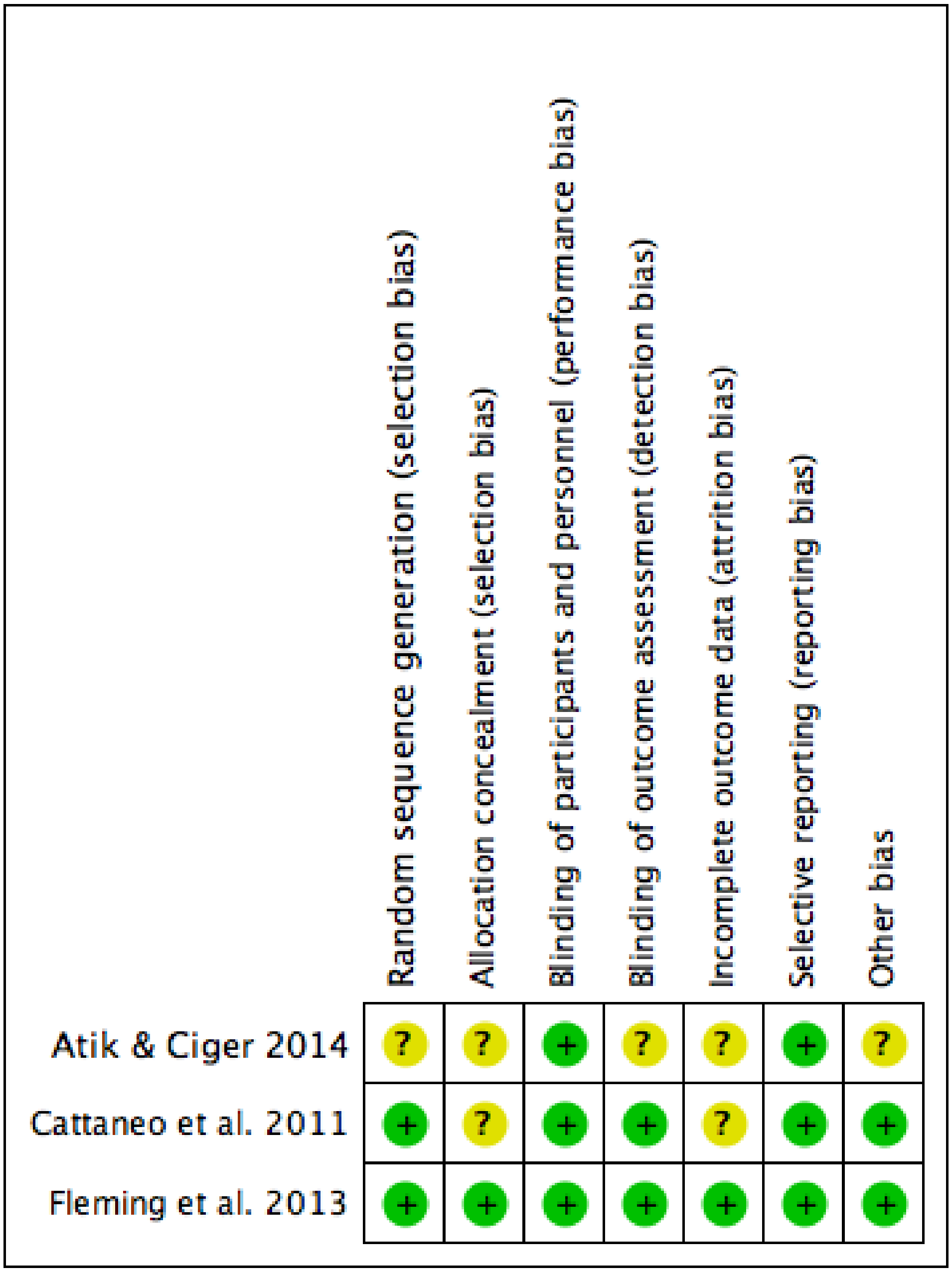

Figure 2.2. Cochrane Bias Tool Summary Chart: The plus sign indicates a low risk of bias. The question mark indicates unclear risk of bias. The minus sign indicates a high risk of bias.

Table 2.5. Methodological Index for Non-Randomized Studies (MINORS)

	A clearly stated aim	Inclusion of consecutive patients	Prospective collection of data	Endpoints appropriate to the aim of the study	Unbiased assessment of the study endpoint	Follow-up period appropriate of the aim of the study	Loss to follow-up less than 5%	Prospective calculation of the study size	An adequate control group	Contemporary groups	Baseline equivalence of groups	Adequate statistical analyses	Total Score
Atik et al. 2016	2	2	2	2	0	2	2	0	2	2	2	2	20
Shook et al. 2014	2	2	2	2	0	2	2	2	2	0	2	2	20
Tecco et al. 2009	2	2	2	2	0	1	2	0	2	2	1	2	18
Vajaria et al. 2011	2	2	2	2	0	2	2	0	2	0	1	2	17

Score 0 (not reported), 1 (reported but inadequate), or 2 (reported and adequate). The ideal total score is 16 for non-comparative studies and 24 for comparative studies. Total score of 24 indicates a low risk of bias. A score between 20-24 indicates a medium risk of bias. A score below 20 indicates a high risk of bias.

8. References

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Appendices 2.1

Search strategy for Cochrane Review database

1. Under “Title, Abstract, Keywords" tab
2. Damon as a search term

Search strategy for Pubmed database

1. damon[Title/Abstract] AND
2. (bracket[Title/Abstract] OR brackets[Title/Abstract] OR appliance[Title/Abstract] OR system[Title/Abstract] OR braces[Title/Abstract])

Search strategy for EMBASE database

1. Damon.mp. [mp=title, abstract, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword, floating subheading]
2. (bracket or brackets or appliance or system or braces).mp. [mp=title, abstract, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword, floating subheading]
3. 1 and 2

2.2 A Literature Review: ***Accuracy and Reliability of 3-Dimensional Maxillofacial Landmarks in CBCT***

Despite wide spread use of Cone-Beam Computed Tomography (CBCT) in orthodontic offices, currently there is no standardized ways to analyze these 3-dimensional images, and interpretation limitations still exists. [1] After reviewing the evidences on the Damon expansion philosophy, the next step was to search for 3-dimensional craniofacial landmarks that can be used to answer the research questions. This step was done to identify 3D landmarks with high accuracy (a degree to which the radiographic landmark agrees to the true anatomical structure) and reliability (the extent to which the radiographic land marking procedure yields the same results on repeated trials) so that dental and skeletal changes in CBCT images can be measured with better confidence.

Accuracy and reliability of 3D landmarks have been extensively researched in the past. Therefore, an electronic search in PubMed and Cochrane was completed on December 10th, 2018 to find any literature reviews or systematic reviews on accuracy and reliability of 3-dimensional maxillofacial landmarks in CBCT. The detailed keyword search strategy is outlined in the appendix section. The inclusion criteria included any review article that described either reliability or accuracy of craniofacial land marking procedure on the cone beam computerized tomography.

In each database result, titles were screened first, and then, abstracts were reviewed in each article. The exclusion criteria included studies focused on effect of head position on landmark, efficiency of automatic land marking software, superimposition technique, 2D reconstruction of image and land marking generated from 3D volumetric imaging. Out of 24 total published articles, 19 articles were excluded based on the exclusion criteria described above, and total of 5 systematic reviews were published. 4 out of 5 systematic reviews were published within the last 5 years (the latest article was published on November, 2018). [2-6]

In terms of accuracy of measurement, one systematic review revealed that the measurement error was less than 1mm between 3D cephalometry landmarks and direct measurement on skulls. [6] There was no overall pattern across all 3D landmarks but each landmark had characteristic pattern of measurement inaccuracy. With repeated practice of landmark identification, the measurement error was reduced. [3] In fact, there are many factors that could influence the accuracy of each landmark such as image quality, geometric location of 3D landmarks, anatomical complexity, and imaging contrasts between two objects. [3]

Furthermore, there are many factors that influence reliability of landmarks such as superimposition of hard and soft tissue, training level of experience, density and sharpness of the images, and nature of cephalometric landmark (shape, size, and anatomical variability). Studies have shown that in general, reliability of 3D landmark identification is better than traditional 2D Cephalometric measurements. [5] Also, reliability of intra-examiner was shown to be higher than the reliability of inter-examiner. [4] Craniofacial landmarks on mid-sagittal plane demonstrated highest reliability followed by bilateral structures. [2,4] Dental landmarks such as maxillary incisors and right and left maxillary molars had high level of reliability. [2,4]

In general, skeletal landmarks presented similar reliabilities compared to dental landmarks but there were great variations depending on each landmark's specific location. [4] Skeletal landmarks on the condyle, orbitale, and porion showed the lowest reliability because these landmarks are located on a prominence or curvature, and thus, identification is difficult. [2,4] The nasion, point A, anterior nasal spine, pogonion, gnathion, and menton showed better reliability than other skeletal structures. [2,4] However, the researchers emphasized the need for more studies on the soft tissue landmarks. [2]

The biggest limitation across all systematic reviews was that various 3D imaging techniques were used as a comparison although each imaging modality has its own limitations and benefits. The different types of 3D imaging techniques ranged from a CBCT, spiral CT, conventional CT, and multi-slice CT. As an example, one research group showed that a CBCT has higher spatial resolution and lower radiation dose compared to a medical multi-slice spiral CT when looking at dental arch region. [7] With increasing use and availability of CBCT in dental offices, a further study to compare accuracy and reliability of the maxillofacial landmarks specifically in CBCT images is needed.

In summary, despite limited evidences on 3D Cephalometric landmarks due to the few number of papers with a low risk of bias, some landmarks showed characteristic pattern across many studies. Many research groups found that dental landmarks can be measured in 3-dimensional images with good precision. Dental landmarks such as maxillary central incisors, maxillary first molars, mandibular central incisors, and mandibular first molars had favorable reliability. [4] Therefore, some of these dental landmarks were chosen for the analysis in the following study. In terms of skeletal landmarks, craniofacial landmarks on mid-sagittal plane demonstrated highest reliability followed by bilateral structures. [2,4] The ease of mid-sagittal plane land marking is most likely due to many clinicians' familiarity with radiographic interpretation of lateral head films. Any skeletal landmarks located on curved surfaces were found to be difficult to identify such as pogonion, orbitale, and condyle. [2] Thus, these landmarks were not included in the following study. Landmarks within the cranial base are relatively unaffected by growth and would allow superimposition of image sets taken over time. [1] Therefore, skeletal landmarks such as foramen magnum, right and left foramen ovale and spinosum were identified on 3D images, and they were used for superimposition in Chapter 3.

After identification of possible 3D landmarks that can be used for the study, the next step was to find a method to identify the landmarks with high repeatability. Skeletal and dental changes associated with the RME device was researched many times in the past. The study by Luebbert et al. (2016) became a particular interest since this study clearly described methods to identify 3D landmarks on CBCT multi-planar images using the Avizo software. [8] With this method, Intraclass Correlation (ICC) for the intra-examiner reliability was greater than 0.99 with a 95% confidence interval for all landmarks.[8] Therefore, their landmark identification methodology was closely followed and practiced many times before commencing the Chapter 3 data collection.

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Appendices

PubMed: Search **(((craniometry[Title/Abstract] OR cephalometry[Title/Abstract] OR landmark*[Title/Abstract])) AND (reliability[Title/Abstract] OR precision[Title/Abstract] OR accuracy[Title/Abstract] OR repeatability[Title/Abstract] OR reproducibility[Title/Abstract] OR validity[Title/Abstract])) AND (cone beam computed tomography[Title/Abstract] OR cone beam computerized tomography[Title/Abstract] OR CBCT[Title/Abstract] OR digital volume tomography[Title/Abstract]) AND (systematic[Title/Abstract] OR review [Title/Abstract]))**

Chapter 3:

Comparison of Skeletal and Dental Changes Obtained from a Tooth-Borne Maxillary Expansion Appliance Compared to the Damon System Assessed Through a Digital Volumetric Imaging

Introduction

A deficiency in maxillary transverse width has considerable implications in orthodontic treatment. Having an inadequate transverse relationship between a maxilla and a mandible can lead to an increased cervical wear (abfraction), dental arch crowding, and possible negative effects on patients' smile esthetics and airways. [1,2] Rapid Maxillary Expansion (RME) is one method to treat narrow maxillary arches by separation of the midpalatal suture. Hyrax is one of the most commonly used RME appliances, which has a screw device positioned across a palatal vault, and the device is activated by turning the screw until the desired maxillary expansion is achieved. [3] Studies have shown side effects associated with the appliance such as active root resorption on the buccal side of the first premolars used for anchorage. [4,5] The device also has been reported to expand the upper arch mainly by tipping and extruding the maxillary posterior teeth. [6,7] This type of tooth movement is often contraindicated and prone to relapse.[8]

The Damon appliance (Ormco, Orange, California) is one of the self-ligating bracket systems that claims to have benefits over traditional bracket systems. The system claims to apply just enough force to generate "optimal force zone" so that dental arch expansion can be achieved without the use of a mechnical expander. [9] The Damon philosophy argues that the light force produced by the system allows the connective tissue and alveolar bone to follow tooth movement that results more predictable expansion of maxillary arch in non-extraction cases.[10] As a result, common side effects seen in the RME such as dental tipping, extrusion, and root resorption may be minimized in the Damon System.[11] In addition to benefits listed above, the company also advertises the "lip bumper" effect on the incisors (minimizing anterior tipping), faster treatment, greater comfort, and better facial esthetics result.[9,10]

Despite numerous claims of clinical advantages made by the Damon bracket manufacture, the evidence behind their philosophy is weak.[10] There is currently only one peer-reviewed article (non-english) that compares skeletal and dental changes between the Damon and traditional RME treatment. Yu et al. (2008) concluded that both treatment methods could increase the arch width along with buccal tipping of posterior teeth.[12] However, their study had a small sample size (19 patients total), and the analysis was based on a 2-dimensional image, which often does not provide accurate measurement of craniofacial changes. With the advance of 3-dimensional imaging techniques and increasing availability in many offices, the need for 3-dimensional analysis of skeletal and dental changes between two treatment methods are needed.

The primary objective of this study was to compare dental and skeletal changes obtained from the Damon and RME expansion over 6 months using 3-dimensional imaging. The secondary objective was to evaluate dental and skeletal changes over 6 months of treatment time regardless of the appliance type.

Methods

This randomized clinical trial was done at the Orthodontic Clinic in the University of Alberta (Alberta, Canada) with the ethics approval from the University of Alberta Research Ethics Board (Pro00013379). In order to compare 2 different appliances, a minimum sample size of 44 patients per group was calculated to be needed when the effect size index was 0.70, α=0.05 and power=0.90. [13] 45 patients in each group was initially planned to account for any dropouts during the treatment.

Inclusion criteria were adolescents from 11-16 years of age with diagnosis of maxillary transverse deficiency with unilateral or bilateral crossbite requiring maxillary expansion. Patients were in permanent dentition except for the eruption of permanent second molars. All patients had a minimum of 5 mm maxillary constriction determined by calculating the differences between inter-molar widths of maxilla and mandible (palatal cusp tips of upper molars to the central fossae of lower molars). Exclusion criteria included patients with syndromic characteristics, systemic diseases, or history of previous maxillary expansion/orthodontic treatment. Each patient had an orthodontic clinical examination and a Cone Beam Computed Tomography (CBCT) digital volumetric image (iCAT, Imaging Science International, Hatfield, PA, USA) prior to treatment (a large field of view 16 x 13.3 cm, voxel size 0.30 mm, 120 kVp, 18.54 mAS, and 8.9 seconds). A person external to the research group generated random number blocks for all patients using an excel worksheet to randomly allocate patients to each group once they accepted participation in the study.

Patients in Group A received orthodontic treatment using the Damon system (0.022 inch dimension, self-ligating brackets). CBCT images were taken two times (baseline and six months into treatment) which was when leveling and alignment phase were completed. Initial alignment was done sequentially with Insignia prefabricated 0.014 NiTi, 0.016 NiTi, and 0.014x0.025 NiTi archwires in Damon Arch Form. In addition, as per recommendation by the company's treatment consultant, patients wore crossbite elastics full-time until 6 months into treatment (buttons were bonded on palatal cusp surface of upper first molar and first premolar, elastics used were 3/16 inch, 2 ounce force). Bite ramps were also placed on palatal cusps of upper first molars.

Group B treatment consisted of maxillary expansion using the Hyrax appliance attached to the first premolars and first permanent molars. This treatment lasted approximately 16 days with a daily activation of the appliance with one turn of the screw/twice a day (0.25 mm per turn, 0.5 mm daily) until 6-10 mm of expansion (depending on the patient's need) was achieved. On the same day of the Hyrax insertion, non self-ligating brackets (Insignia, Mini Diamond Ormo) were bonded from maxillary right canine to left canine and mandibular right first molar to left first molar. The bonding was done following the Insignia (Ormco, Orange, California) protocol of indirect bonding set-up and placement. After completion of the active expansion treatment, the screw was tied with a ligature, and the Hyrax stayed passive for a 5 months retention period prior to removal. A CBCT image was taken two times (baseline and after removal of appliance (approximately 6 months into treatment)).

Initially, 90 patients had pre-treatment records. 4 patients in each group decided to not start treatment due to financial concerns. However, once the treatment has been started, there was no drop out. Total of 41 patients in the Damon group and 41 patients in the Hyrax group started and completed treatment. Table 3.1 shows the demographic characteristics of patients who completed the study. The mean age for the Damon group was 13.5 years and for Hyrax group was 13.3 years. The Damon group contained 13 male and 28 female patients, whereas the Hyrax group had 19 males and 22 female patients (Table 3.1). All diagnostic records were coded. The principal investigator was blinded with respect to treatment group and timing of each record when analyzing the diagnostic records.

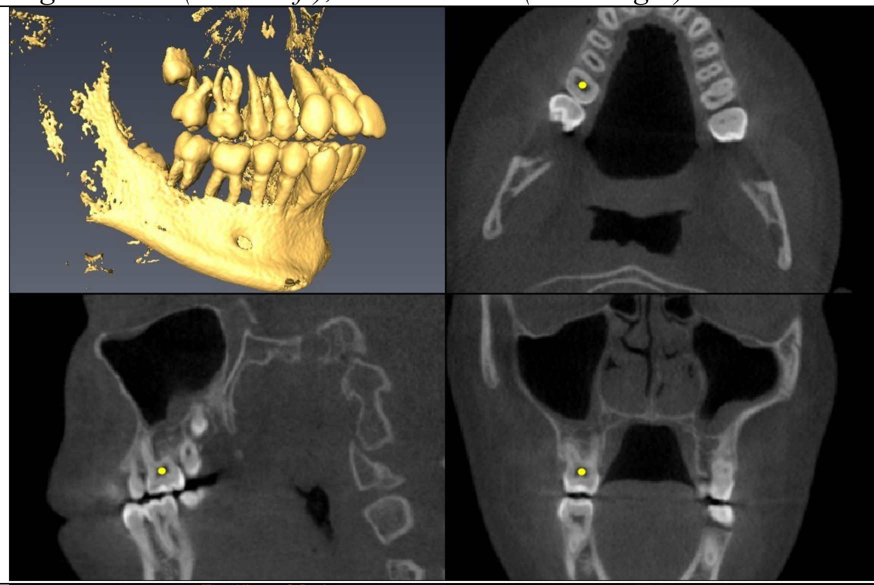
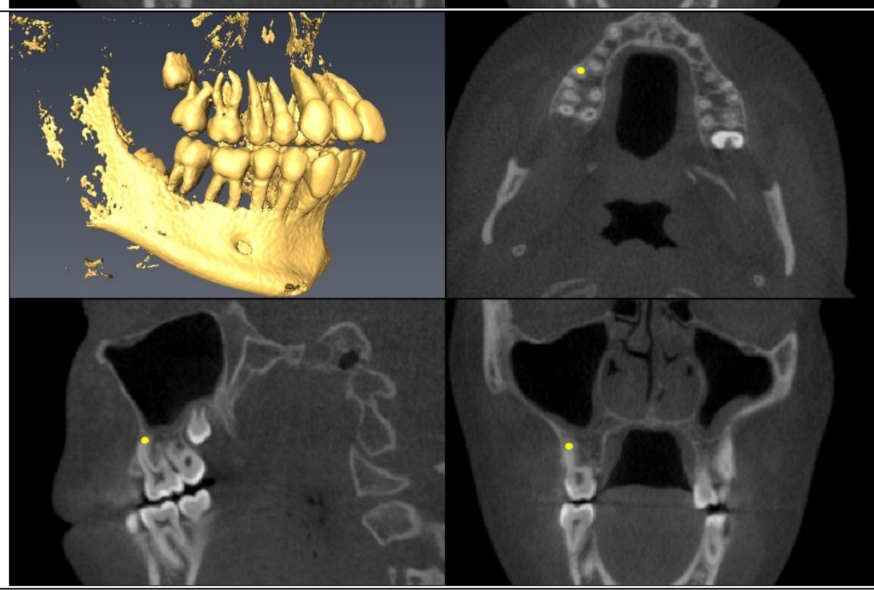
Table 3.1. Demographic characteristics of the sample

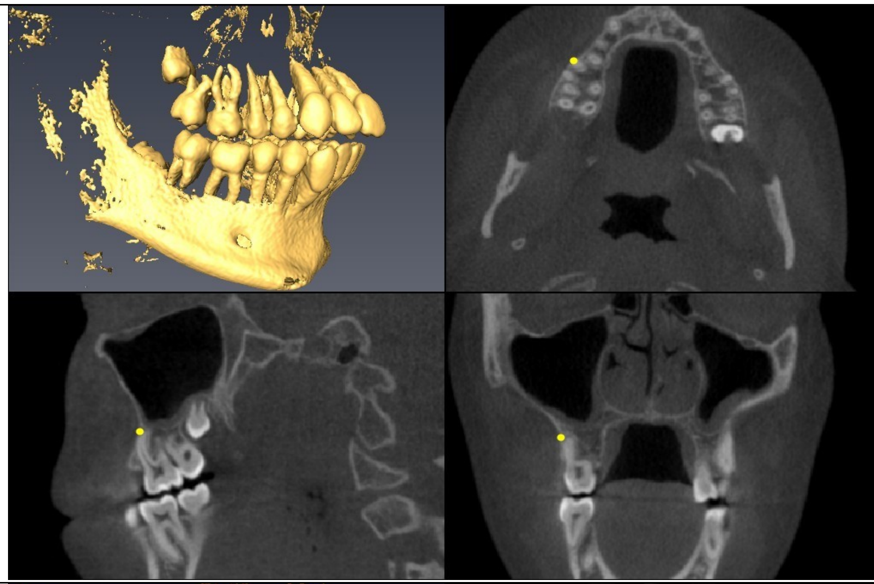
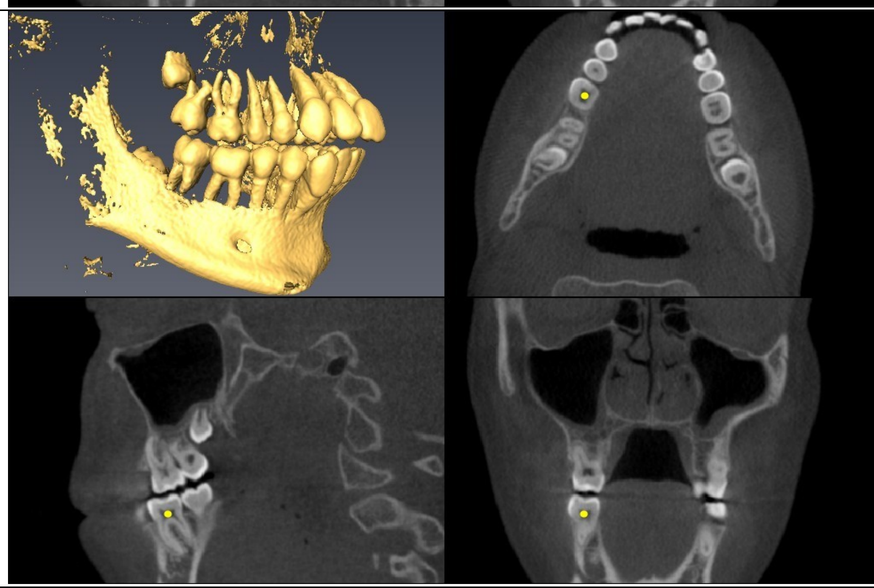
Variable	*Group A (Damon) Mean (SD) or n (%)*	*Group B (Hyrax) Mean (SD) of n (%)*	*P value*
Age (y)	13.8 (1.6)	13.3 (1.5)	0.188
Sex			0.174
Male	13 (31.7%)	19 (46.3%)	
Female	28 (68.3%)	22 (53.7%)	

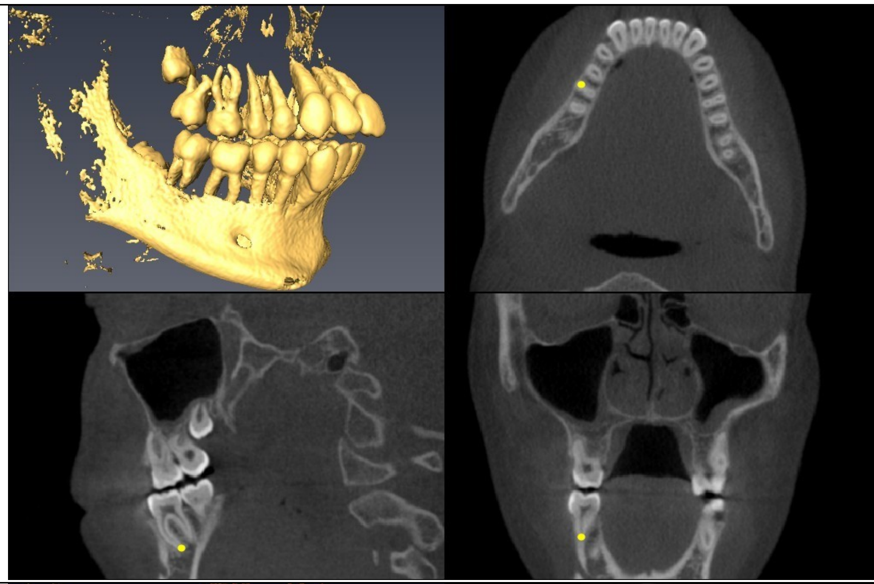
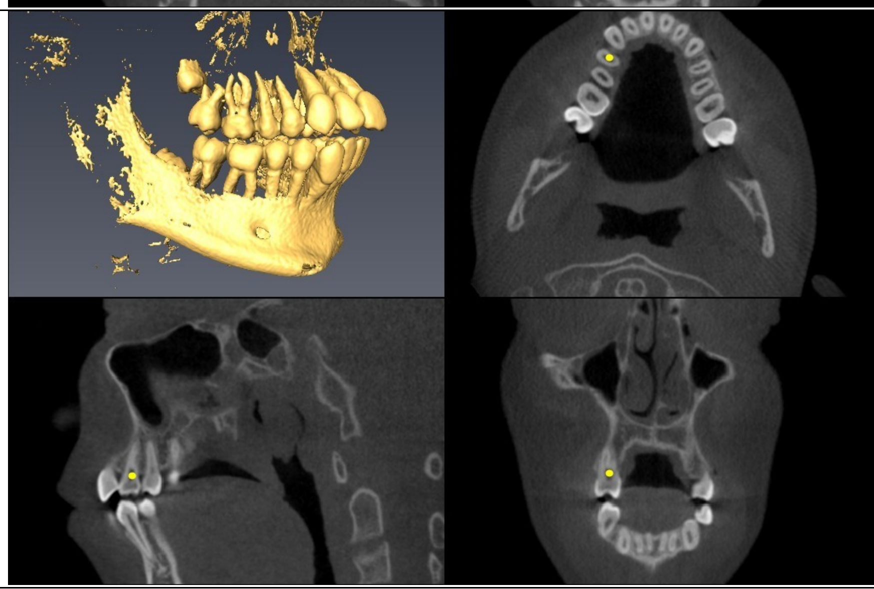
Raw CBCT DICOM images were loaded to the Avizo software 8.0 (Visualization Sciences Group, Burlington, MA, USA), which was used with the ISO-surface and exposure of 300-1000 as a setting. All landmarks were identified used a 0.5 mm diameter spherical marker. A total of 25 dental and skeletal 3-dimensional landmarks were identified on CBCT images, and out of 25 landmarks, 7 landmarks (Foramen magnum, Right/Left Foramen Ovale, Right/Left Foramen Spinosum, Right/Left External Auditory Meatus) were only used as a 3D anatomical reference for superimposition. 18 landmarks used for the analysis are listed and defined with their acronym (Table 3.2 and 3.3). Each landmark was located using sagittal, axial, and coronal multiplanar slices with x, y, and z coordinates. Once all coordinates of landmarks were obtained in AVIZO software, the collected data were exported as an Excel 2007 spreadsheet. The Matlab (Matrix Laboratory, Natik, MA, USA) software then used the excel data to create new coordinates and generate the optimization. The cranial base landmarks were used to align the excel data in three planes based on a 3D Cartesian coordinate system. Landmark-derived superimposition technique was used to superimpose all traced CBCT images, and a few groups had previously published the detailed description and error associated with this superimposition technique. [15,16] As a result of superimposition and optimization, a positive change in X, Y, and Z coordinates represent left, front, and upward direction respectively. A negative change in X, Y, and Z coordinates represent right, back, and downward direction respectively.

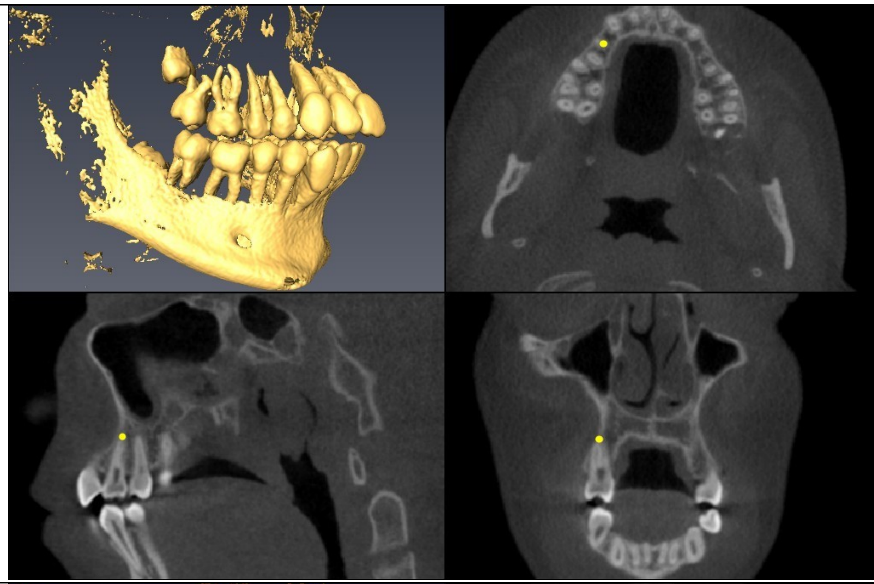
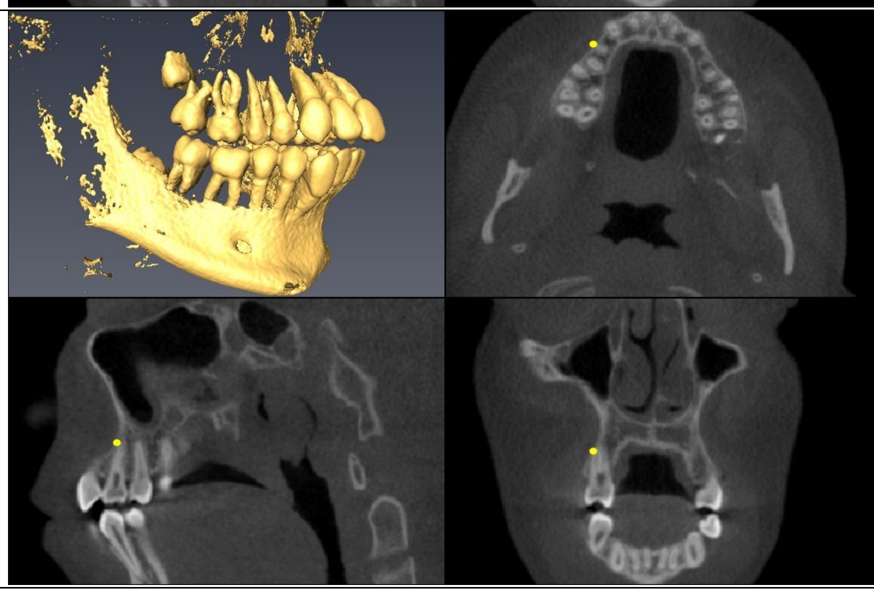
Table 3.2. Eighteen Dental and Skeletal Landmarks Chosen for the Study

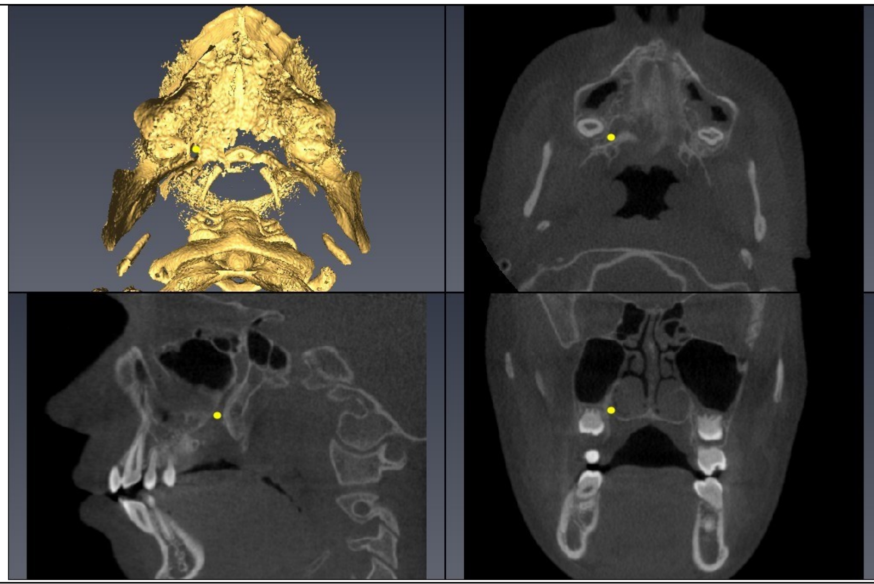
Acronym	*Landmark Full Name*	*Acronym*	*Landmark Full Name*
UR6P	Upper Right First Molar Pulp Chamber	UL6R	Upper Left First Molar Mesial Root Apex
UR6R	Upper Right First Molar Mesial Root Apex	UL6A	Upper Left First Molar Alveolar Bone
UR6A	Upper Right First Molar Alveolar Bone	LL6P	Lower Left First Molar Pulp Chamber
LR6P	Lower Right First Molar Pulp Chamber	LL6R	Lower Left First Molar Mesial Root Apex
LR6R	Lower Right First Molar Mesial Root Apex	UL4P	Upper Left First Premolar Pulp Chamber
UR4P	Upper Right First Premolar Pulp Chamber	UL4R	Upper Left First Premolar Root Apex
UR4R	Upper Right First Premolar Root Apex	UL4A	Upper Left First Premolar Alveolar Bone
UR4A	Upper Right First Premolar Alveolar Bone	RGP	Right Greater Palatine Foramen
UL6P	Upper Left First Molar Pulp Chamber	LGP	Left Greater Palatine Foramen

Table 3.3 Craniofacial Landmarks Identification	
Landmark Description	*3D view (upper left), Axial view (upper right), Sagittal view (lower left), Coronal view (lower right)*
Upper First Molar Pulp Chamber =center of largest cross sectional pulp chamber area	
Upper First Molar Mesial Root Apex =apex of mesio-buccal root	

Upper First Molar Alveolar Bone =alveolar bone next to mesial root apex	
Lower First Molar Pulp Chamber =center of largest cross sectional pulp chamber area	

Lower First Molar Mesial Root Apex =apex of mesial root	
Upper First Premolar Pulp Chamber =center of largest cross sectional pulp chamber area	

Upper First Premolar Root Apex =apex of mesial root	
Upper First Premolar Alveolar Bone =alveolar bone next to mesial root apex	

Greater Palatine Foramen =center of largest cross sectional foramen area	

Statistical Analysis

Intra-Rater Reliability Test

All statistical analysis was performed using the IBM SPSS analysis software. Out of 164 patients' CBCT files (82 patients x 2 files for initial/final), 10 CBCT files were randomly chosen. All 25 landmarks (including cranial base landmarks used for superimposition) were traced 3 times over 2 weeks interval in between trials. The table 3.4 summarizes the average and standard deviation (STDEV) of three times repeated measures for each landmark/coordinate combinations used for the analysis. Intraclass Correlation Coefficient (ICC) for all landmarks were 1.00 with the 95% confidence interval of [1.00, 1.00] except for the right external auditory meatus with ICC of 0.99 [0.96, 1.00] and left external auditory meatus with ICC of 0.98 [0.95, 1.00].

Table 3.4. Intra-rater reliability (average of 10 random patients)

Landmark & Coordinate	*Average*	*STDEV*	*Landmark & Coordinate*	*Average*	*STDEV*
UR6P-x	-0.18	0.31	UL6R-x	0.04	0.39
UR6P-y	-0.20	0.44	UL6R-y	0.00	0.19
UR6P-z	0.01	0.37	UL6R-z	0.21	0.42
UR6R-x	0.11	0.32	UL6A-x	0.07	0.27
UR6R-y	0.08	0.21	UL6A-y	0.00	0.19
UR6R-z	0.20	0.36	UL6A-z	0.31	0.47
UR6A-x	-0.31	0.60	LL6P-x	0.00	0.22
UR6A-y	0.08	0.21	LL6P-y	0.08	0.29
UR6A-z	0.18	0.46	LL6P-z	0.12	0.23
LR6P-x	-0.02	0.37	LL6R-x	0.19	0.28
LR6P-y	0.08	0.37	LL6R-y	-0.08	0.26
LR6P-z	-0.09	0.28	LL6R-z	-0.11	0.52
LR6R-x	-0.06	0.24	UL4P-x	-0.03	0.25
LR6R-y	0.19	0.31	UL4P-y	-0.25	0.29
LR6R-z	-0.10	0.35	UL4P-z	-0.26	0.52
UR4P-x	-0.07	0.26	UL4R-x	-0.15	0.36
UR4P-y	-0.15	0.29	UL4R-y	-0.31	0.32
UR4P-z	-0.20	0.56	UL4R-z	-0.18	0.54
UR4R-x	0.06	0.26	UL4A-x	-0.17	0.24
UR4R-y	-0.30	0.41	UL4A-y	-0.31	0.32
UR4R-z	-0.12	0.61	UL4A-z	-0.07	0.55
UR4A-x	0.05	0.31	RGP-x	-0.05	0.36
UR4A-y	-0.30	0.41	RGP-y	-0.44	0.80
UR4A-z	-0.08	0.57	RGP-z	-0.34	0.72
UL6P-x	0.04	0.38	LGP-x	0.03	0.40
UL6P-y	-0.26	0.41	LGP-y	-0.19	0.42
UL6P-z	0.13	0.25	LGP-z	-0.36	0.56

Repeated Measures Mixed ANOVA

The normality of the data was assessed by constructing box plots for representative dental (UR6P) and skeletal (RGP) landmarks (Figure 3.1 in appendix). The overall box plot showed a normal distribution with a few outliers in the Damon group. Normality was not critical in this case due to equal sample sizes between two groups. The assumption of sample independence was met because samples were taken from independent population. Mauchly's test of Sphericity result is also shown in Table 3.5 of appendix section. The equal variances were tested using the rule of thumb. Descriptive Statistics chart is shown in Table 3.6 of appendix section. The largest standard deviation

(2.85) was not more than twice as large as the smallest sample standard deviation (1.61) (Table 3.6 in appendix). Therefore, the rule of thumb for variance is met. Last, scatter plots were constructed on a representative dental (UR6P) and a skeletal (RGP) landmark to check the linearity assumption (Figure 3.2 in appendix section). Both plots show a random displacement with no clustering or systematic pattern, and therefore, linearity was assumed based on the visual assessment. The Repeated Measures Mixed ANOVA was performed to assess within group and between group differences from T1 to T2 (Table 3.7 in appendix). In order to investigate the specific interaction between the coordinate, landmark, treatment time, and treatment group, a post-hoc test was performed. Since the research design was done with an unplanned manner, the Bonferroni test was applied (Table 3.8 and 3.9)

Table 3.8. Within Group Pairwise Comparisons (T_1-T_0)

Landmark	*Coordinate*	*Mean Difference (T_1-T_0)*	*Std. Error*	*Sig.b*	*95% Confidence Interval for Difference[b]* *Lower Bound*	*Upper Bound*
<Damon Group>						
UR6P	x	-0.61*	0.23	0.009	-1.07	-0.15
	y	0.81*	0.30	0.007	0.23	1.40
	z	-1.51*	0.35	<0.0001	-2.20	-0.82
UR6R	x	-0.53*	0.25	0.040	-1.03	-0.03
	y	0.95*	0.26	0.001	0.43	1.48
	z	-1.56*	0.40	<0.0001	-2.35	-0.77
UR6A	x	0.35	0.31	0.259	-0.26	0.95
	y	0.92*	0.27	0.001	0.39	1.45
	z	-1.59*	0.40	0.000	-2.40	-0.79
LR6P	x	0.63*	0.26	0.018	0.11	1.15
	y	1.45*	0.44	0.002	0.56	2.33
	z	-1.80*	0.34	<0.0001	-2.49	-1.12
LR6R	x	-0.23	0.30	0.443	-0.83	0.37
	y	1.24*	0.54	0.023	0.17	2.30
	z	-1.64*	0.36	<0.0001	-2.34	-0.93
UR4P	x	-1.15*	0.27	<0.0001	-1.68	-0.62
	y	0.82*	0.33	0.016	0.16	1.49
	z	-1.78*	0.43	<0.0001	-2.64	-0.92

UR4R	x	0.46	0.27	0.090	-0.07	0.98
	y	0.51	0.28	0.080	-0.06	1.07
	z	-1.99*	0.44	<0.0001	-2.87	-1.11
UR4A	x	0.22	0.26	0.408	-0.31	0.74
	y	0.49	0.29	0.089	-0.08	1.06
	z	-2.00*	0.45	<0.0001	-2.90	-1.11
UL6P	x	0.36	0.24	0.133	-0.11	0.83
	y	0.50	0.30	0.102	-0.10	1.10
	z	-1.36*	0.35	<0.0001	-2.06	-0.66
UL6R	x	0.26	0.24	0.287	-0.22	0.73
	y	0.56*	0.26	0.034	0.04	1.07
	z	-1.26*	0.39	0.002	-2.03	-0.49
UL6A	x	-0.35	0.24	0.148	-0.83	0.13
	y	0.60*	0.27	0.028	0.07	1.13
	z	-1.24*	0.39	0.002	-2.01	-0.46
LL6P	x	-0.24	0.25	0.352	-0.73	0.26
	y	1.06*	0.45	0.020	0.17	1.96
	z	-1.67*	0.33	<0.0001	-2.33	-1.02
LL6R	x	0.48	0.29	0.102	-0.10	1.06
	y	0.97	0.52	0.065	-0.06	2.00
	z	-1.48*	0.33	<0.0001	-2.12	-0.83
UL4P	x	0.99*	0.29	0.001	0.41	1.57
	y	0.56	0.35	0.114	-0.14	1.26
	z	-1.41*	0.43	0.002	-2.27	-0.55
UL4R	x	-0.60*	0.29	0.041	-1.18	-0.03
	y	0.56	0.30	0.066	-0.04	1.16
	z	-1.45*	0.44	0.001	-2.32	-0.58
UL4A	x	-0.30	0.29	0.298	-0.88	0.27
	y	0.54	0.30	0.077	-0.06	1.14
	z	-1.39*	0.44	0.002	-2.28	-0.51
RGP	x	-0.32*	0.14	0.029	-0.60	-0.03
	y	0.88*	0.20	<0.0001	0.48	1.28
	z	-0.54*	0.25	0.032	-1.03	-0.05
LGP	x	0.16	0.14	0.254	-0.12	0.45
	y	0.73*	0.22	0.001	0.30	1.16
	z	-0.34	0.26	0.190	-0.86	0.17
<Hyrax Group>						
UR6P	x	-2.97*	0.23	<0.0001	-3.43	-2.51
	y	0.15	0.30	0.609	-0.44	0.74
	z	-1.03*	0.35	0.004	-1.72	-0.34
UR6R	x	-2.61*	0.25	<0.0001	-3.11	-2.11
	y	-0.03	0.26	0.906	-0.56	0.50
	z	-1.48*	0.40	<0.0001	-2.27	-0.69
UR6A	x	-0.94*	0.31	0.003	-1.54	-0.33
	y	-0.07	0.27	0.805	-0.60	0.46
	z	-1.52*	0.40	<0.0001	-2.33	-0.72
LR6P	x	0.38	0.26	0.153	-0.14	0.90
	y	1.03*	0.44	0.023	0.14	1.91
	z	-1.96*	0.34	<0.0001	-2.65	-1.28
LR6R	x	0.16	0.30	0.586	-0.43	0.76

	y	0.93	0.54	0.086	-0.14	1.99
	z	-1.82*	0.36	<0.0001	-2.52	-1.11
UR4P	x	-2.66*	0.27	<0.0001	-3.19	-2.13
	y	0.20	0.33	0.557	-0.47	0.86
	z	-1.41*	0.43	0.002	-2.27	-0.55
UR4R	x	-2.55*	0.27	<0.0001	-3.08	-2.02
	y	-0.02	0.28	0.950	-0.58	0.55
	z	-1.39*	0.44	0.002	-2.27	-0.51
UR4A	x	-1.78*	0.26	<0.0001	-2.30	-1.26
	y	-0.03	0.29	0.917	-0.60	0.54
	z	-1.41*	0.45	0.002	-2.31	-0.52
UL6P	x	3.25*	0.24	<0.0001	2.78	3.72
	y	0.25	0.30	0.409	-0.35	0.85
	z	-0.79*	0.35	0.027	-1.50	-0.09
UL6R	x	2.47*	0.24	<0.0001	2.00	2.94
	y	-0.05	0.26	0.859	-0.56	0.47
	z	-1.24*	0.39	0.002	-2.01	-0.47
UL6A	x	0.97*	0.24	<0.0001	0.49	1.44
	y	-0.06	0.27	0.818	-0.60	0.47
	z	-1.16*	0.39	0.004	-1.93	-0.39
LL6P	x	0.16	0.25	0.527	-0.34	0.66
	y	1.11*	0.45	0.015	0.22	2.00
	z	-1.67*	0.33	<0.0001	-2.32	-1.02
LL6R	x	0.27	0.29	0.353	-0.31	0.85
	y	0.91	0.52	0.084	-0.13	1.93
	z	-1.40*	0.33	<0.0001	-2.05	-0.75
UL4P	x	3.33*	0.29	<0.0001	2.75	3.92
	y	0.38	0.35	0.284	-0.32	1.08
	z	-1.42*	0.43	0.001	-2.28	-0.56
UL4R	x	2.69*	0.29	<0.0001	2.11	3.26
	y	0.33	0.30	0.268	-0.26	0.93
	z	-1.35*	0.44	0.003	-2.22	-0.48
UL4A	x	2.22*	0.29	<0.0001	1.65	2.80
	y	0.33	0.30	0.276	-0.27	0.93
	z	-1.32*	0.44	0.004	-2.20	-0.44
RGP	x	-0.78*	0.14	<0.0001	-1.06	-0.49
	y	0.64*	0.20	0.002	0.24	1.04
	z	-1.09*	0.25	<0.0001	-1.58	-0.60
LGP	x	0.82*	0.14	<0.0001	0.53	1.10
	y	0.57*	0.22	0.010	0.14	0.99
	z	-0.80*	0.26	0.003	-1.32	-0.29

Based on estimated marginal means
*** The mean difference is significant at the**
b Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Table 3.9. Between Group Pairwise Comparisons

Landmark	Coordinate	Mean Difference (Damon-Hyrax)	Std. Error	Sig.b	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
UR6P	x	2.36*	0.32	<0.0001	1.71	3.00
	y	0.66	0.42	0.116	-0.17	1.49
	z	-0.48	0.49	0.331	-1.46	0.50
UR6R	x	2.09*	0.36	<0.0001	1.38	2.79
	y	0.98*	0.37	0.010	0.24	1.73
	z	-0.08	0.56	0.892	-1.19	1.04
UR6A	x	1.28*	0.43	0.004	0.42	2.14
	y	0.99*	0.38	0.011	0.24	1.74
	z	-0.07	0.57	0.900	-1.21	1.07
LR6P	x	0.26	0.37	0.491	-0.48	0.99
	y	0.42	0.63	0.507	-0.83	1.67
	z	0.16	0.49	0.744	-0.81	1.13
LR6R	x	-0.40	0.42	0.354	-1.24	0.45
	y	0.31	0.76	0.686	-1.20	1.81
	z	0.18	0.50	0.722	-0.82	1.18
UR4P	x	1.51*	0.38	<0.0001	0.76	2.26
	y	0.63	0.47	0.189	-0.31	1.57
	z	-0.37	0.61	0.542	-1.59	0.84
UR4R	x	3.01*	0.38	<0.0001	2.26	3.75
	y	0.52	0.40	0.197	-0.28	1.32
	z	-0.60	0.63	0.341	-1.84	0.65
UR4A	x	2.00*	0.37	<0.0001	1.26	2.74
	y	0.52	0.40	0.200	-0.28	1.32
	z	-0.59	0.64	0.359	-1.85	0.68
UL6P	x	-2.89*	0.33	<0.0001	-3.55	-2.22
	y	0.25	0.43	0.562	-0.60	1.10
	z	-0.57	0.50	0.259	-1.56	0.43
UL6R	x	-2.21*	0.34	<0.0001	-2.89	-1.54
	y	0.60	0.37	0.104	-0.13	1.33
	z	-0.02	0.55	0.971	-1.11	1.07
UL6A	x	-1.32*	0.34	<0.0001	-2.00	-0.64
	y	0.66	0.38	0.085	-0.09	1.42
	z	-0.08	0.55	0.890	-1.17	1.02
LL6P	x	-0.39	0.35	0.270	-1.10	0.31
	y	-0.04	0.63	0.945	-1.30	1.22
	z	-0.01	0.46	0.988	-0.93	0.92
LL6R	x	0.21	0.41	0.612	-0.61	1.03
	y	0.06	0.73	0.933	-1.40	1.52
	z	-0.07	0.46	0.876	-0.99	0.85
UL4P	x	-2.35*	0.42	<0.0001	-3.17	-1.52
	y	0.18	0.50	0.715	-0.807	1.17
	z	0.01	0.61	0.988	-1.20	1.22
UL4R	x	-3.29*	0.41	<0.0001	-4.10	-2.47
	y	0.22	0.42	0.598	-0.62	1.07
	z	-0.11	0.62	0.866	-1.34	1.13

UL4A	x	-2.52*	0.41	<0.0001	-3.34	-1.71
	y	0.21	0.43	0.624	-0.64	1.06
	z	-0.07	0.63	0.906	-1.32	1.18
RGP	x	0.46*	0.20	0.025	0.06	0.86
	y	0.24	0.28	0.404	-0.33	0.80
	z	0.55	0.35	0.120	-0.15	1.24
LGP	x	-0.65*	0.20	0.002	-1.05	-0.25
	y	0.16	0.30	0.597	-0.44	0.77
	z	0.46	0.37	0.216	-0.27	1.19

Based on estimated marginal means
*** The mean difference is significant at the**
b Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Results

Since each landmark was analyzed in 3 different planes, a total of 54 landmark/coordinate combinations were present. 1mm was chosen to be the threshold for clinical significance because all landmarks used for the analysis except right greater palatine foramen had intra-rater measurement error of <1mm. Thus, the measurement error cannot be larger than the means between groups to become clinically significant. Previous studies also noted that the intra-examiner's mean difference for CBCT landmarks were less than 1.50 mm. [17] Furthermore, many clinicians would agree that less than 1mm change does not have meaningful therapeutic effect in orthodontics. Such small change would not affect majority of clinicians' diagnosis and treatment planning decision.

In order to assess individual landmark, Table 3.10 summarizes landmarks that showed statistically significant difference between two treatment groups. In terms of skeletal landmarks, alveolar bone next to right and left maxillary first premolar and molar root apex showed more lateral movement in the Hyrax group. The left and right greater palatine foramen also showed more lateral movement in the hyrax group although this difference was not clinically significant. Dental landmarks representing upper right and left first molars and first premolars showed the largest difference between treatment groups. The pulp chamber of upper right first molar (UR6P) in the hyrax group moved 2.36 ± 0.64 mm more right than in the Damon group while the pulp chamber of upper left first molar (UL6P) moved 2.89 ± 0.66 mm more left than in the Damon group. The pulp chamber of upper right first premolar (UR4P) in the hyrax group moved 1.51 ± 0.75 mm more right than in the Damon group while the pulp chamber of upper left first premolar (UL4P) moved 2.35 ± 0.82 mm more left than in the Damon group. The only landmarks with significant difference between groups in antero-posterior direction were the upper right first molar root apex (UR6R) and upper right first molar alveolus (UR6A), however these differences were not clinically significant. There was no statistically significant difference between groups in Z coordinate.

Table 3.10. Summary of Statistically Significant Findings Between Treatment Groups

Landmark	Mean difference (Damon-Hyrax)	95% Confidence Interval Lower bound	Upper bound	Significance P-value	Clinical (>1mm)
Transverse Changes (X coordinate)					
UR6P	2.36	1.71	3.00	<0.0001	Yes
UR6R	2.09	1.38	2.79	<0.0001	Yes
UR6A	1.28	0.42	2.14	0.004	Yes
UR4P	1.51	0.76	2.26	<0.0001	Yes
UR4R	3.01	2.26	3.75	<0.0001	Yes
UR4A	2.00	1.26	2.74	<0.0001	Yes
UL6P	-2.89	-3.55	-2.22	<0.0001	Yes
UL6R	-2.21	-2.89	-1.54	<0.0001	Yes
UL6A	-1.32	-2.00	-0.64	<0.0001	Yes
UL4P	-2.35	-3.17	-1.52	<0.0001	Yes
UL4R	-3.29	-4.10	-2.47	<0.0001	Yes

UL4A	-2.52	-3.34	-1.71	<0.0001	Yes
RGP	0.46	0.06	0.86	0.025	No
LGP	-0.65	-1.05	-0.25	0.002	No
Antero-posterior Changes (Y coordinate)					
UR6R	0.98	0.24	1.73	0.010	No
UR6A	0.99	0.24	1.74	0.011	No
Vertical Changes (Z coordinate)					
None					

For the within group analysis, regardless of treatment group, on average, all landmarks showed the greatest mean change in Z coordinate (vertical dimension). In Damon group, the only clinically significant mean change in X coordinate was UR4P (-1.15 ± 0.53 mm). In the Hyrax group, landmarks representing upper right and left first molars and premolars showed the largest transverse change over 6 months. In both groups, the pulp chamber of mandibular right and left first molar showed the greatest mean change in Y coordinate.

Discussion

Comparison between two treatment groups revealed that most clinically significant changes occurred in dental landmarks. Skeletal landmarks such as right and left greater palatine foramen showed more lateral movement in the Hyrax group but the values were not clinically significant. This finding agrees with previous studies that treatment effects from the RME device are primarily on the dental structures compared to the skeletal structures. [18,19]

The Hyrax device showed more transverse changes than the Damon group. On average, there was 4-5mm more transverse expansion in the Hyrax group. The Hyrax device is cemented in the patient's mouth anchored to upper premolar and molar teeth bilaterally. Therefore, the largest mean difference was found in upper right and left first premolar and molar regions (Table 3.10). Indeed, the pulp chamber of upper right and left molars showed more lateral movements compared to their root apex (Table 8). This finding is in agreement with previous studies that buccal tipping of molar occurs during expansion instead of bodily movement of tooth. [18] Since both Hyrax and Damon system are used to widen maxillary arch transversely, the greatest difference between two groups was noted in the X-coordinate. No clinically significant changes were observed in vertical (Z-coordinate) and antero-posterior (Y-coordinate) direction.

Furthermore, alveolar bone next to root apex of maxillary first premolar and molar showed clinically significant lateral movement in the Hyrax group only (Table 3.8). However, the magnitude of alveolar bone's lateral movement was smaller than the changes in pulp chamber location. For example, maxillary right first molar pulp chamber moved 2.97 ± 0.46 mm laterally while its alveolar bone next to root apex moved 0.94± 0.60 mm (Table 3.8). This may suggest that lateral movement of maxillary posterior teeth could produce buccal bone apposition, however, the amount of bone apposition is far less than the amount of tooth movement, and there is net thinning of the buccal alveolar bone. [20,21] Furthermore, the right greater palatine foramen moved laterally by 0.78 ± 0.28 mm, which is roughly the same amount of movement as the alveolar bone. Thus, one could also argue that 0.94 mm lateral movement of alveolar bone next to first molar can be merely from the overall buccal movement of bony segment from the expansion at the suture line.

Caution must be taken when analyzing the within group analysis. Since there is no control group, the changes over 6 months cannot be distinguished between the growth of patients and treatment effect. In both treatment groups, there the largest change was in the Z coordinate (downward vertical displacement of all landmarks) between initial and 6 months records. Previous research has shown that with maxillary expansion, anchoring maxillary teeth follow downward maxillary displacement, and as a consequence, vertical downward and backward rotation of mandible is observed. [22] However, there was a large variation in the magnitude of vertical change between individuals. Since the study was based on adolescent patients, vertical change is most likely related to growth and not from the maxillary expansion.

In the Damon group, bite ramps were placed on upper first molars, and patients wore full-time crossbite elastics (from upper first molar to lower first molar) to help with arch expansion based on a recommendation from the Damon system's expert. Therefore, lower first right and left molars were included in this analysis to assess the effect of crossbite elastics and maxillary expansion on lower dentition. There was clinically significant downward and forward movements of lower first molar's pulp chamber in both treatment groups but no clinically signifcant changes in transverse dimention. In fact, 17 out of 41 patients in the Damon group still had posterior crossbite after 6 months of treatment. The vertical and antero-posterior movement of lower molar teeth are likely mainly from the growth of the patients. It seems that there is no clear effect of crossbite elastics and maxillary expansion on lower molar in transverse dimension.

Furthermore, through the bite elastics and the Damon archwire are designed to produce force for wider arch development. [9] However, most transverse changes were noted only in the Hyrax group despite the Damon system's claim that their device can result in predictable maxillary dental expansion. The Damon system also argues for its capability of reducing negative side effects seen in Hyrax appliances such as downward displacement of maxillary teeth (Damon, 1998). However, similar vertical displacement of maxillary teeth was noted in both Damon and Hyrax groups in this paper although the clear distinction between the growth and treatment effect is not clear in the study.

Limitations

Although CBCT is currently the only readily available option for analyzing alveolar bone thickness, it has limitations. The voxel size (resolution) and partial volume average effect of CBCT can influence the accuracy in the measurement. [23,24] Since the voxel size used for the study was 0.3 mm, unless the buccal bone is at least 0.6 mm thick, the alveolar bone is not discernable. [20] Identification of alveolar bone defect such as fenestration is 3 times more likely to be detected in CBCT compared to direct skull analysis, suggesting false positive change based on CBCT. [23] Next, if the voxel lies between two objects of different densities such as alveolar bone and tooth apex, the image will reflect the average density value, and therefore, the precise tooth apex identification can be more challenging.

In Damon group, during initial alignment and leveling stage, a new archwire was inserted every 2 months. Therefore, most patients had 0.014x0.025 NiTi archwire for 2 months in the mouth when the 6 months progress CBCT was taken. Some clinicians could argue that 0.014x0.025 NiTi archwire is not strong enough to generate force for arch expansion. However, if the Damon's claim that the light and continuous force can translate tooth, 0.014x0.025 NiTi archwire should generate enough force for adequate arch expansion. Yet, this claim was not supported by our finding. Further investigation of completed treatment records of each group will be helpful in assessing the final arch dimension and stability of expansion. In addition, Records were taken at initial and 6 months into treatment, and therefore, 6 months may not be long enough for the formation of alveolar bone in response to tooth movement. [25] The long-term post retention study is indicated to assess the possible bone formation after the treatment is completed.

Conclusion

This study shows the three-dimensional changes in craniofacial landmarks in response to different expansion appliances (the Damon and Hyrax) used in a clinic setting. Comparison between two groups showed that more transverse expansion was noted in the Hyrax group. Largest transverse changes were observed in maxillary molar and premolar teeth with buccal tipping movement. Alveolar bone next to root apex of maxillary first premolar and molar showed clinically significant lateral movement in the Hyrax group suggesting a possible bone apposition following teeth movement.

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Appendices

Figure 3.1. Box plots for a representative dental landmark (UR6P) and a skeletal landmark (RGP).

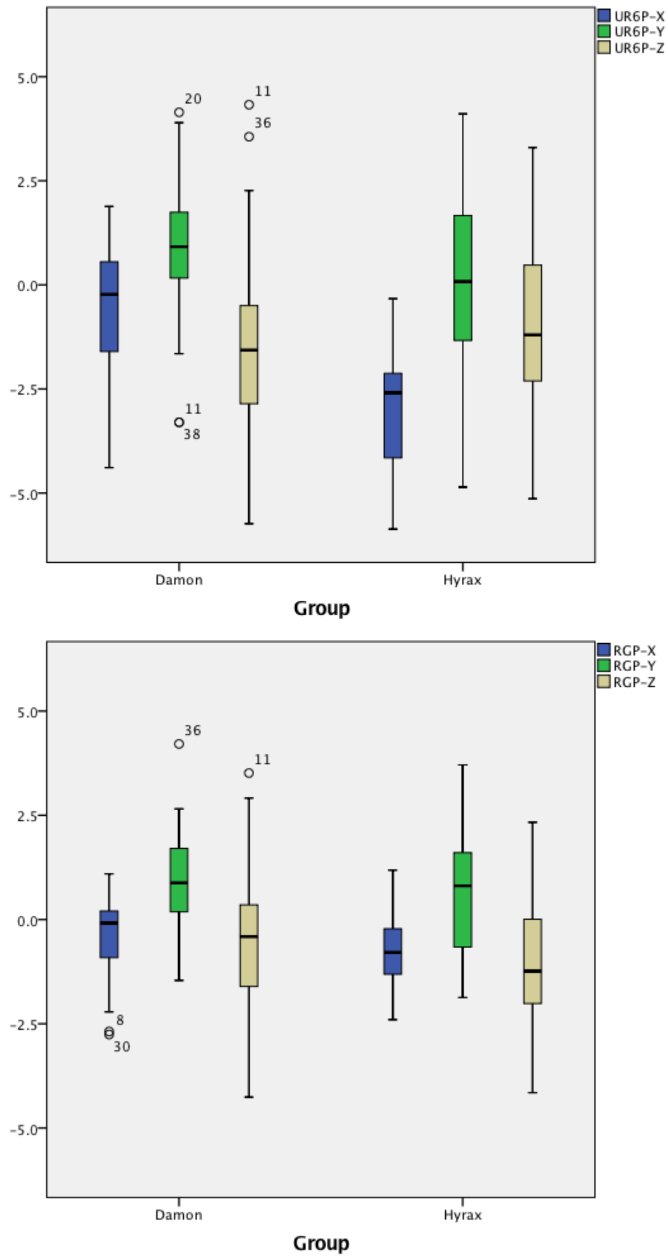

Table 3.5. Mauchly's Test of Sphericity					
Within Subjects Effect	*Mauchly's W*	*Chi-Square*	*df*	*Sig.*	*Greenhouse-Geisser*
Landmark	0.00	1230.19	152	<0.0001	0.26
Coordinate	0.55	47.14	2	<0.0001	0.69
Landmark*Coordinate	0.00	2985.86.11	594	<0.0001	0.24

Table 3.6. Descriptive Statistics Chart							
Landmark & Coordinate	*N*	*Mean*	*Std. Deviation*	*Landmark & Coordinate*	*N*	*Mean*	*Std. Deviation*
UR6P-x	82	-1.79	1.88	UL6R-x	82	1.36	1.88
UR6P-y	82	0.48	1.91	UL6R-y	82	0.26	1.68
UR6P-z	82	-1.27	2.22	UL6R-z	82	-1.25	2.47
UR6R-x	82	-1.57	1.92	UL6A-x	82	0.31	1.67
UR6R-y	82	0.46	1.75	UL6A-y	82	0.27	1.74
UR6R-z	82	-1.52	2.52	UL6A-z	82	-1.20	2.47
UR6A-x	82	-0.29	2.04	LL6P-x	82	-0.04	1.61
UR6A-y	82	0.43	1.77	LL6P-y	82	1.09	2.85
UR6A-z	82	-1.56	2.57	LL6P-z	82	-1.67	2.09
LR6P-x	82	0.50	1.67	LL6R-x	82	0.38	1.85
LR6P-y	82	1.24	2.84	LL6R-y	82	0.94	2.29
LR6P-z	82	-1.88	2.19	LL6R-z	82	-1.44	2.08
LR6R-x	82	-0.03	1.92	UL4P-x	82	2.16	2.21
LR6R-y	82	1.08	2.41	UL4P-y	82	0.47	2.24
LR6R-z	82	-1.73	2.26	UL4P-z	82	-1.41	2.74
UR4P-x	82	-1.90	1.86	UL4R-x	82	1.04	2.47
UR4P-y	82	0.51	2.15	UL4R-y	82	0.45	1.91
UR4P-z	82	-1.60	2.76	UL4R-z	82	-1.40	2.79
UR4R-x	82	-1.05	2.27	UL4A-x	82	0.96	2.23
UR4R-y	82	0.24	1.83	UL4A-y	82	0.43	1.92
UR4R-z	82	-1.69	2.83	UL4A-z	82	-1.36	2.83
UR4A-x	82	-0.78	1.95	RGP-x	82	-0.55	1.94

UR4A-y	82	0.23	1.83	RGP-y	82	0.76	1.28
UR4A-z	82	-1.71	2.88	RGP-z	82	-0.81	1.59
UL6P-x	82	1.80	2.09	LGP-x	82	0.49	0.96
UL6P-y	82	0.37	1.92	LGP-y	82	0.65	1.37
UL6P-z	82	-1.08	2.26	LGP-z	82	-0.57	1.67

Figure 3.2. Multiple 2-D scatter plots of landmarks UR6P and RGP constructed for the linearity test

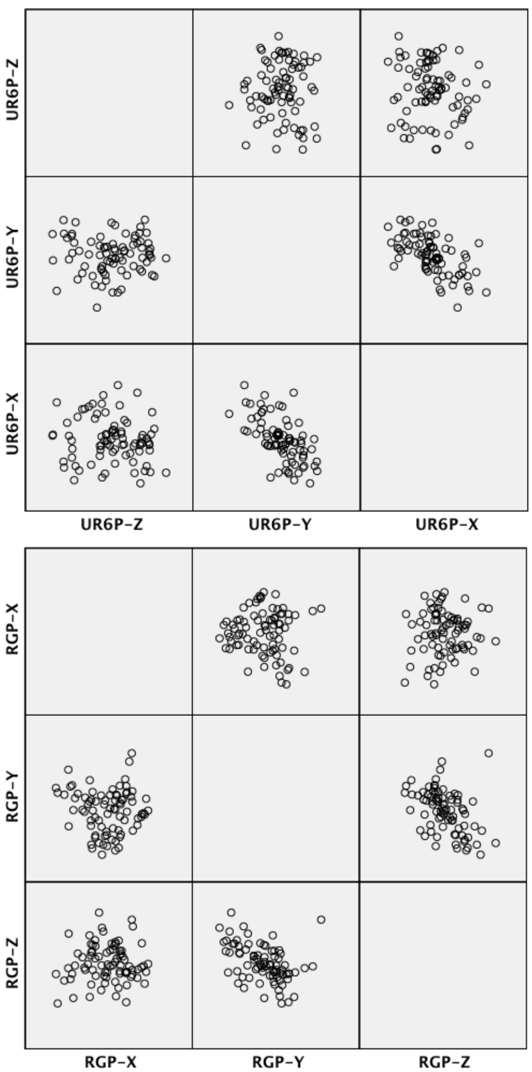

Table 3.7. Test of Within-Subjects Effects						
Source		*Type III Sum of Squares*	*df*	*Mean Square*	*F*	*Sig.*
Landmark*Coordinate* Group	Greenhouse-Geisser	913.80	8.3	110.76	23.77	<0.0001

Chapter 4 General Discussion & Major Conclusions

Summary of Findings

The Damon bracket system is heavily marketed in the orthodontic community as the "revolutionary braces" that has many benefits over conventional brackets. [1] One of their main claims is that "light biologically-sensible forces" of the bracket system reduces the need for a rapid palatal expander or extractions. They also advertise faster treatment time, better facial esthetics, and greater comfort with their system. [1] In this study, we wanted to test one of their most popular claims that the system can results in predictable maxillary expansion without many side effects associated with a rapid palatal expander.

The first step was to search for current evidences on the Damon bracket system in comparison to any other orthodontic mechanics. The systematic review was conducted on October 5th, 2018 on three major databases (Cochrane, PubMed, Embase). Seven studies were included for the analysis (3 randomized clinical trials, 2 prospective clinical trials, and 2 retrospective clinical trials). [2-8] Six studies compared the Damon system to conventional (non self-ligating) brackets while one study used a Quad helix in the comparison group. [2] All studies used a 2-dimensional imaging such as lateral and/or anteroposterior cephalograms except one research group used a Cone Beam Computed Tomography (CBCT) for their analysis. [4] The majority of studies found an increase in maxillary intercanine, interpremolar, and intermolar distance after the treatment in both the Damon and comparison groups. Yet, all studies concluded that there is no significant difference in the final transverse dimension between two groups. One study also found that the transverse expansion was achieved mainly by tipping movement of posterior dentition, and a decrease in the posterior buccal bone area was evident in both groups after treatment.[4]

Next, a separate literature review was conducted on December 10th, 2018 to search for the accuracy and reliability of 3-dimensional maxillofacial landmarks in CBCT. After searching through Cochrane and PudMed databases, 5 systematic review articles were found, and 4 of them were published within the last 5 years.[9-13] In terms of measurement accuracy, a 3-dimensional cephalometry compared to the direct skull measurement was less than 1mm, and each anatomical landmark had unique pattern of measurement inaccuracy.[11,12] In terms of reliability, craniofacial landmarks on the median sagittal plane demonstrated highest reliability. Dental landmarks such as maxillary incisors and right and left maxillary molars also had high level of reliability.[13] On the other hand, any landmarks on the condyle, orbitale, and porion showed the lowest reliability.[9] In addition, Lubbert et al. (2016) had similar research topic, and they used same Avizo software for their analysis of 3D CBCT images with high reliability.[14] Thus, the methodology of their study was closely followed and practiced before commencing any data collection.

After conducting two different literature reviews, there was a clear need for a well designed randomized clinical trial on the Damon system using a 3-dimensional imaging. The objective of the present study was to determine the skeletal and dental changes associated with the Damon and RME expansion in comprehensive orthodontic treatment.

There were 2 main objectives/questions for the study:

1) Compare the dental and skeletal changes obtained from the Damon and RME appliances using a 3-dimensional imaging
2) Evaluate dental and skeletal changes associated with the Damon and RME expansion over 6 months

Primary Research Question

Dental landmarks representing upper right and left first molars and first premolars showed the largest difference between treatment groups. Although patients in the Damon group wore full-time crossbite elastics to aid in maxillary expansion, lateral/transverse movement of maxillary first molars and premolars were statistically greater in the Hyrax group. The lateral movement of posterior teeth was also associated with buccal tipping of crowns. No clinically significant difference in the vertical or antero-posterior direction between two groups was noted. Landmarks representing skeletal structures did not show any clinically significant difference except the alveolar bone. The alveolar bone next to root apex of maxillary first premolar and molar showed clinically significant lateral movement in the Hyrax group only.

Seondary Research Question

Since there is no control group, the changes over 6 months cannot be distinguished between the growth of patients and treatment effect. Regardless of treatment group, on average, all landmarks showed downward displacement over 6 months of treatment time. This finding agrees with previous research that with maxillary expansion, anchoring maxillary teeth follow downward maxillary displacement, and therefore, displacing all landmarks in vertical direction. On the other hand, there was a large variation in the magnitude of vertical change between individuals. Since the study was based on adolescent patients, vertical change is most likely related to growth and not from the maxillary expansion.

Limitations

- In contrast to direct skull measurement, craniofacial analysis on CBCT images has some limitations. Smaller voxel size can increase the resolution of the image, but the patient will be exposed to a higher radiation. In our current study, the voxel size was 0.3 mm, which means that the alveolar bone has to be at least 0.6 mm thick to be discernable. Also, the partial volume average effect of CBCT decreases the accuracy of tooth volume reconstruction. If the voxel lies between two objects of different densities such as alveolar bone and tooth apex, the image will reflect the average density value. Therefore, the precise tooth apex identification can be more challenging.

  Furthermore, streak artifacts were present in some images due to high-attenuation objects (eg. metal composition of Damon brackets). Due to the effect of bright and dark streaks, the resolution of the image was degraded.
- The inclusion criteria for this study were adolescent patients from 11-16 years old. The amount of skeletal expansion with RME is known to be different in pre-

pubertal and post-pubertal patients.[14,15] Therefore, sub-analysis of the data based on pubertal stages of patients may be useful since the maxillary skeletal expansion is more predictable in younger patient.

- Some previous studies have shown that a long-term retention is required for the bony adaptation after tooth movement. The low-dose computed tomography (CT) taken immediately after active RME expansion showed a significantly lesser alveolar bone deposition compared to 6 months post-retention CT.[15] Several months in retention may be necessary for the recovery of alveolar bone in response to tooth movement. Therefore, a long-term post retention study is necessary to assess the possible bone formation after the treatment is completed.

Future Recommendations

- Post-treatment CBCT images are available for the majority of patient in this study. The next step is to collect and analyze these files to assess the stability of expansion post-treatment. Also, the investigator can assess possible alveolar bone formation next to maxillary premolar and molar teeth 1-2 years after initial expansion.
- CBCT imaging is a powerful tool that can provide clinicians with lots of information other than teeth location. Other uses for the collected CBCT files include assessment of the airway dimension, root resorption, condylar changes pre- and post- orthodontic treatment.
- Most currently available systematic reviews on CBCT indicated a lack of high quality studies on the accuracy and reliability of 3-dimensional landmarks.

Further study is needed to develop a systematic method to accurately identify dental and skeletal landmarks on CBCT.

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