Buccal Alveolar Bone Changes in Adult Non-extraction Clear Aligner Patients: A Retrospective CBCT Study

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Abstract

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Introduction: The aims of this retrospective study were to investigate maxillary and mandibular alveolar bone height and width changes associated with non-extraction Clear Aligner Therapy (CAT), and to identify risk factors associated with these changes.

Methods: This retrospective study recruited adult aligner patients, aged 18-45. Based on width changes at the 1st premolars and 1st molars, arches were divided into maxillary and mandibular expansion (≥ 3 mm width increase at the 1st premolars OR 1st molars) or control (< 1.5 mm width increase at the 1st premolars AND the 1st molars) groups. A total of 84 arches (44 maxilla, 40 mandible) met the criteria for these 4 groups. Buccal alveolar bone height (BH) and thickness at 3mm (BW-3) and 6mm (BW-6) from the cemento-enamel junction (CEJ) were measured and assessed for changes at the central incisors, first premolars, and mesio-buccal roots of the first molars using CBCTs. Descriptive analyses were performed, and multivariate linear regression was conducted to identify predictors for the observed changes in alveolar bone height and width.

Results: The maxillary and mandibular expansion groups exhibited the largest width changes at the first premolars, with mean values of 3.80 mm and 3.70 mm, respectively. Mean upper and lower central incisor labial movements and proclination were minimal (less than 1 mm and 3 degrees) in the expansion groups. The mean changes in the control groups were $\leq$ 0.6 mm of expansion at the first premolars and molars in both the upper and lower arches, and less than 1 mm and 1 degree of labial movement and proclination at the central incisors. There was a strong correlation between arch width changes and buccal tipping of posterior teeth. For buccal alveolar bone height and width changes in the maxillary arch, the only significant difference between the expansion and control groups was a small change in BW-6 at the maxillary first molars (-0.16 mm). The greatest mean changes observed in the lower arch were the reduction in bone height at the lower incisors (-1.5 mm) and lower first premolars (-1.4 mm) in the expanded patients. There was almost 1 mm greater reduction in bone height at the first premolars of the expansion group compared to control group. Regression models controlling for age, gender and treatment time found that belonging to the expansion group and undergoing labial movement were associated with lower incisor bone loss. For the lower premolars, the strongest predictors for bone loss were increased premolar width and buccal tipping.

Conclusion: The mean change in antero-posterior position and angulation of incisors in these mild to moderately crowded Class I adult patients treated with CAT was minimal. Posterior expansion was accomplished primarily by tipping, and the teeth exhibiting the most expansion were the first premolars. Tipping teeth labially or buccally was most strongly associated with alveolar bone loss in the lower arch.

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I. INTRODUCTION

Since the introduction of thermoplastic aligners approximately 20 years ago, the technique has gained popularity among orthodontists and their patients due to better esthetics, improvement in patients' experience and comfort level, and possibly shorter treatment time with proper case selection(Ke, et al., 2019). Align Technology has claimed that aligners may be indicated for around 90% of orthodontic patients, ranging from mild to moderate crowding, non-skeletal constricted arches, and individuals with relapse (Boyd & Vlaskalic, 2001). Typically, aligner cases are treated non-extraction, and crowding is managed mainly by expansion of the arches, with or without interproximal reduction (IPR) (Moya & Zafra, 2021). In non-growing patients, it is important to know if expansion with aligners results in any negative periodontal effects. While most systematic reviews concluded that there is a reduction of bone thickness and height in patients undergoing traditional orthodontic treatment techniques (Guo, et al., 2021; Sendyk, et al., 2019), there are limited studies that assess the periodontal effect of aligners. The objective of this study was to determine if expansion with aligners has a negative impact on bone levels in adult patients.

1. INTRODUCTION AND STATEMENT OF THE PROBLEM

In the late 1990s, clear aligners became available as an innovative orthodontic technique. It utilized the concepts of force application, engagement, anchorage, and biomechanics with a new concept, new materials, and a new treatment sequencing system. Aligner thermoplastic material moves teeth primarily with a pushing force, instead of the pulling force created by our traditional wires and brackets. Aligner materials and techniques have been continuously developed by Align Technology to optimize force delivery, improve tooth engagement, and expand the range of cases that can be successfully treated with clear aligners.

Even though the market has expressed positivity in clear aligners being used for all malocclusions, current protocols recommended the following case selection criteria for greater predictability (Moya & Zafra, 2021):

- Class I with minor or moderate crowding or spacing,
- Half-cusp Class II with minor crowding,

- Class III with minimal overbite/overjet non-extraction cases,
- Deep bite or open bite that can be treated by altering tooth positioning and inclination,
- Lower incisor extraction.

Despite the current limitations in case selection, it has been reported that over 17 million people have been treated with Invisalign Clear Aligners (Align Technology, 2024). Initially focused on resolving mild to moderate crowding cases, Align Technology has continuously introduced advancements to improve the effectiveness and efficiency of Clear Aligners. Research comparing treatment time in non-extraction patients found a 67% reduction in treatment duration in the Invisalign group with proper case selection (Buschang et al., 2014). Numerous studies have consistently proved clear aligner systems as a viable option for non-extraction orthodontic therapy in correction of mild to moderate malocclusion (AlMogbel, 2023; Shrivastava et al., 2023).

Current biomechanics to relieve arch length deficiency without extractions using Clear Aligner Therapy (CAT) include increasing the arch perimeter through a combination of buccal expansion and anterior tooth proclination/advancement, with or without interproximal reduction (IPR). A retrospective study on growing patients with Class I malocclusion treated with non-extraction therapy showed that crowding relief was achieved by generalized expansion, with 52% of the variance in crowding resolution attributed to an increase in arch perimeter (Weinberg & Sadowsky, 1996). While earlier studies focused on traditional arch-wire expansion, recent evidence on Invisalign treatment for non-growing patients showed that aligners are only effective in producing mild arch width expansion, with predictability ranging from 60% to 80% of planned movements and being most effective at premolar areas (Bouchant et al., 2023; Lione et al., 2021; Ma & Wang, 2023; Morales-Burruezo et al., 2020). Boyd, et al. also reported that Invisalign can achieve buccal expansion in the range of 2-4 mm (Boyd & Vlaskalic, 2001).

A significant concern with orthodontic therapy in adults is the high existing prevalence of alveolar bone defects in patients with malocclusions, and the potential for worsening with substantial buccal expansion. Dehiscence, fenestration, loss of bony housing, and abnormal tooth positioning are recognized as anatomical risk factors for recession (Kassab & Cohen, 2003). The occurrence of dehiscence and fenestration during orthodontic treatment depends on direction of tooth movement, level of orthodontics forces, as well as the volume and anatomic integrity of periodontal supporting structures (Wehrbein, et al., 1996). According to a CBCT study investigating changes in alveolar bone post-orthodontic treatment, individuals over 30 years old exhibited notably greater dehiscence depth with increased vertical bone loss (Jäger, et al., 2017). Any newly developed orthodontic treatment modality, like CAT, requires understanding of the periodontal complex's response to prevent long-term periodontal health complications (Jepsen et al., 2023).

Since tooth movement relies on bone resorption and remodeling induced by orthodontic forces, expanding the dentition through CAT may create or exacerbate bony defects. A retrospective study by Hellak, et al. concluded that treatment for adult crowding with Clear Aligners and IPR have a positive effect on the interradicular bone volume with a slight increase in bone quantity (0.12 ± 0.73mm) (Hellak, et al., 2018). However, an earlier study conducted by the same group looking at changes in bone volume relative to non-extraction treatment with aligners found bony reduction in vertical and sagittal dimensions. Significant decreases in mean bone thickness were observed in the lower anterior teeth (-0.17 to -0.42 mm), while significant reductions in mean buccal bone height were evident in both maxilla and mandible (-0.24 mm and -2.42 mm, respectively). The authors concluded that reduction in bone height with labial tooth movement was greater than the change in bone thickness. Nevertheless, since 93% of the patients included in the study were women, and no specification regarding the types of malocclusions apart from anterior crowding were included in selection criteria, interpretation of their results is limited (Hellak, et al., 2016). Given the study's focus on the anterior regions, the conclusions lack insight into posterior bone response, especially since posterior expansion is one of the primary methods to alleviate crowding.

Assessment of bone thickness and height with high accuracy was made possible with the advent of cone-beam computed tomography (CBCT), which allows visualization and measurement using 3-dimensional imaging. Mandelaris, et al. suggested that CBCT imaging can help determine risk assessment through periodontal diagnostics with orthodontic treatment, thus aiding development of preventative or interceptive periodontal augmentation therapies (Mandelaris, et al., 2017). By comparing direct and CBCT measurements of buccal bone height and thickness in cadavers, Timock, et al. concluded that both dimensions can be measured accurately using CBCT.

He reported mean absolute differences of 0.30 mm and 0.18 mm, respectively, and no pattern of under- or over-estimation. (Timock, et al., 2011). A more current systematic review and analysis on accuracy of CBCT in quantifying alveolar bone dimensions concluded that there is no significant difference between this 3D imaging modality and direct measurement. Mean differences between CBCT measurements and the gold standard references for bone height and bone thickness were reported at 0.03 mm and 0.11 mm, respectively (Li, et al., 2019). These small differences would seem to justify the use of CBCT to assess small alveolar bone changes after orthodontic treatment.

The purpose of this retrospective study was to investigate buccal alveolar bone changes in adult Class I patients treated with Clear Aligner Therapy. Pre- and post- treatment CBCT scans were used to measure both bone height and thickness, and regression models were created to identify predictors for bone loss.

2. AIMS

Aim #1: Investigate how buccal alveolar bone height and thickness change in adults treated with non-extraction Clear Aligner Therapy (CAT).

Aim #2: Identify risk factors for bone loss by evaluating the association between alveolar bone and treatment-related parameters (changes in inter-arch widths, protraction distance of incisors, changes in bucco-lingual or facial-lingual inclination, and treatment time), as well as initial patient factors (gender, age, initial crowding).

II. METHODS

This retrospective study received UW IRB approval (#00015968) and collected data from participating orthodontic clinics in the greater Seattle, WA area, as well as from Japan. Adult Class I patients who had pre- and post-treatment CBCTs were identified for inclusion. Final inclusion into the expansion and non-expansion groups was based on transverse measurements at the premolars/molars on the axial slices of the CBCTs. To qualify as an expansion arch, the requirement was $\geq$ 3 mm of total expansion at the 1st premolars OR the first molars. To qualify as a non-expansion (control) arch, the requirement was < 1.5 mm total expansion at the 1st premolars

AND 1st molars. Patient-related data (age, gender, total treatment time), as well as pre- (T0) and post-treatment (T1) CBCT scans were obtained from patients' electronic records.

T0 and T1 CBCT scans were deidentified, randomized and imported into InVivoDental software (Anatomage, San Jose, CA, USA) for analysis and data abstraction. For each arch, the teeth on one side of the arch were randomly chosen for measurement. Buccal alveolar bone height (BH) and thickness (BW-3 and BW-6) in both the expansion and control groups were measured at the maxillary and mandibular central incisors (I), first premolars (PM) and the mesio-buccal root of the first molars (M). The CBCTs were also used to measure changes in buccal-lingual inclination (ΔINCL), incisal protraction distance (IPD), and changes in inter-arch width at the premolars and molars (ΔW). Multivariate models were used to identify potential risk factors using initial clinical characteristics and the above-mentioned treatment-related parameters.

1. SAMPLE

a. SAMPLE

INITIAL SCREENING

Patients were selected based on the following initial criteria, with final inclusion based on CBCT verification of posterior expansion:

(1) Class I molar relationship with crowding,

(2) Full permanent dentition anterior to the first molars,

(3) 18-45 years old,

(4) Were treated exclusively with non-extraction CAT,

(5) Treatment duration of at least 6 months, and

(6) Pre- (T0) and post-treatment (T1) CBCT scans taken within 6 months of starting or completing treatment, with voxel size of $\leq$ 0.4 mm.

Any patients with craniofacial anomalies, history of periodontal disease, history of metabolic bone disease (i.e., Paget's, osteoporosis, osteomalacia, rickets, renal osteodystrophy, et.), surgical treatment, supplemental arch expansion with expanders, and incomplete records were excluded.

Regarding CBCT voxel size and its impact on visualizing alveolar bone, Patcas et al. evaluated bone height and thickness in lower anterior teeth in cadavers and found that 0.4 mm voxel size produced results as accurate as 0.125 mm voxel size (Patcas et al., 2012). Torres and coauthors also found no differences in linear bone measurements in human dry mandibles between images taken at voxel sizes of 0.2, 0.3 and 0.4 mm (Torres et al., 2012). Therefore, a voxel size of 0.4 mm or less was an inclusion criterion.

FINAL SCREENING

Final inclusion into the upper and lower expansion and control groups was established by these criteria:

- Expansion – At least 3 mm of expansion at either 1st premolars or 1st molars, measured at the buccal cusp tips, or
- Non-expansion (Control) – less than 1.5 mm of expansion at both the 1st premolars and 1st molars, also measured at the buccal cusp tips.

Measurements for final criteria were done by 2 examiners (K.N. and V.V.). In the case of conflicts, a third examiner (P.L.) was recruited, and final determination was based on the consensus of all three.

Other information obtained from the providers for each case included:

- Age,
- Gender,
- Treatment time,
- CBCT imaging specifications (type of machine, mA, kV, voxel size, and exposure time).

b. SAMPLE SIZE CALCULATION

Prior systematic reviews on facial alveolar bone thickness report a mean thickness about 1 mm in maxillary incisors and canines and 0.5 mm in mandibular anterior teeth at 5 mm from the bone crest (Morad, et al., 2014). Other studies also showed an increase in thickness moving posteriorly in the arch (Rojo-Sanchis, et al., 2021). As reduced bone thickness increases the risk of gingival recession, a 0.5 mm of mean difference in alveolar bone thickness from T0 to T1 was considered clinically meaningful. In addition, a 1 mm reduction in alveolar bone height was considered clinically significant for our research.

According to Morais, et al., the average change (SD) in bone thicknesses at 3 mm from the CEJ was -0.2 (SD=0.3), which corresponds to an effect size of 0.67 standard deviations, and for bone thickness at 6 mm the average change was -0.1 (SD=0.4), which corresponds to an effect size of 0.25 standard deviations. The average change in bone height (mm) was 0.4 (SD=0.5), which corresponds to an effect size of 0.8 (Morais et al., 2018). Study power was based on achieving 80% power to detect an effect size of 2/3, resulting in sample sizes of 20 expansion patients and 20 control patients, using a two-sided paired t-test with 0.05 significance level (Table 1).

Table 1. Power to demonstrate a change in bone thickness and height based on 15 to 40 treated patients based on a paired t-test at a two-sided 0.05 significance level.

Change in bone thickness or height	Number of patients in each group					
Effect size*	15	20	25	30	35	40
1/2	44%	56%	66%	75%	81%	86%
2/3	67%	80%	89%	94%	96%	98%
3/4	77%	89%	95%	97%	99%	99%
1	94%	98%	99%	99%	99%	99%

*Effect size in standard deviation units (average change / standard deviation of the changes).

2. APPARATUS AND PROCEDURES

a. APPARATUS AND PROCEDURES

Records were obtained for each patient that met initial inclusion criteria. Data were de-identified and assigned study ID numbers prior to measurements for final inclusion screening. Final inclusion in the expansion and non-expansion groups was based on CBCT measurements assessing arch width changes at first premolars and molars (ΔW) between T0 and T1 scans.

After qualified arches were placed into their respective groups, T0 and T1 scans from each qualified subject were randomly divided into Folder #1 and Folder #2 prior to alveolar bone measurements for Aim #1. Thus, examiners were blinded to both group and time point. As bone height (BH) and widths (BW-3, BW-6) measurements were collected with reference to CEJ, the CEJ to cusp tip distances from the slice of each measured tooth (CEJ-CT) from Folder #1 were transferred to the respective Folder #2 slices. It was assumed that cusp tips had minimal changes during treatment, as teeth were covered with aligners the majority of the time. Assessment of this method on 5 pairs of scans confirmed reliable location of CEJs among the 2 scans.

All Aim #1 measurements were performed in a blinded and random manner. Measurements were done by 2 examiners (K.N. and V.V.). Training and calibration for CBCT scan processing and data abstraction were conducted by a board-certified Oral and Maxillofacial radiologist from the University of Washington School of Dentistry (P.L.).

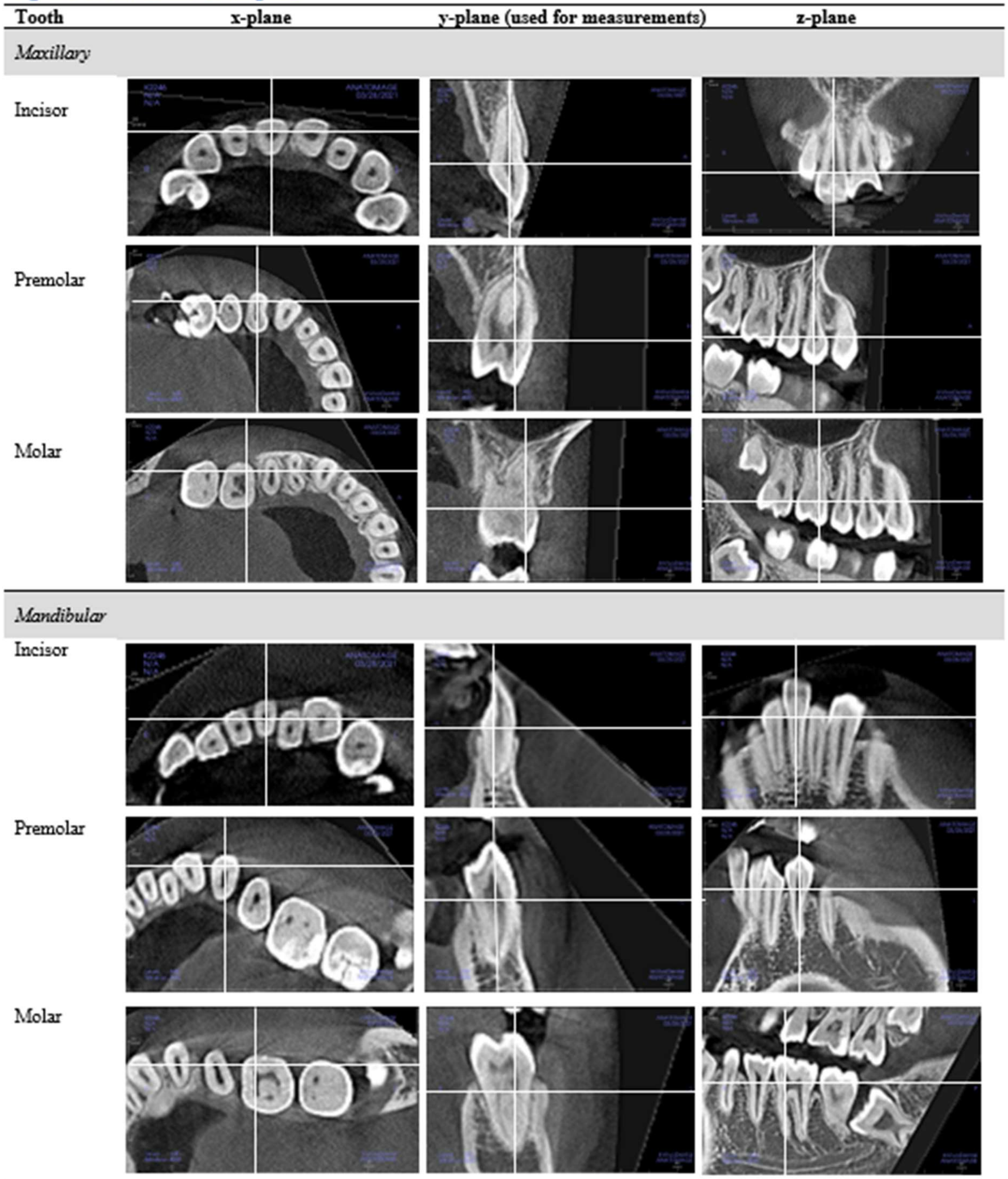
Prior to collecting Aim #2's treatment-related parameters, skeletal orientation was performed, and T0 and T1 scans were superimposed based on the best fit for the maxilla and the mandible. Tooth inclination (ΔINCL) to skeletal horizontal planes and incisal protraction distance (IPD) were obtained directly from superimposed volumetric-rendered 3D images. The initial crowding amount (Cr-T0) for each arch was assessed separately by 2 board certified orthodontists (GH, DJ) for arch length deficiency (in millimeters) using volume-rendered 2D images (captured parallel to the occlusal plane) of whole arch from scans. The values were averaged, unless the difference in measurements was larger than 2 mm, in which the raters met and arrived at a crowding value by consensus.

3D IMAGE PROCESSING AND ORIENTATION

DICOM file format from CBCT scans were imported into InVivo Dental software (Anatomage, San Jose, CA, USA). To measure buccal bone height and thickness, each tooth was divided mesial-distally by the following reference points:

- Central Incisors: root apex and midpoint of the incisal edge,
- First premolars: root apex (1-rooted) or buccal root apex (2-rooted) and buccal cusp tip,
- First molars: mesio-buccal root apex and mesio-buccal cusp tip.

Figure 1: Tooth orientation in all planes



Tooth orientation (Figure 1) (utilizing the long axis of each tooth): note that the tooth of interest is the object for orientation. The middle panel (y-plane) illustrates the slices that were used for bone height and width measurement:

- x-plane: perpendicular to the longitudinal axis of the tooth at the level of CEJ (at tooth's buccal surface) – *Dividing the tooth into coronal and apical portions,*
- y-plane: bisecting the tooth's long axis at (a) the mid-plane of the incisor CEJ or (b) the tangent line to the tooth's mesial contour at premolars/molars' CEJ level – *Dividing tooth into mesial and distal portions.*
- z-plane: Parallel to the tooth's longitudinal axis - *Dividing tooth into buccal and lingual portions.*

Skeletal reference planes were set separately for Maxillary and Mandibular arches using the protocols below. These orientation methods established horizontal planes of the scans to evaluate changes in tooth inclination and incisor protraction distance.

Maxillary orientation (Figure 2,4) (Eksriwong & Thongudomporn, 2021; Lin, et al., 2015)

- x-plane (axial section): parallel to palatal plane identified in the sagittal plane at the level of anterior nasal spine (ANS) and posterior nasal spine (PNS) – *Visualizing the patient as upper and lower portions.*
- y-plane (sagittal section): bisecting palate at level of ANS and PNS identified in the axial plane – *Visualizing the patient as left and right portions.*
- z-plane (coronal section): tangent to the nasal floor at its most inferior level as seen in the coronal plane – *Visualizing the patient as front and back portions.*

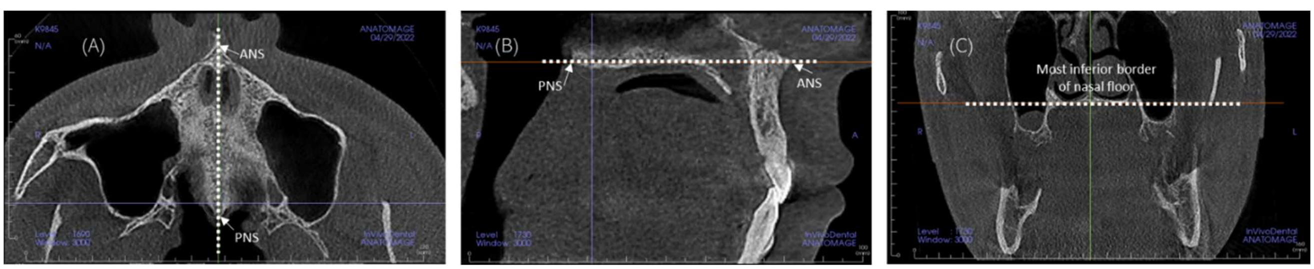


Figure 2: Maxillary orientation, using patient as the object for definition of planes: (A) Axial, (B) Sagittal slice, (C) Coronal slice.

*Mandibular orientation (Figure 3,4) M*andibular orientation used landmarks from the inferior border of the mandible, since scans obtained at different time points had different mandibular positionings relative to maxilla):

- x-plane (axial section): parallel to the mandibular plane at the level of Menton (Me) and the line connecting the left and right Gonion (Go-R and Go-L), identified in the sagittal plane - *Visualizing the patient as upper and lower portions.*

- y-plane (sagittal section): bisecting the mandibular plane at the level of Me and midpoint of the line connecting Go-R and Go-L identified in the coronal plane - *Visualizing the patient as left and right portions.*
- z-plane (coronal section): parallel to the line connecting Go-R and Go-L - *Visualizing the patient as front and back portions.*

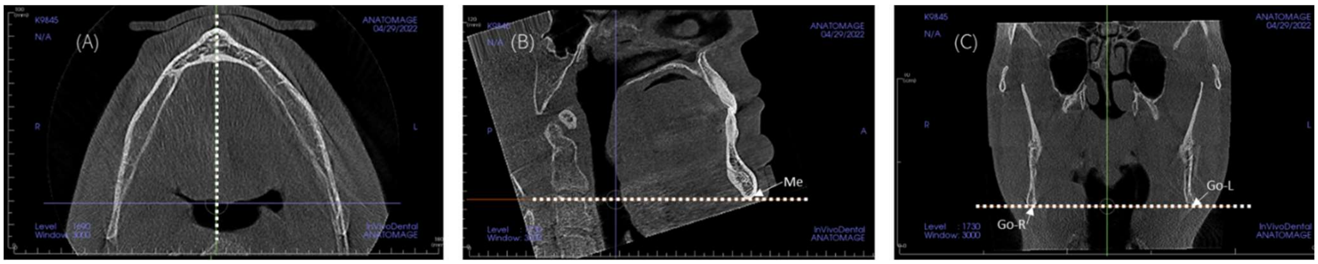


Figure 3: Mandibular orientation, using patient as the object for definition of planes: (A) Axial, (B) Sagittal slice, (C) Coronal slice.

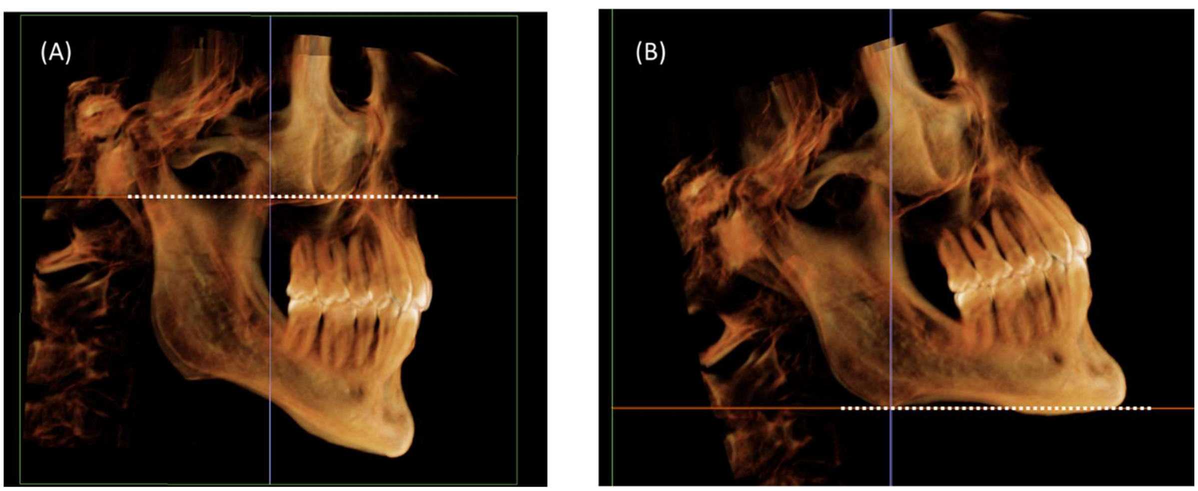


Figure 4: Demonstration of skeletal orientation of (A) Maxillary and (B) Mandibular jaws on 3D-rendering images

DATA ABSTRACTION

a) Locating CEJ and alveolar bone measurements (CEJ-CT, BH, BW-3 and BW-6)

T0 and T1 scans were randomly assigned to either Folder #1 or #2. Sagittal slices using our tooth orientation protocol from CBCT scans in Folder #1 were assessed for the following variables. Measurements were made perpendicular or parallel to the longitudinal axis of the tooth (Figure 5).

- BW-3 and BW-6: buccal bone thickness at 3 and 6 mm from CEJ,
- BH: buccal bone height (distance from the alveolar bone to the CEJ at mid-facial aspect of the respective teeth), and

- CEJ-CT: Distance of CEJ from the midpoint of incisal edge or (mesio)-buccal cusp tip of first premolars/first molars.

CEJ-CT measurements were then transferred to the other deidentified respective scan of each sample in Folder #2. Examiners used these measurements to locate CEJ of the same subject on the other scan that was obtained at different timepoint, where they collected BH, BW-3 and BW-6 measurements using the above definition.

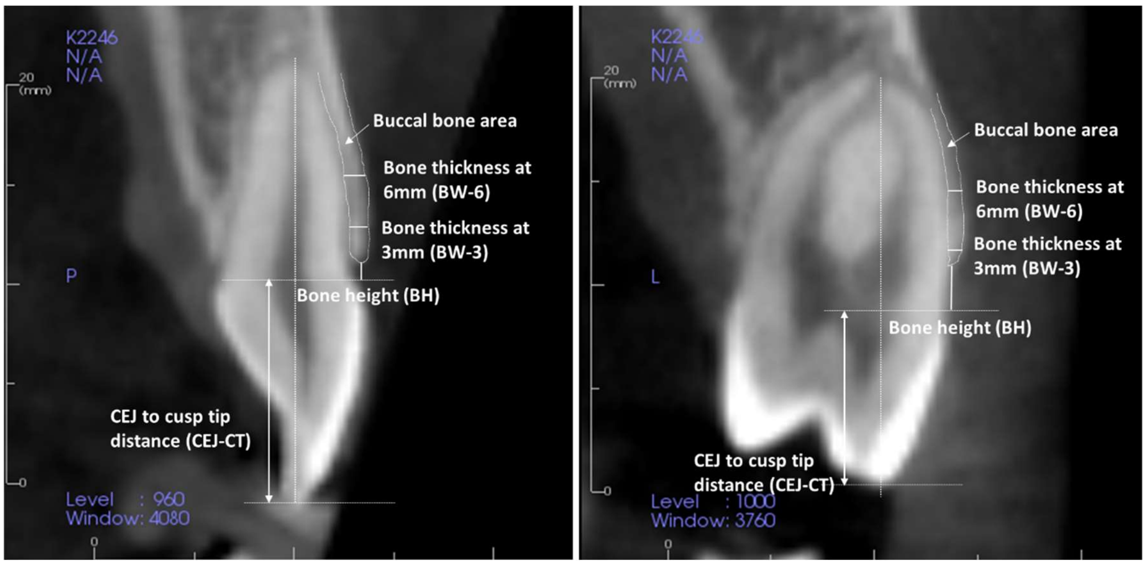


Figure 5: Alveolar bone measurements of each tooth using buccal-lingual cross-sectional images.

b) Inter-dental parameters (inter-premolar width W-PMs and inter-molar width W-Ms)

Inter-dental parameters were measured from cusp tip to cusp tip at the first premolars and first molars in the coronal plane, after verifying axial positioning on de-identified and

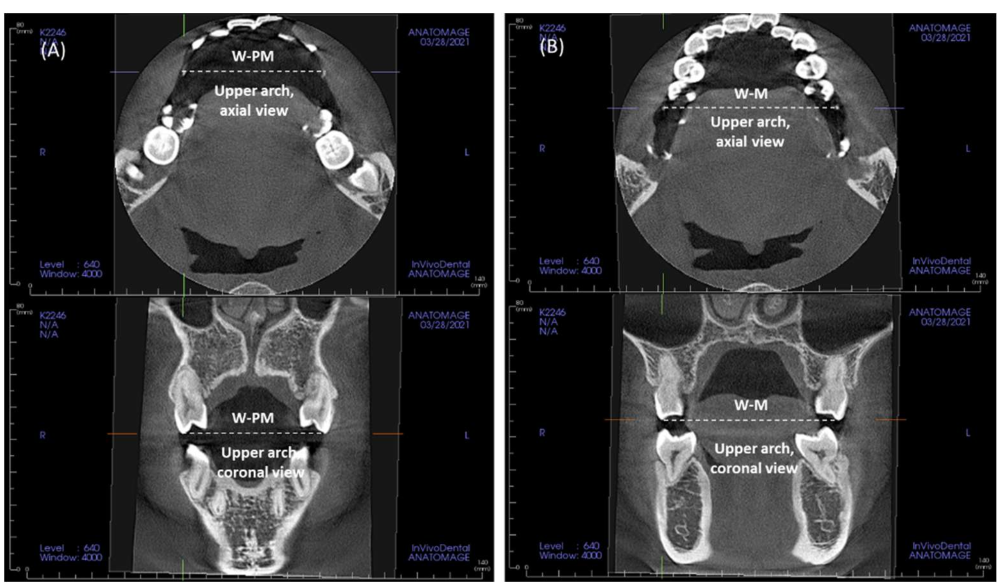


Figure 6: Inter-premolar and inter-molar width measurements using CBCT slices; (A) Axial (top) and Coronal (bottom) views of upper arch at inter-premolar width, (B) Axial and Coronal views of upper arch at inter-molar width.

randomized T0 and T1 scans. Changes (T1-T0) obtained were used for final screening and sample assignments to groups, and to study predictive models (Figure 6).

c) *Incisal protraction distance (IPD)*

Regional superimposition was done to ensure consistency in establishing the horizontal plane for IPD and tooth inclination (INCL) measurements. All T0 scans were reoriented prior to superimposition to establish a consistent horizontal plane (palatal plane for maxillae, and mandibular inferior border for mandibles. IPD was measured as horizontal displacement of the incisal edge, with positive values representing protraction, and negative as retraction using the superimposed sagittal plane bisecting the measured incisor at the midpoint of the incisal edge. (Figure 6)

d) *Tooth inclination (INCL)*

Tooth inclination was measured as the angle formed between the horizontal line (H-line) and the longitudinal axis of the tooth connecting cusp tip to apex. H-line was defined separately for anterior vs posterior, and for upper vs lower arches. (Figure 7)

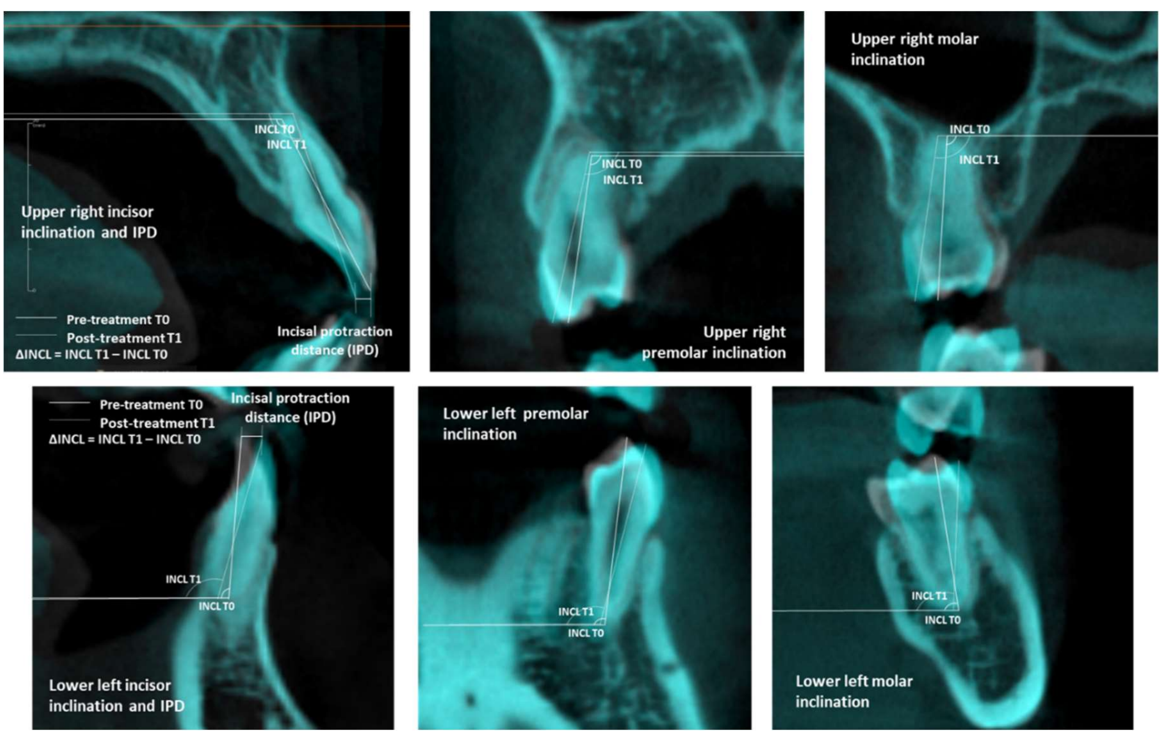


Figure 7: Tooth inclination and Incisal Protraction Distance measurements using superimposed cross-sectional images.

Maxillary H-line for:

- Incisors: parallel to palatal plane established by ANS-PNS
- Premolars/Molars: parallel to the line tangent to the nasal floor at its most inferior level

Mandibular H-line for:

- Incisors: parallel to mandibular inferior border established by Go-R/Go-L and Me,
- Premolars/Molars: parallel to line connecting Go-R and Go-L.

e) Initial crowding amount (Cr-T0)

Volume-rendered 2D images of qualified arches at T0 were captured parallel to the occlusal plane. 2 orthodontists (G.H., D.J.) separately assessed the amount of arch length deficiencies (in millimeters) using the images. Obtained values were averaged. Any differences in arch length assessments larger than 2 mm were discussed to arrive at a consensus value. (Figure 8)

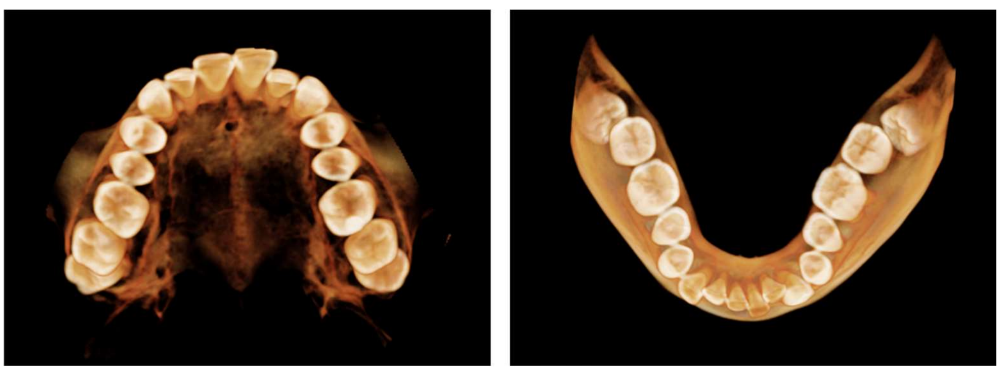


Figure 8: Volumetric rendered 2D images of maxillary and mandibular arches

Lastly, patient and treatment characteristics were obtained from chart notes. Treatment time was calculated (in months) using dates on T0 and T1 CBCT scans to allow consistent computation. Offices were contacted to verify treatment times as needed.

A summary table of variables that were abstracted from CBCT scans, together with their descriptions and abbreviations, are below:

Table 2: Descriptions of variables abstracted from CBCT scans

Measurement	Abbreviation	Description
Buccal bone thickness-3mm	BW-3-tooth	Measured from cross-section image at 3mm from cementoenamel junction (CEJ) – Sagittal view
Buccal bone thickness-6mm	BW-6-tooth	Measured from cross-section image at 6mm from CEJ – Sagittal view
Buccal bone height	BH-tooth	Measured from CEJ to the buccal alveolar bone crest. Measurements registered as negative values. – Sagittal view
CEJ-cusp tip distance	CEJ-CT	Distance from CEJ to mid-point of incisal edge or (mesio)-buccal cusp tip of first premolar/molar. – Sagittal view
Inter-premolar or Inter-molar width	W-PMs or W-Ms	Distance between first premolar buccal or first molar mesio-buccal cusp tips – Coronal view
Incisal protraction distance	IPD	Horizontal displacement of the incisal edge ((+) protraction, (-) retraction) using superimposed sagittal plane bisecting the measured incisor at midpoint of incisal edge – Sagittal view
Tooth inclination	INCL	The angle formed between the horizontal line (H-line) and the longitudinal axis of the tooth connecting cusp tip to apex. – Sagittal (anterior) or coronal (posterior) views
Initial crowding	Cr-T0	Estimated amount of arch length deficiency (in millimeters) using volumetric-rendered occlusal-view 2D images of qualified arches
Tooth	I	Central incisors
	PM	First premolars
	M	Mesiobuccal root of first molars

Δ, Change (T1-T0); T0, pre-treatment; T1, post-treatment.

b. DATA ANALYSIS

10 randomly selected arches (4 expansion and 6 control) were measured by both examiners (K.N, V.V), and then remeasured at least 4 weeks later. To determine intra- and inter-examiner reliability of the measurements, the mean and standard deviation (SD) were computed for each set of measurements. Then the mean differences, the intraclass correlation coefficient (ICC), and Dahlberg's error (Kim, 2013) were calculated.

Descriptive analyses were performed for all measured variables. With normally distributed data, differences between T0 and T1 variables were evaluated with paired t-tests, while independent-samples t-tests were conducted to assess differences between groups. 95% confidence intervals for the average change between T0 and T1 and the difference between groups were computed. Univariate/multivariable linear regression analyses were used to assess the association between changes in alveolar bone and the influence of patient's initial presentation and treatment-related parameters on alveolar bone. Prior to running regression analysis, correlation was assessed using Spearman rank correlation to identify relationships between factors. The level of statistical significance of all tests was set at $P<0.05$. R statistical software was used for the statistical analysis (R Core Team, 2020).

Statistical analyses were completed by a project statistician (L.M.) from the Department of Oral Health Sciences.

IV. RESULTS

INTER-RATER AND INTRA-RATER RELIABILITY

Inter-rater reliabilities for different alveolar bone parameters were excellent with ICC of at least 0.94 (95% CI). Examiner 1 also showed excellent intra-reliability with ICC ranging from 0.89-0.97; while Examiner 2 demonstrated good to excellent ICC values at 0.78-0.93. Largest average Dahlberg's errors were at 0.3 mm for bone height, and 0.2 mm for bone widths. The period

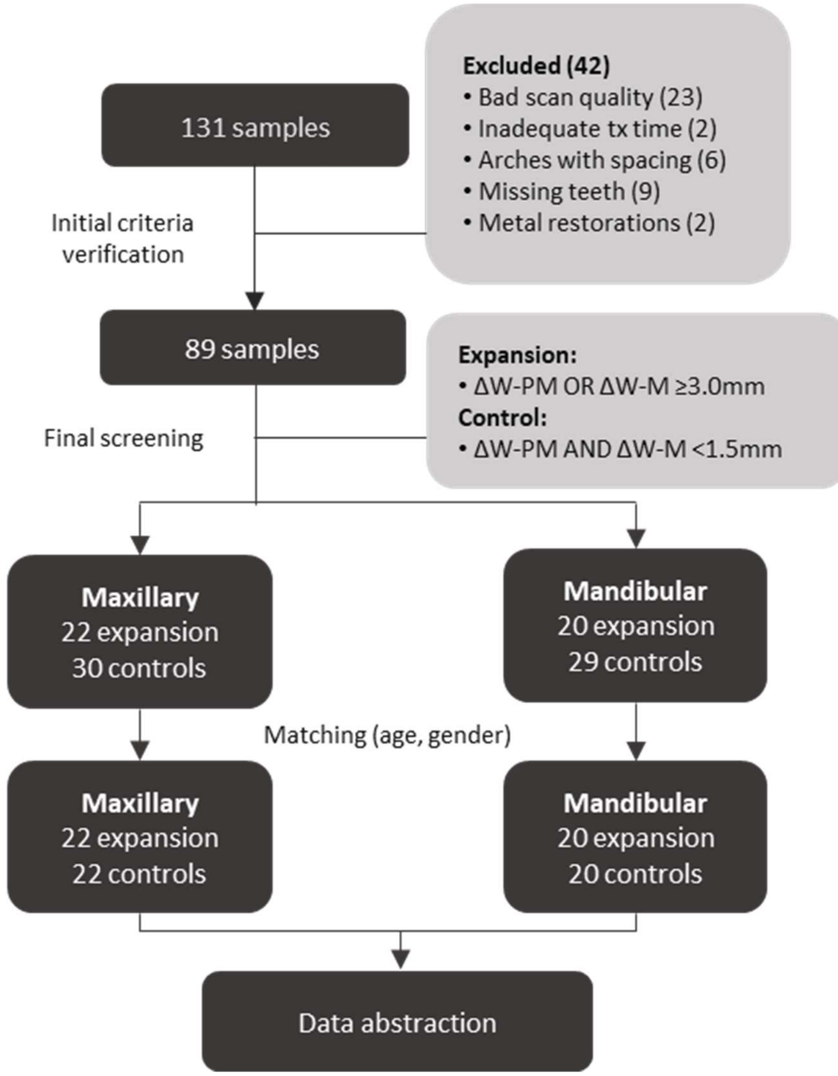
Table 3: Inter- and Intra-examiner reliability

Measure	ICC (95% CI)	Dahlberg's Error (Min, Max)
Inter-examiner reliability		
Bone height	0.99 (0.99, 1.00)	0.1 3% (0.0, 0.4)
Bone width at 3mm	0.97 (0.91, 0.99)	0.1 12% (0.0, 0.3)
Bone width at 6mm	0.94 (0.88, 0.97)	0.1 13% (0.0, 0.4)
Intra-examiner reliability for Examiner 1		
Bone height	1.00 (1.00, 1.00)	0.1 3% (0.0, 0.3)
Bone width at 3mm	0.89 (0.79, 0.96)	0.1 15% (0.0, 0.4)
Bone width at 6mm	0.97 (0.93, 0.99)	0.1 7% (0.0, 0.3)
Intra-examiner reliability for Examiner 2		
Bone height	0.90 (0.80, 0.95)	0.3 10% (0.0, 0.8)
Bone width at 3mm	0.93 (0.87, 0.97)	0.1 18% (0.0, 0.4)
Bone width at 6mm	0.78 (0.58, 0.89)	0.2 25% (0.0, 0.5)

between re-measurements was between 5 – 10 weeks. Examiner 1 collected 66% of data from maxillary arches and 100% data from mandibular arches. (Table 3)

SAMPLE

Figure 9: Flow chart of sample selection results



Scans from 131 subjects treated with CAT between 2019-2023 were assessed for inclusion. Subjects were obtained from 3 main sources: a corporate practice in Seattle (*Corp*, 88 subjects), a local private practice in the greater Seattle area (*PrvPrc*, 22 samples), and private practices from Japan (*Jpn*, 21 samples). 42 subjects were excluded due to treatment time < 6 months, poor scan quality, multiple metal restorations that prevented visualization of bone, missing teeth, and those with spaced arches, which resulted in 89 qualifying subjects. (Figure 9).

Among 89 subjects, 22 maxillary and 20 mandibular arches qualified for inclusion in the expansion group, whereas 30 maxillary and 29 mandibular arches met the requirements for the control group. Because more control arches were qualified, control arches were matched to the expansion arches in a one-to-one ratio based on gender and age.

Demographic and treatment characteristics of expansion and control groups

A descriptive summary of qualified expansion subjects and matched controls is provided in Table 4. Mean ages were between 30.2 to 31.8 year, with relatively equal number of male and female patients. However, other initial characteristics, including treating offices, initial crowding and treatment time were significantly different. The initial amount of crowding was significantly larger in expansion than control groups (2.9 mm versus 1.0 mm in maxilla, respectively, and 4.0 mm versus 1.7 mm in the mandible, respectively). Assessors for initial crowding agreed within 2 mm for 100% of the arches, and their mean values were used in analyses. Expansion subjects had a significantly longer treatment time, at 16.5 months (versus 11.7 months) for the maxillary arches, and 16.6 months (compared to 12.0 months) for the mandibular arches (Table 4). Additionally, based on collected data about CBCT scan specifications, 64% of T0 and T1 scans (58% of expansion and 71% of control) were taken using the same settings. The typical change in settings was a 50% reduction in exposure time from T0 to T1, while keeping the same mA and kV, and did not appear to impact image quality significantly.

Table 4: Comparison of initial characteristics between expansion and control groups

Characteristics	Maxillary			Mandibular		
	Expansion, n=22	*Control, n=22*	*p-value*[1]	*Expansion, n=20*	*Control, n=20*	*p-value*[1]
Age (years)			0.66			0.50
Mean (SD)	31.0 (6.7)	31.8 (5.1)		30.2 (7.4)	31.6 (5.4)	
Range	18.3, 44.8	22.2, 39.3		18.3, 44.8	22.2, 39.8	
Sex, n (%)			>0.99			>0.99
Female	11 (50)	11 (50)		11 (55)	11 (55)	
Office, n (%)			<0.001*			<0.001*
Corp	2 (9.1)	20 (91)		2 (10)	16 (80)	
PvtPrc	12 (55)	2 (9.1)		11 (55)	3 (15)	
Jpn	8 (36)	0 (0)		7 (35)	1 (5.0)	
Initial crowding (mm)			<0.001*			<0.001*
Mean (SD)	2.9 (1.6)	1.0 (1.1)		4.0 (0.9)	1.7 (1.0)	
Range	0.0,7.0	0.0, 4.0		2.5, 6.5	0.0, 4.5	
Tx time (months)			0.003*			0.010*
Mean (SD)	16.5 (5.8)	11.7 (4.4)		16.6 (5.5)	12.0 (5.0)	
Range	7.0, 28.0	6.0, 19.0		7.0, 28.0	6.0, 21.0	

[1]Welch Two Sample t-test; Pearson's Chi-squared test; Fisher's exact test,

*Statistically significant at P<0.05,

SD, standard deviation; mm, millimeters.

Dental changes after CAT

In the expansion group, the premolars and molars exhibited significantly greater expansion and buccal tipping compared to the control groups. However, the mean upper and lower incisor changes in protraction and inclination were small and not significantly different between the expansion and control groups (Table 5). Examples of typical changes in expanded upper and lower arches after CAT can be seen in Figure 10.

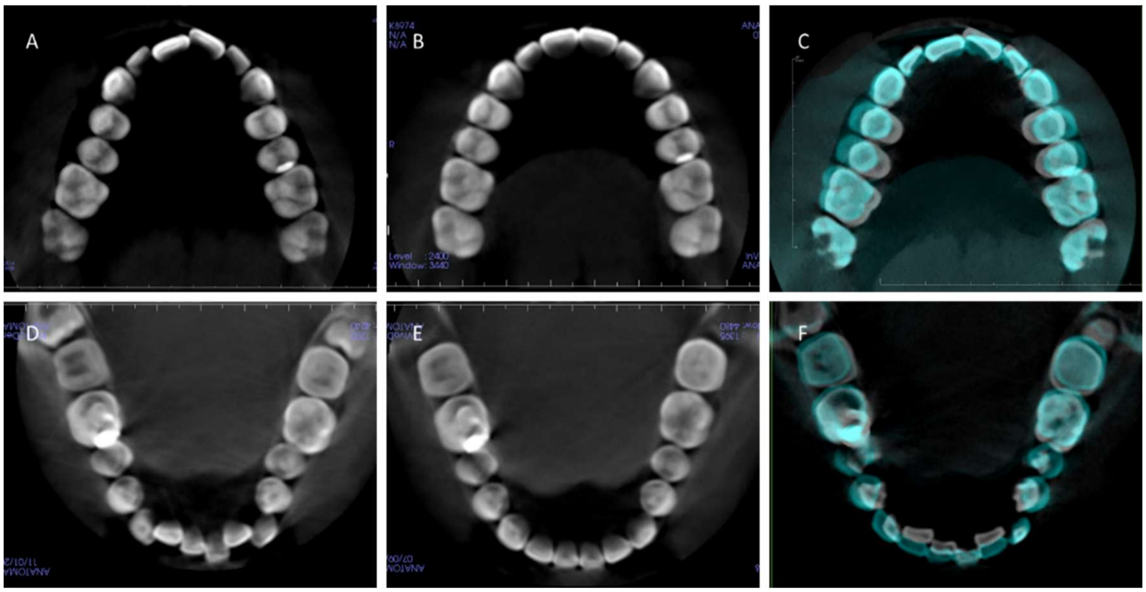


Figure 10: Examples of expanded upper and lower arches after CAT generated from CBCT scans. (A, D) T0 arch, (B, E) T1 arch, (C, F) skeletally superimposed arches that demonstrated changes after treatment (White: T0, Blue: T1).

Table 5: Comparison of dental changes after CAT treatment between expansion and control groups

Treatment-related parameters	**Maxillary (T1-T0),** Mean (SD)			**Mandibular (T1-T0),** Mean (SD)		
	Expansion, n=22	*Control, n=22*	*p-value*[1]	*Expansion, n=20*	*Control, n=20*	*p-value*[1]
Central Incisors						
IPD (mm)	-0.2 (1.4)	-0.1 (0.7)	0.62	0.6 (1.3)	0.2 (0.7)	0.32
ΔINCL (deg)	-0.6 (6.4)	-0.4 (6.4)	0.87	2.9 (6.5)	0.9 (2.8)	0.23
1st Premolars						
ΔW-PM (mm)	3.8 (1.1)	0.6 (0.50)	<0.001*	3.7 (1.1)	0.6 (0.5)	<0.001*
ΔINCL (deg)	8.7 (3.6)	1.3 (1.2)	<0.001*	6.8 (2.5)	0.9 (1.1)	<0.001*
1st Molars						
ΔW-M (mm)	2.4 (1.3)	0.5 (0.4)	<0.001*	2.6 (1.7)	0.6 (0.4)	<0.001*
ΔINCL (deg)	4.6 (2.7)	0.7 (0.8)	<0.001*	4.0 (2.7)	1.0 (1.0)	<0.001*

[1]Welch Two Sample t-test,

*Statistically significant at P<0.05.

CHANGES IN ALVEOLAR BONE

In expanded maxillary arches, no significant changes in incisors' alveolar bone were detected after treatment. At premolars, the expansion group demonstrated significant reduction in BH (-0.41 mm, p<0.001) and BW3 (-0.19 mm, p=0.023). At the molars, bone height changes almost reached a level of significance (-0.70 mm, p=0.056), whereas reduction in bone widths were small but significant (BW-3: -0.24 mm, p=0.017; BW-6: -0.20 mm, p=0.003). On the other hand, changes in the control group were only significant at the premolar bone height, with a mean reduction of 0.20 mm (p=0.034). (Table 6)

Comparing differences between the maxillary expansion and control group, only a small difference in BW-6 at molars (-0.16 mm, p=0.035) was statistically significant. The largest mean difference between the groups was the change in molar BH, at -0.54 mm. However, this value did not reach statistical significance (p=0.15). (Table 6)

Table 6: Changes in alveolar bone in Maxillary arches (in mm)

Variables	Expansion			Control			Expansion vs control	
	T0	*T1-T0 (95% CI)*[13]	*p-value*[1]	*T0*	*T1-T0 (95% CI)*[13]	*p-value*[1]	*Difference (95%CI)*[23]	*p-value*[2]
Central incisors								
BH	-1.92 (0.63)	-0.09 (-0.23, 0.05)	0.20	-2.21 (0.59)	-0.05 (-0.22, 0.11)	0.50	-0.04 (-0.24, 0.17)	0.73
BW-3	0.70 (0.39)	-0.04 (-0.17, 0.09)	0.54	0.61 (0.27)	-0.04 (-0.18, 0.10)	0.55	0.00 (-0.18, 0.19)	0.98
BW-6	0.68 (0.31)	-0.02 (-0.16, 0.12)	0.79	0.66 (0.26)	0.00 (-0.11 to 0.11)	0.97	-0.02 (-0.19, 0.16)	0.85
1st premolars								
BH	-2.53 (0.83)	**-0.41** (-0.62, -0.20)	**<0.001***	-2.45 (0.71)	**-0.20** (-0.39, -0.02)	**0.034***	-0.21 (-0.48, -0.06)	0.12
BW-3	0.61 (0.55)	**-0.19** (-0.36, -0.03)	**0.023***	0.73 (0.46)	-0.10 (-0.23, 0.03)	0.11	-0.09 (-0.29, 0.11)	0.36
BW-6	0.73 (0.50)	-0.05 (-0.17, 0.07)	0.38	1.03 (0.82)	-0.04 (-0.22, 0.14)	0.65	-0.01 (-0.22, 0.20)	0.92
1st molars								
BH	-2.58 (0.90)	-0.70 (-1.4, 0.02)	0.056	-2.64 (1.41)	-0.16 (-0.36, 0.03)	0.10	-0.54 (-1.3, 0.20)	0.15
BW-3	0.82 (0.88)	**-0.24** (-0.43, -0.05)	**0.017***	0.74 (0.65)	-0.09 (-0.22, 0.04)	0.17	-0.15 (-0.38, 0.07)	0.18
BW-6	1.26 (1.02)	**-0.20** (-0.32, -0.07)	**0.003***	1.05 (0.88)	-0.03 (-0.13, 0.06)	0.50	**-0.16** (-0.32, -0.01)	**0.035***

[1]Paired t-test, [2]Welch Two Sample t-test, [3]CI = Confidence Interval.
*Statistically significant at P<0.05.

Figure 11 shows dental and alveolar bone changes in an expanded maxillary arch before and after treatment. In this case, the changes were not significant at upper incisors and upper right premolars. However, the buccal bone at the upper right molar (UR6) in T1 was no longer visible, whereas a thin buccal bone shelf could be seen at T0. This was interpreted as a notable bone loss after treatment.

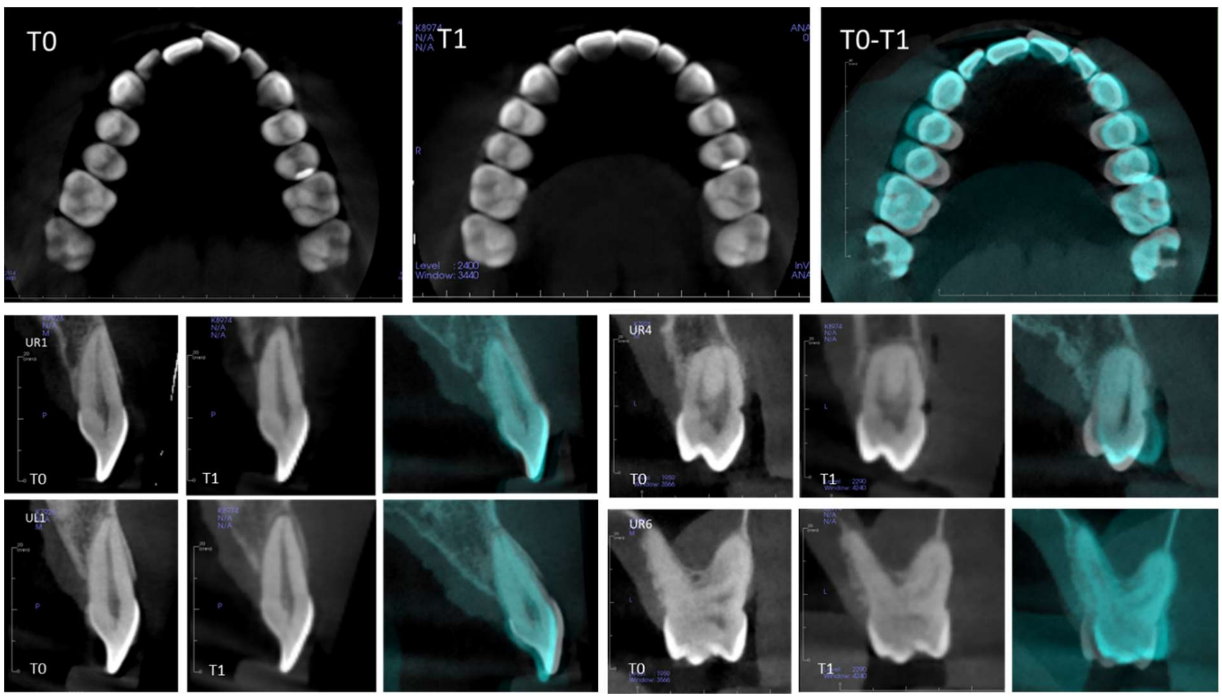


Figure 11: An example of an expanded maxillary arch after CAT. Upper right molar's (UR6) buccal bone was not visualizable at T1, exhibiting significant bone reduction with tooth movement.

In the mandibular expansion group, changes in buccal alveolar bone after expansion with CAT were significantly different at all sites, except the premolar and molar bone widths at 6 mm. The largest changes were seen in bone height at the incisors (-1.50 mm, $p=0.004$) and premolars (-1.40 mm, $p < 0.001$), whereas molar bone height showed a smaller but significant reduction (-0.41 mm, $p = 0.003$).

In the mandibular control group, the only significant change in bone height or width was in the premolar bone height (-0.49 mm, $p=0.037$). It is worth noting that the reduction in bone height at the lower incisors of the control group was almost one millimeter, but this was not statistically significant (-0.83 mm, p=0.071). (Table 10)

Comparing the mandibular expansion and control groups, the only statistically significant change was observed for premolar bone height, with -0.89 mm more vertical bone loss in the expansion group (p=0.023). The lower incisors in the expansion group exhibited 0.67 mm more reduction in bone height than the controls, but this value did not reach statistical significance (p=0.29).

Table 7: Changes in alveolar bone in Mandibular arches (in mm)

Variables	Expansion			Control			Expansion vs control	
	T0	*T1-T0 (95% CI)[13]*	*p-value[1]*	*T0*	*T1-T0 (95% CI)[13]*	*p-value[1]*	*Difference (95%CI)[23]*	*p-value[2]*
Central incisors								
BH	-2.24 (1.45)	**-1.50** (-2.50, -0.54)	**0.004***	-1.50 (0.83)	-0.83 (-1.7, 0.08)	0.071	-0.67 (-1.9, 0.60)	0.29
BW-3	0.34 (0.27)	**-0.16** -0.28 to -0.04)	**0.011***	0.57 (0.45)	-0.07 (-0.17, 0.02)	0.11	-0.08 (-0.23, 0.06)	0.24
BW-6	0.44 (0.29)	**-0.16** -0.28 to -0.04)	**0.011***	0.36 (0.20)	-0.07 (-0.13, -0.01)	0.25	-0.09 (-0.22, 0.04)	0.17
1st premolars								
BH	-2.02 (1.02)	**-1.4** (-2.0, -0.75)	**<0.001***	-1.81 (0.70)	**-0.49** (-0.95, -0.03)	**0.037***	**-0.89** (-1.6, -0.13)	**0.023***
BW-3	0.42 (0.32)	**-0.21** (-0.37, -0.04)	**0.019***	0.48 (0.23)	-0.13 (-0.22, -0.04)	0.07	-0.07 (-0.24, 0.11)	0.43
BW-6	0.54 (0.34)	-0.14 (-0.29, 0.01)	0.058	0.52 (0.13)	-0.08 (-0.14, -0.02)	0.13	-0.06 (-0.22, 0.09)	0.41
1st molars								
BH	-1.84 (0.70)	**-0.41** (-0.66, -0.16)	**0.003***	-1.67 (0.62)	-0.24 (-0.62, 0.14)	0.21	-0.17 (-0.61, 0.27)	0.43
BW-3	0.73 (0.53)	**-0.22** (-0.41, -0.04)	**0.019***	0.76 (0.40)	-0.13 (-0.27, 0.01)	0.069	-0.10 (-0.32, 0.13)	0.39
BW-6	1.21 (0.59)	-0.16 (-0.45, 0.12)	0.24	1.00 (0.51)	-0.03 (-0.17, 0.11)	0.65	-0.13 (-0.44, 0.17)	0.38

[1] Paired t-test, [2] Welch Two Sample t-test, [3] CI = Confidence Interval.
*Statistically significant at P<0.05.

An example of alveolar bone changes in an expanded mandibular arch is demonstrated in Figure 12. The main areas of bone loss can be seen at the lower left incisor (with more protraction compared to lower right incisor), and the lower left premolar.

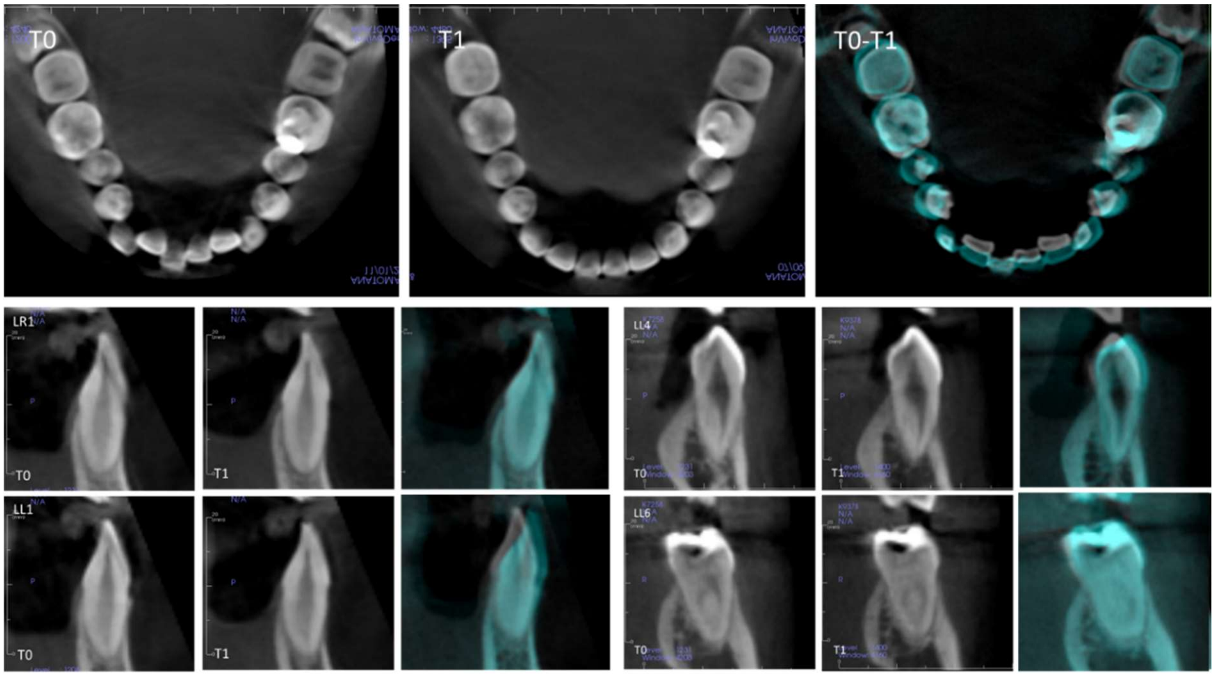
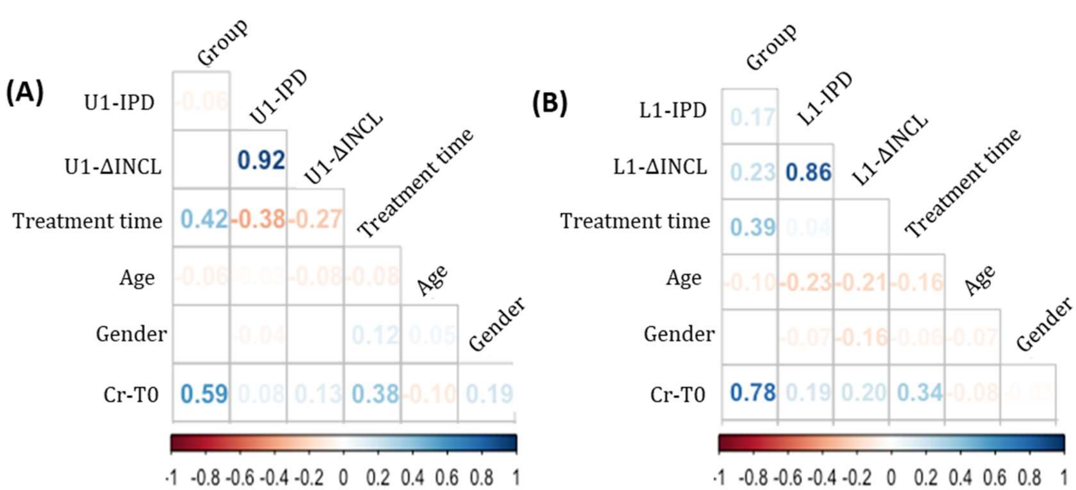


Figure 12: An example of an expanded mandibular arch after CAT. Apparent bone loss observed at lower left incisors (the one with more protraction post treatment), and lower left premolar.

Prior to univariate/multivariate regression analysis, variables were assessed to identify those that had high correlations. This analysis identified changes in inter-arch width (premolars/molars), IPD (incisors), tooth inclination, initial crowding, and group (expansion or control) as being highly correlated. For incisors (Figure 13.A and 13.B), there were high correlation between IPD and ΔINCL, and between group and Cr-T0. For premolars (Figure 13.C and 13.D) and molars (not shown), high correlations were found between group, ΔW, ΔINCL and Cr-T0.



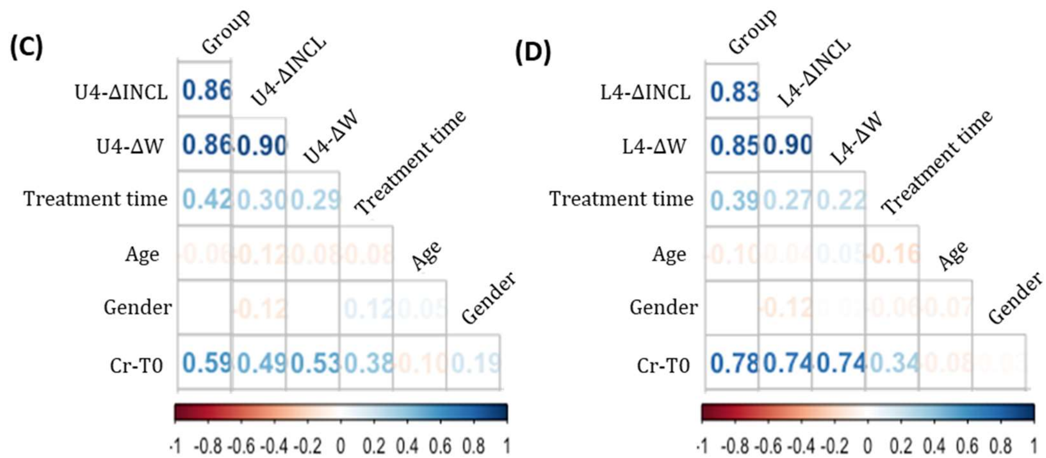


Figure 13: Spearman rank correlation was used to assess correlation between variables.
(A,B) Correlation assessment for upper and lower incisors, (C,D) Correlation assessment for upper and lower premolars. (Group: expansion vs control)

LINEAR REGRESSION ANALYSIS OF MAXILLARY ALVEOLAR BONE AFTER TREATMENT

For maxillary incisors, after adjusting for potentially confounding variables, including treatment time, age and gender, no significant associations were found that allowed us to predict bone response for the incisors (See Appendices).

For upper premolars, the only independent significant predictive variable for bone height loss was increase in premolar width. However, this value was small, at -0.08 mm reduction in bone height for every millimeter of expansion, and not significant in adjusted models (See Appendices).

For upper molars, being in the expansion group (β= -0.16, p=0.039), having increased tooth inclination (β= -0.03, p=0.019) and having increased treatment time (β= -0.02, p=0.007) were all associated with increased reduction in bone width at 6 mm in univariate analyses. However, when controlling for gender and age, only treatment time remained as a significant variable when either amount of expansion, change in inclination, or initial crowding were included in the mode (Table 8).

Table 8: Univariate and Multivariate models testing predictor factors and their effects on changes in upper molars bone width at 6mm (ΔBW-6)

U/ molars, ΔBW-6	Univariate		Multivariate (Mul.)							
N=44			Mul. w/ group		Mul. w/ ΔW		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value
Group										
Control	—		—							
Expansion	**-0.16 (-0.32 to -0.01)**	**0.039 ***	-0.08 (-0.26 to 0.11)	0.408						
ΔW	-0.06 (-0.12 to 0.00)	0.064			-0.02 (-0.08 to 0.03)	0.414				
ΔINCL	**-0.03 (-0.06 to -0.01)**	**0.019 ***					-0.02 (-0.05 to 0.01)	0.238		
Cr-T0 (mm)	-0.03 (-0.07 to 0.02)	0.249							0.00 (-0.05 to 0.05)	0.968
Tx time, T1 - T0	**-0.02 (-0.03 to -0.01)**	**0.007 ***	-0.02 (-0.03 to 0.00)	0.060	**-0.02 (-0.03 to 0.00)**	**0.034 ***	**-0.02 (-0.03 to 0.00)**	**0.047 ***	**-0.02 (-0.04 to 0.00)**	**0.014***
Age	0.01 (0.00 to 0.02)	0.170	0.01 (-0.01 to 0.02)	0.370	0.01 (-0.01 to 0.02)	0.370	0.01 (-0.01 to 0.02)	0.440	0.01 (-0.01 to 0.02)	0.401
Sex										
F	—		—		—		—		—	
M	0.06 (-0.10 to 0.23)	0.436	0.08 (-0.07 to 0.24)	0.291	0.08 (-0.07 to 0.23)	0.311	0.07 (-0.08 to 0.22)	0.325	0.09 (-0.07 to 0.25)	0.276
R2			0.249		0.243		0.262		0.231	

[1]CI = Confidence Interval

Since the differences in bone height and width changes in the maxillary expansion vs control groups were generally small and not statistically significant, it was not surprising that these models were not very useful in predicting alveolar bone changes.

LINEAR REGRESSION ANALYSIS OF MANDIBULAR ALVEOLAR BONE AFTER TREATMENT

In the mandibular arch, after adjusting for treatment time, age, and gender, the largest correlations were found between incisor protraction distance (IPD) and gender for lower incisor bone height change, although both variables failed to reach statistical significance (See Appendices).

For lower incisors, the significant predictors for bone width at 3 mm included being in the expansion group and the months of treatment time (Table 9). The prediction formula is:

$$\text{Incisor-}\Delta\text{BW3 (mm)} = -0.17\text{ (group)} - 0.02\text{ (mos tx time)} + 0.01\text{ (age in years)} - 0.07\text{ (gender)}$$

With Group: Expansion = 1, Control = 0; Gender: Male = 1, Female = 0.

Premolar changes in bone height showed significant correlation with independent changes in inter-premolar widths, changes in tooth inclination, and being in the expansion group. These factors were also each significant in adjusted models, with the best models (i.e., highest R^2) including either change in premolar inclination or change in premolar width (Table 10). The model using change in premolar width is:

$$\text{PM-}\Delta\text{BH (mm)} = -0.29\ (\Delta\text{W mm}) - 0.03\text{ (mos tx time)} + 0.02\text{ (age in years)} + 0.16\text{ (gender)}$$

With Gender: Male = 1, Female = 0.

No significant predictors were identified in multivariate analyses for bone changes in height or width for mandibular molars. (See Appendices)

Table 9: Univariate and Multivariate models testing predictor factors and their effects on changes in lower incisors bone width

L/ incisors, ΔBW-3 N=40	Univariate		Multivariate (Mul.)							
			Mul. w/ group		Mul. w/ IPD		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value
Group										
Control	—		—							
Expansion	-0.08 (-0.23 to 0.06)	0.254	-0.17 (-0.32 to -0.02)	0.030 *						
IPD	-0.05 (-0.11 to 0.01)	0.106			-0.06 (-0.11 to 0.00)	0.045 *				
ΔINCL	-0.01 (-0.02 to 0.00)	0.241					-0.01 (-0.02 to 0.00)	0.083		
Cr-T0 (mm)	-0.10 (-0.40 to 0.20)	0.497							-0.02 (-0.07 to 0.03)	0.444
Tx time, T1 - T0	-0.01 (0.00 to 0.03)	0.054	-0.02 (0.01 to 0.04)	0.005 *	-0.02 (0.00 to 0.03)	0.017 *	-0.02 (0.00 to 0.03)	0.018 *	-0.02 (0.00 to 0.03)	0.024 *
Age	0.00 (-0.01 to 0.02)	0.443	0.01 (0.00 to 0.02)	0.162	0.01 (0.00 to 0.01)	0.240	0.01 (0.00 to 0.02)	0.239	0.01 (0.00 to 0.02)	0.168
Sex										
F	—		—		—		—		—	
M	-0.08 (-0.24 to 0.08)	0.307	-0.07 (-0.21 to 0.07)	0.344	-0.09 (-0.24 to 0.06)	0.248	-0.09 (-0.25 to 0.07)	0.256	-0.07 (-0.23 to 0.08)	0.349
R2			0.307		0.250		0.227		0.200	

[1]CI = Confidence Interval

Table 10: Univariate and Multivariate models testing predictor factors and their effects on changes in lower premolars bone height (ΔBH)

L/ premolars, ΔBH N=40	Univariate		Multivariate (Mul.)							
			Mul. w/ group		Mul. w/ ΔW		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value
Group										
Control	—		—							
Expansion	-0.89 (-1.7 to -0.11)	0.026 *	-0.76 (-1.44 to -0.08)	0.029 *						
ΔW	-0.30 (-0.53 to -0.08)	0.009 *			-0.29 (-0.48 to -0.09)	0.006 *				
ΔINCL	-0.17 (-0.28 to -0.06)	0.004 *					-0.15 (-0.26 to -0.05)	0.005 *		
Cr-T0 (mm)	-0.17 (-0.47 to 0.13)	0.260							-0.11 (-0.42 to 0.19)	0.458
Tx time, T1 - T0	-0.06 (-0.14 to 0.03)	0.193	-0.03 (-0.11 to 0.06)	0.532	-0.03 (-0.11 to 0.05)	0.453	-0.03 (-0.11 to 0.05)	0.462	-0.04 (-0.13 to 0.05)	0.343
Age	0.02 (-0.03 to 0.07)	0.434	0.01 (-0.05 to 0.06)	0.746	0.02 (-0.04 to 0.07)	0.555	0.01 (-0.04 to 0.06)	0.717	0.01 (-0.05 to 0.07)	0.741
Sex										
F	—		—		—		—		—	
M	0.09 (-0.77 to 0.95)	0.836	0.08 (-0.79 to 0.95)	0.852	0.16 (-0.64 to 0.96)	0.684	0.05 (-0.77 to 0.88)	0.895	0.05 (-0.86 to 0.97)	0.907
R2			0.146		0.226		0.245		0.083	

[1]CI = Confidence Interval

V. DISCUSSION

This study utilized CBCTs to assess buccal alveolar bone changes after non-extraction Clear Aligner Therapy to resolve mild to moderate crowding in adult patients. Even though CBCT allows precise visualization for bone measurements, thin objects can still be challenging to measure due to image resolution. X-ray tube current (milliamperage) and exposure time are directly proportional to radiation dose (Ludlow, et al., 2015), and a loss in low contrast resolution has been observed in CT images taken at 6-20mA, while resolution was similar with settings between 40-100mA (Leung, et al., 2010). However, a compromise between radiation dose and image quality is justified due to the ALARA principle. The scans for our patients were all taken at less than 20mA. Therefore, the accuracy of linear measurements of thin objects, like thin buccal alveolar bone, could be affected. To maximize the validity of our data interpretation, we considered investigating spatial resolution, or the actual minimum distance required to distinguish two objects, using a line pair phantom, as reporting voxel size alone is inadequate (Molen, 2010). Unfortunately, due to the CBCTs being collected from various offices, conducting such investigations was not possible.

We did employ other measures to maximize the validity of our data. For example, we implemented a criterion for CBCT voxel size in the initial selection process (≤ 0.4 mm), guided by previous studies' findings (Patcas et al., 2012; Spin-Neto et al., 2013; Torres et al., 2012) to minimize inaccuracy of alveolar bone measurements. We also included control groups in order to compare bony changes in minimally expanded arches, which were matched 100% by gender and as close as possible by age to the expanded patients. Additionally, measurements were conducted at pre-specified locations, and when indicated, the examiners viewed axial slices to aid in the identification of bone. All data collection was conducted in a blinded manner (both time point and group), to prevent bias. Considering the limitations of CBCT to draw conclusion on the absolute presence of absence of buccal bone shelf as compared to direct visualization (Molen, 2010), we are simply reporting the changes in thickness or height that were observable in the scans that we assessed (Figure 14,15,16).

In their Best Evidence Consensus statement on CBCT application in dentistry, the American Academy of Periodontology expert panel members concluded that CBCT is the only radiographic modality that can objectively detect changes of buccal bone following orthodontic tooth movement. Consequently, the consensus recommended the use of CBCT scans for bone assessment in certain scenarios to evaluate the risk of periodontal structures, particularly in cases involving advanced tooth movements in high-risk patients (Mandelaris, Scheyer, et al., 2017). The findings support using currently available CBCT scans to gain insights on periodontal and bone response following any orthodontic treatment modality, or in this case, clear aligners.

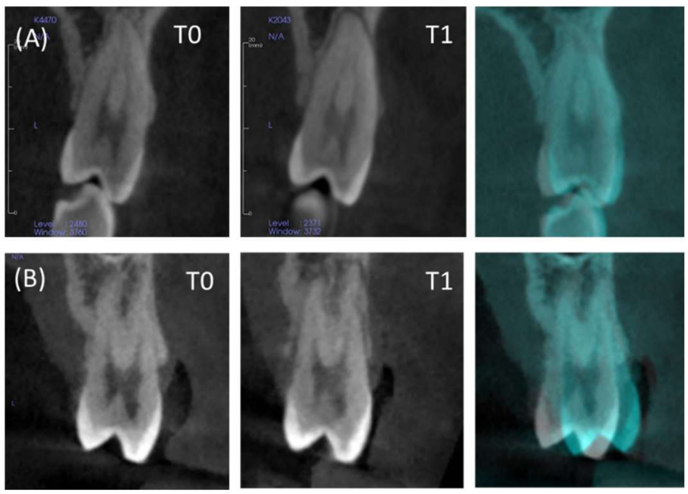


Figure 14: Examples depicting alveolar bone loss at maxillary premolars from 2 different arches. For superimposed images: white: T0, blue: T1

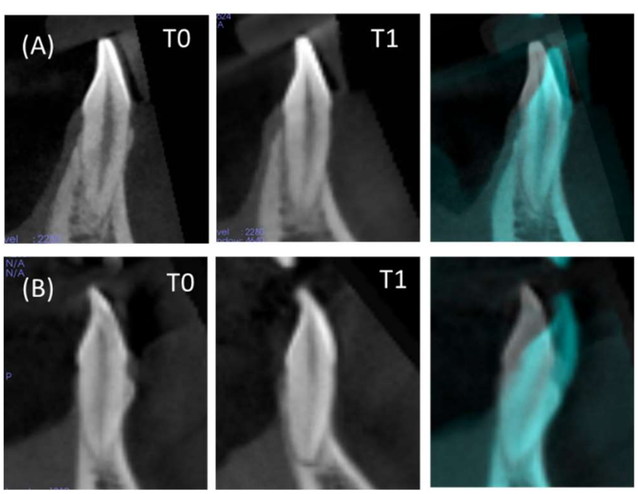


Figure 15: Examples depicting alveolar bone loss at mandibular incisors from 2 different arches. For superimposed images: white: T0, blue: T1

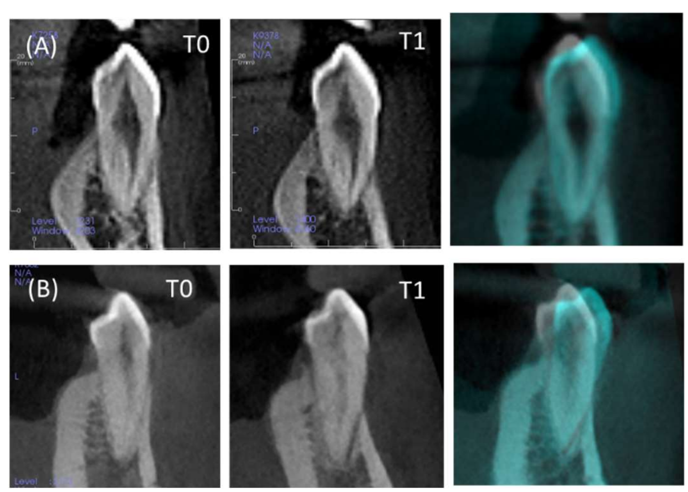


Figure 16: Examples depicting alveolar bone loss at mandibular premolars from 2 different arches. For superimposed images: white: T0, blue: T1

Orthodontic treatment has been linked with alveolar bone loss during tooth movements in adult patients, as indicated by the current literature on both traditional fixed appliances and CAT. Lund, et al. conducted a study investigating alveolar bone changes after premolar extraction using CBCT scans and found remodeling of the alveolar bone in areas undergoing dental retraction, with 84% of lingual surfaces of mandibular central incisors exhibiting a decrease in bone height of over 2 mm (Lund, et al., 2012). In non-extraction orthodontic therapy, CBCT assessment revealed a reduction in bone height in 57% of evaluated surfaces post-treatment (Castro, et al., 2016). Similarly, another retrospective CBCT study documented a reduction of 0.82 mm in bone height, and 0.56 mm in bone width at 5 mm from CEJ following treatment with fixed appliances (Jäger, et al., 2017).

The self-ligating bracket system is comparable to CAT in its potential for posterior expansion. Mean expansion reported by Morais et al. was 4.3 mm ±1.6 mm at maxillary first premolars (Morais et al., 2018). It was once proposed that with heat-activated super-elastic archwires, controlled dental expansion, and precise torque prescriptions, self-ligating systems could promote bone growth following tooth movements (Damon, 1998). However, studies have shown that negative bony response still followed non-extraction alignment with self-ligating appliances. Significant bone loss in both thickness and height was observed at maxillary central incisors and first molars, with the largest alveolar bone change noted at maxillary first molars (bone width at 3 mm -0.6 ± 0.6 mm) (Morais et al., 2018). Cattaneo, et al. also documented a 12-23% reduction of buccal bone thickness at second premolars with this system (Cattaneo, et al., 2011).

With CAT, our findings also showed a net reduction in alveolar bone after treatment. The buccal bone response was particularly pronounced in areas with thin bone (lower incisors) and greater tooth movements, notably premolars, which exhibited the largest changes in inclination and linear movement in both arches (3.8 mm at upper premolars, 3.7 mm at lower premolars). The results aligned with recent studies indicating mean expansion of 3-4 mm in crowded arches using CAT (Deregibus et al., 2020; Duncan et al., 2016a; Lione et al., 2021), which was most prominent at the first premolars (Morales-Burruezo et al., 2020; Zhou & Guo, 2020), and occurred primarily through dental tipping. There is a strong correlation between the 2 parameters according to several systematic reviews (Bouchant et al., 2023; Ma & Wang, 2023; Papadimitriou et al., 2018). Despite significant changes in dental arch morphology, changes in maxillary alveolar bone were not clinically significant, with a potential reduction in bone height and width of 0.41 mm and 0.19 mm, respectively (Table 9). Previous studies have also reported minimal changes in periodontal parameters in the maxilla following expansion with Invisalign (Barreda et al., 2020; de Figueiredo et al., 2023). In contrast, mandibular premolars exhibited significantly greater bone height loss at -1.4 mm, although changes in bone width were small and comparable to those in the maxilla (Table 10). Compared to the control group, the reduction in bone height at mandibular premolars was significantly higher. Given a similar amount of expansion, mandibular premolars may be at a higher risk of bone height loss compared to maxillary premolars.

When assessing the anterior segments, maxillary incisors exhibited, on average, a mild post-treatment retraction, while mandibular teeth showed, on average, minor protraction and proclination (Table 5). This tendency for proclination in lower incisors during crowding alleviation was also reported by Duncan, et al (Duncan, et al., 2016). Interestingly, despite minor and statistically insignificant mean changes in mandibular incisor position, a significant reduction in BH was observed in both the expansion and control groups (-1.5 mm and -0.83 mm, respectively) (Table 10). Findings reported by Zhang, et al. on mandibular incisors with Invisalign treatment also found a significant labial bone height loss, ranging from -0.61 ± 1.59 mm to -1.09 ± 2.26 mm among incisors (Zhang & Cai, 2023). Conversely, changes in bone width, although significant, were small. It is worth noting the thin buccal bone measured at lower incisors prior to treatment, averaging around 0.3 to 0.6 mm in both expansion and control groups. Therefore, a small amount of labial tipping and/or bodily movement could move the root outside of the alveolar housing.

The literature reports that buccal expansion might not be as desirable to resolve crowding in the lower arch, potentially requiring supplemental strategies like interproximal tooth reduction (IPR), distalization, or extraction (Geran et al., 2006; Yared et al., 2006). Our mean incisal labial movements were minimal, but there was some variability, as indicated by the standard deviations. Obviously, the crowding was mostly alleviated through either posterior expansion and/or interproximal tooth reduction (IPR).

One of the limitations of this study is the lack of information regarding the amounts of IPR performed. A prior study reported that 48% of maxillary crowding was resolved with interproximal reduction, while 58% of non-extraction cases would have their crowding relieved from a combination of IPR and incisor protrusion/proclination (Krieger, et al., 2012). Studies have reported significant proclination and protrusion of lower incisors following treatment for arches with >6 mm of crowding (Duncan, et al., 2016). While buccal expansion and IPR are important for preserving periodontal health and treatment stability, the accuracy of IPR as part of aligner treatment is variable, with one study reporting only 45% of the planned IPR was accomplished in the upper arch, and 37% in the lower (de Felice, et al., 2020). Due to challenges in measuring sub-millimeter changes in tooth widths after interproximal reduction (IPR) on CBCT scans, our study could not assess the contribution of IPR in resolution of crowding. That is why we based the expansion group on actual increases in arch width rather than initial crowding. In our models, initial crowding was not identified as a significant predictor of bone loss, possibly because varying amounts of crowding might have been addressed by IPR. While future studies may consider methods to accurately assess the amount of IPR that was performed, our results indicate that it may be adequate and more important to assess the actual changes in arch dimension.

After controlling for highly correlated variables (e.g., group (control vs. expansion), ΔW, ΔINCL and Cr-T0), multivariate models did not significantly differ from univariate ones in predicting bone changes (See Appendices). In the maxillary arch, changes associated with these variables were generally weak. However, the mandibular arch exhibited some statistically significant predictors for bone loss, specifically facial movement of teeth (IPD and ΔW) (Table 9, 10). Premolars typically express the greatest expansion, as compared to molars (Zhao et al., 2017), which could be explained by larger roots of molars, increased alveolar bone thickness in the molar region, higher posterior mastication load, and greater resistance of soft tissue of the cheeks (Bouchant et al., 2023).

On the other hand, mandibular incisor bone height changes appeared to be associated with labial tooth movements, although these relationships did not quite reach statistical significance (See Appendices). Additionally, a small but significant association was found between decrease in lower incisor bone width at 3 mm in the expansion group, and incisal protraction distance in multivariate models. A previous study did report a significant association between inclination changes and mandibular incisors' alveolar bone height change (Zhang & Cai, 2023). Another retrospective study using cephalometric radiographs and digital study models found that in arches with severe initial crowding (>6.0 mm), Invisalign treatment resulted in 3.2 mm of mean expansion at first premolars, while incisors were protracted by an average of 1.6 mm (Duncan et al., 2016). Further investigation using CBCT scans focusing on the anterior segment with more targeted selection criteria, larger samples, and accurate accounting of IPR are needed.

In March 2022, Align Technology announced the integration of CBCT scans into their ClinCheck treatment planning software (Align Technolgy, 2022), a feature that has since gained popularity across various aligner and digital setup platforms. This integration allows visualization of roots and bone, along with tooth crown structures, providing orthodontists with additional information to plan tooth movement with greater control and confidence. However, since the feature assumes static bone structure that simulates teeth moving "through" bone, understanding the dynamic changes of alveolar bone with treatment is required to accurately predict bone response under tooth movement. It's crucial to recognize that alveolar bone loss is just a surrogate marker of periodontal status, whereas a patient would perceive recession, tooth mobility, or tooth loss as more significant sequela of orthodontic treatment (Bollen et al., 2008). While gingival recession frequently is accompanied by hypersensitivity, root caries, non-carious cervical lesions, and impaired esthetics, a meta-analysis found no significant effect between its progression and long-term survival of teeth (Chambrone & Tatakis, 2016). The current literature is unclear regarding the changes in alveolar bone during retention. It is possible that additional bone may form over time, and it is also possible that relapse may allow roots to move back into the alveolar housing, at least partially. Articles from 50 years ago address the potential for bone to form over roots that were moved outside of the alveolar housing (Mulie & Hoeve, 1976; Ten Hoeve & Mulie, 1976), while another study reported that bone only covered the roots if they were moved back into the alveolus (Wainwright, 1973). Studies that link CBCT findings and comprehensive clinical data are needed to explore the clinical impact of alveolar bone changes over time.

CONCLUSIONS

The mean change in antero-posterior position and angulation of incisors in these mild to moderately crowded Class I adult patients treated with Clear Aligner Therapy was minimal. Posterior expansion was accomplished primarily by tipping, and the teeth exhibiting the most expansion were the first premolars. Tipping teeth labially or buccally was most strongly associated with alveolar bone loss in the lower arch.

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VI. APPENDICES

UPPER AIM #2 LINEAR REGRESSION

1) Upper incisors:

U/ incisors, ΔBH N=44	Univariate		Multivariate (Mul.)							
			Mul. w/ group		Mul. w/ IPD		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**
Group										
Control	—		—							
Expansion	-0.04 (-0.25 to 0.18)	0.741	-0.10 (-0.38 to 0.18)	0.494						
IPD	-0.05 (-0.19 to 0.09)	0.450			-0.05 (-0.19 to 0.10)	0.510				
ΔINCL	-0.01 (-0.03 to 0.02)	0.660					0.00 (-0.03 to 0.02)	0.753		
Cr-T0 (mm)	0.01 (-0.05 to 0.07)	0.693							0.00 (-0.07 to 0.07)	0.975
Tx time, T1 - T0	0.01 (-0.02 to 0.03)	0.517	0.01 (-0.02 to 0.04)	0.492	0.00 (-0.02 to 0.03)	0.763	0.01 (-0.02 to 0.03)	0.627	0.01 (-0.02 to 0.04)	0.623
Age	-0.01 (-0.02 to 0.01)	0.336	-0.01 (-0.02 to 0.01)	0.400	-0.01 (-0.02 to 0.01)	0.340	-0.01 (-0.02 to 0.01)	0.367	-0.01 (-0.03 to 0.01)	0.437
Sex										
F	—		—		—		—		—	
M	-0.04 (-0.25 to 0.17)	0.721	-0.05 (-0.30 to 0.20)	0.696	-0.05 (-0.30 to 0.20)	0.707	-0.05 (-0.30 to 0.20)	0.714	-0.04 (-0.28 to 0.19)	0.706
R2			0.054		0.056		0.040		0.038	

[1]CI = Confidence Interval

U/ incisors, ΔBW-3 N=44	Univariate		Multivariate (Mul.)							
			Mul. w/ group		Mul. w/ IPD		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**
Group										
Control	—		—							
Expansion	0.00 (-0.18 to 0.19)	0.977	0.07 (-0.15 to 0.29)	0.518						
IPD	0.06 (-0.02 to 0.15)	0.148			0.05 (-0.07 to 0.17)	0.440				
ΔINCL	0.02 (0.00 to 0.04)	0.070					0.01 (-0.01 to 0.04)	0.237		
Cr-T0 (mm)	-0.02 (-0.07 to 0.04)	0.489							0.00 (-0.06 to 0.06)	0.922
Tx time, T1 - T0	-0.01 (-0.03 to 0.00)	0.071	-0.01 (-0.03 to 0.00)	0.114	-0.01 (-0.03 to 0.01)	0.503	-0.01 (-0.03 to 0.01)	0.497	-0.01 (-0.03 to 0.01)	0.187
Age	0.00 (-0.01 to 0.02)	0.556	0.00 (-0.01 to 0.02)	0.639	0.00 (-0.01 to 0.02)	0.627	0.00 (-0.01 to 0.02)	0.594	0.00 (-0.01 to 0.02)	0.653
Sex										
F	—		—		—		—		—	
M	-0.14 (-0.32 to 0.04)	0.127	-0.13 (-0.31 to 0.06)	0.183	-0.13 (-0.32 to 0.06)	0.187	-0.12 (-0.31 to 0.06)	0.182	-0.13 (-0.32 to 0.06)	0.178
R2			0.115		0.128		0.160		0.104	

[1]CI = Confidence Interval

U/ incisors, ΔBW-6 N=44	Univariate		Multivariate (Mul.)							
			Mul. w/ group		Mul. w/ IPD		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**
Group										
Control	—		—							
Expansion	-0.02 (-0.19 to 0.16)	0.853	0.05 (-0.13 to 0.23)	0.566						
IPD	0.06 (-0.04 to 0.17)	0.229			0.05 (-0.06 to 0.16)	0.378				
ΔINCL	0.01 (-0.01 to 0.04)	0.258					0.01 (-0.01 to 0.04)	0.352		
Cr-T0 (mm)	-0.02 (-0.09 to 0.05)	0.582							0.00 (-0.07 to 0.07)	0.943
Tx time, T1 - T0	-0.01 (-0.02 to 0.00)	0.090	-0.01 (-0.03 to 0.00)	0.076	-0.01 (-0.02 to 0.01)	0.335	-0.01 (-0.02 to 0.01)	0.296	-0.01 (-0.03 to 0.00)	0.175
Age	0.01 (-0.01 to 0.02)	0.281	0.01 (-0.01 to 0.02)	0.372	0.01 (-0.01 to 0.02)	0.334	0.01 (-0.01 to 0.02)	0.350	0.01 (-0.01 to 0.02)	0.377
Sex										
F	—		—		—		—		—	
M	0.03 (-0.15 to 0.21)	0.749	0.04 (-0.14 to 0.22)	0.646	0.04 (-0.14 to 0.23)	0.649	0.04 (-0.14 to 0.23)	0.647	0.04 (-0.15 to 0.23)	0.663
R2			0.083		0.107		0.116		0.077	

[1]CI = Confidence Interval

2) Upper premolars:

U/ premolars, ΔBH N=44	Univariate		Multivariate (Mul.)							
			Mul. w/ group		Mul. w/ ΔW		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**
Group										
Control	—		—							
Expansion	-0.21 (-0.49 to 0.07)	0.131	-0.18 (-0.52 to 0.15)	0.280						
ΔW	**-0.08 (-0.14 to -0.01)**	**0.018 ***			-0.07 (-0.15 to 0.01)	0.084				
ΔINCL	-0.03 (-0.05 to 0.00)	0.062					-0.03 (-0.06 to 0.01)	0.130		
Cr-T0 (mm)	-0.04 (-0.15 to 0.08)	0.521							-0.02 (-0.14 to 0.10)	0.753
Tx time, T1 - T0	-0.02 (-0.04 to 0.01)	0.173	-0.01 (-0.04 to 0.02)	0.557	-0.01 (-0.03 to 0.01)	0.446	-0.01 (-0.03 to 0.01)	0.402	-0.01 (-0.04 to 0.01)	0.271
Age	-0.01 (-0.04 to 0.02)	0.575	-0.01 (-0.04 to 0.02)	0.496	-0.01 (-0.04 to 0.02)	0.471	-0.01 (-0.04 to 0.02)	0.458	-0.01 (-0.04 to 0.02)	0.484
Sex										
F	—		—		—		—		—	
M	-0.23 (-0.51 to 0.05)	0.102	-0.22 (-0.51 to 0.07)	0.138	-0.20 (-0.48 to 0.07)	0.145	-0.23 (-0.52 to 0.06)	0.113	-0.20 (-0.47 to 0.07)	0.145
R2			0.146		0.179		0.174		0.117	

[1]CI = Confidence Interval

U/ premolars, ΔBW-3	Univariate		Multivariate (Mul.)							
N=44			Mul. w/ group		Mul. w/ ΔW		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value
Group										
Control	—		—							
Expansion	-0.09 (-0.30 to 0.11)	0.369	-0.06 (-0.34 to 0.21)	0.651						
ΔW	-0.03 (-0.10 to 0.03)	0.321			-0.03 (-0.11 to 0.06)	0.527				
ΔINCL	-0.02 (-0.04 to 0.01)	0.219					-0.01 (-0.05 to 0.02)	0.385		
Cr-T0 (mm)	-0.01 (-0.09 to 0.07)	0.883							0.00 (-0.10 to 0.10)	>0.999
Tx time, T1 - T0	-0.01 (-0.03 to 0.01)	0.251	-0.01 (-0.03 to 0.01)	0.471	-0.01 (-0.03 to 0.01)	0.424	-0.01 (-0.03 to 0.01)	0.443	-0.01 (-0.03 to 0.01)	0.251
Age	-0.01 (-0.03 to 0.01)	0.470	-0.01 (-0.03 to 0.01)	0.440	-0.01 (-0.03 to 0.02)	0.445	-0.01 (-0.03 to 0.02)	0.438	-0.01 (-0.03 to 0.01)	0.412
Sex										
F	—		—		—		—		—	
M	-0.01 (-0.22 to 0.19)	0.889	0.00 (-0.21 to 0.21)	0.983	0.00 (-0.21 to 0.22)	0.979	-0.01 (-0.22 to 0.20)	0.897	0.00 (-0.22 to 0.22)	0.994
R2			0.057		0.070		0.088		0.050	

[1]CI = Confidence Interval

U/ premolars, ΔBW-6	Univariate		Multivariate (Mul.)							
N=44			Mul. w/ group		Mul. w/ ΔW		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value
Group										
Control	—		—							
Expansion	-0.01 (-0.23 to 0.21)	0.926	-0.02 (-0.26 to 0.22)	0.866						
ΔW	-0.02 (-0.09 to 0.04)	0.429			-0.03 (-0.10 to 0.04)	0.386				
ΔINCL	0.00 (-0.03 to 0.02)	0.736					0.00 (-0.03 to 0.02)	0.726		
Cr-T0 (mm)	-0.05 (-0.11 to 0.01)	0.077							-0.07 (-0.14 to 0.00)	0.045
Tx time, T1 - T0	0.00 (-0.02 to 0.02)	0.848	0.00 (-0.02 to 0.02)	0.919	0.00 (-0.02 to 0.02)	0.769	0.00 (-0.02 to 0.02)	0.898	0.01 (-0.01 to 0.03)	0.488
Age	-0.01 (-0.02 to 0.01)	0.375	-0.01 (-0.02 to 0.01)	0.396	-0.01 (-0.02 to 0.01)	0.392	-0.01 (-0.02 to 0.01)	0.387	-0.01 (-0.02 to 0.00)	0.167
Sex										
F	—		—		—		—		—	
M	0.08 (-0.14 to 0.29)	0.468	0.08 (-0.15 to 0.31)	0.492	0.08 (-0.15 to 0.32)	0.480	0.07 (-0.15 to 0.30)	0.505	0.11 (-0.12 to 0.33)	0.334
R2			0.026		0.048		0.030		0.126	

[1]CI = Confidence Interval

3) Upper molars

U/ molars, ΔBH N=44	Univariate		Multivariate (Mul.)							
			Mul. w/ group		Mul. w/ ΔW		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	**Beta (95% CI)**[1]	**p-value**	**Beta (95% CI)**[1]	**p-value**	**Beta (95% CI)**[1]	**p-value**	**Beta (95% CI)**[1]	**p-value**	**Beta (95% CI)**[1]	**p-value**
Group										
Control	—		—							
Expansion	-0.54 (-1.3 to 0.20)	0.151	-0.71 (-1.98 to 0.56)	0.264						
ΔW	0.04 (-0.12 to 0.20)	0.649			-0.01 (-0.33 to 0.32)	0.962				
ΔINCL	-0.04 (-0.17 to 0.09)	0.529					-0.05 (-0.27 to 0.17)	0.653		
Cr-T0 (mm)	0.03 (-0.09 to 0.15)	0.625							0.09 (-0.10 to 0.29)	0.335
Tx time, T1 - T0	0.01 (-0.08 to 0.09)	0.880	0.05 (-0.09 to 0.18)	0.505	0.02 (-0.10 to 0.14)	0.760	0.03 (-0.11 to 0.17)	0.688	0.01 (-0.09 to 0.10)	0.848
Age	0.06 (-0.06 to 0.18)	0.311	0.06 (-0.06 to 0.19)	0.324	0.06 (-0.07 to 0.20)	0.343	0.06 (-0.07 to 0.19)	0.346	0.07 (-0.07 to 0.20)	0.310
Sex										
F	—		—		—		—		—	
M	-0.44 (-1.2 to 0.31)	0.245	-0.51 (-1.47 to 0.45)	0.285	-0.48 (-1.46 to 0.49)	0.323	-0.51 (-1.54 to 0.51)	0.317	-0.52 (-1.46 to 0.42)	0.272
R2			0.204		0.132		0.143		0.146	

[1]CI = Confidence Interval

U/ molars, ΔBW-3 N=44	Univariate		Multivariate (Mul.)							
			Mul. w/ group		Mul. w/ ΔW		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	**Beta (95% CI)**[1]	**p-value**	**Beta (95% CI)**[1]	**p-value**	**Beta (95% CI)**[1]	**p-value**	**Beta (95% CI)**[1]	**p-value**	**Beta (95% CI)**[1]	**p-value**
Group										
Control	—		—							
Expansion	-0.15 (-0.38 to 0.08)	0.188	-0.07 (-0.29 to 0.15)	0.548						
ΔW	-0.11 (-0.24 to 0.02)	0.104			-0.08 (-0.20 to 0.03)	0.135				
ΔINCL	-0.05 (-0.12 to 0.02)	0.183					-0.04 (-0.09 to 0.02)	0.206		
Cr-T0 (mm)	0.00 (-0.06 to 0.07)	0.906							0.02 (-0.05 to 0.09)	0.520
Tx time, T1 - T0	-0.02 (-0.05 to 0.02)	0.272	-0.02 (-0.05 to 0.02)	0.314	-0.01 (-0.04 to 0.02)	0.369	-0.01 (-0.04 to 0.01)	0.312	-0.02 (-0.06 to 0.01)	0.215
Age	0.00 (-0.02 to 0.02)	0.894	0.00 (-0.02 to 0.01)	0.664	0.00 (-0.02 to 0.01)	0.719	-0.01 (-0.02 to 0.01)	0.533	0.00 (-0.02 to 0.02)	0.782
Sex										
F	—		—		—		—		—	
M	0.14 (-0.09 to 0.37)	0.226	0.16 (-0.10 to 0.43)	0.216	0.13 (-0.11 to 0.38)	0.270	0.14 (-0.10 to 0.39)	0.243	0.16 (-0.10 to 0.42)	0.224
R2			0.141		0.212		0.192		0.143	

U/ molars, ΔBW-3	Univariate		Multivariate (Mul.)							
N=44			Mul. w/ group		Mul. w/ ΔW		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**

[1]CI = Confidence Interval

U/ molars, ΔBW-6	Univariate		Multivariate (Mul.)							
N=44			Mul. w/ group		Mul. w/ ΔW		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**
Group										
Control	—		—							
Expansion	**-0.16 (-0.32 to -0.01)**	**0.039 ***	-0.08 (-0.26 to 0.11)	0.408						
ΔW	-0.06 (-0.12 to 0.00)	0.064			-0.02 (-0.08 to 0.03)	0.414				
ΔINCL	**-0.03 (-0.06 to -0.01)**	**0.019 ***					-0.02 (-0.05 to 0.01)	0.238		
Cr-T0 (mm)	-0.03 (-0.07 to 0.02)	0.249							0.00 (-0.05 to 0.05)	0.968
Tx time, T1 - T0	**-0.02 (-0.03 to -0.01)**	**0.007 ***	-0.02 (-0.03 to 0.00)	0.060	**-0.02 (-0.03 to 0.00)**	**0.034 ***	**-0.02 (-0.03 to 0.00)**	**0.047 ***	**-0.02 (-0.04 to 0.00)**	**0.014***
Age	0.01 (0.00 to 0.02)	0.170	0.01 (-0.01 to 0.02)	0.370	0.01 (-0.01 to 0.02)	0.370	0.01 (-0.01 to 0.02)	0.440	0.01 (-0.01 to 0.02)	0.401
Sex										
F	—		—		—		—		—	
M	0.06 (-0.10 to 0.23)	0.436	0.08 (-0.07 to 0.24)	0.291	0.08 (-0.07 to 0.23)	0.311	0.07 (-0.08 to 0.22)	0.325	0.09 (-0.07 to 0.25)	0.276
R2			0.249		0.243		0.262		0.231	

[1]CI = Confidence Interval

LOWER AIM #2 LINEAR REGRESSION

1) Lower incisors:

L/ incisors, ΔBH	Univariate		Multivariate (Mul.)							
N=40			Mul. w/ group		Mul. w/ IPD		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value
Group										
Control	—		—							
Expansion	-0.67 (-2.0 to 0.63)	0.303	-0.80 (-2.02 to 0.43)	0.194						
IPD	-0.57 (-1.2 to 0.06)	0.074			-0.61 (-1.24 to 0.03)	0.060				
ΔINCL	-0.10 (-0.22 to 0.03)	0.128					-0.11 (-0.22 to 0.00)	0.058		
Cr-T0 (mm)	-0.03 (-0.48 to 0.42)	0.898							-0.05 (-0.48 to 0.39)	0.830
Tx time, T1 - T0	-0.01 (-0.12 to 0.14)	0.903	-0.05 (-0.08 to 0.18)	0.433	-0.03 (-0.10 to 0.16)	0.657	-0.03 (-0.11 to 0.17)	0.641	-0.03 (-0.11 to 0.16)	0.679
Age	0.08 (-0.02 to 0.17)	0.109	0.08 (-0.02 to 0.17)	0.119	0.06 (-0.03 to 0.15)	0.173	0.06 (-0.02 to 0.15)	0.155	0.08 (-0.03 to 0.18)	0.136
Sex										
F	—		—		—		—		—	
M	-0.99 (-2.3 to 0.37)	0.148	-0.92 (-2.26 to 0.42)	0.173	-1.14 (-2.46 to 0.18)	0.089	-1.16 (-2.50 to 0.18)	0.087	-0.94 (-2.32 to 0.44)	0.176
R2			0.157		0.221		0.191		0.124	

[1]CI = Confidence Interval

L/ incisors, ΔBW-3	Univariate		Multivariate (Mul.)							
N=40			Mul. w/ group		Mul. w/ IPD		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value
Group										
Control	—		—							
Expansion	-0.08 (-0.23 to 0.06)	0.254	-0.17 (-0.32 to -0.02)	0.030 *						
IPD	-0.05 (-0.11 to 0.01)	0.106			-0.06 (-0.11 to 0.00)	0.045 *				
ΔINCL	-0.01 (-0.02 to 0.00)	0.241					-0.01 (-0.02 to 0.00)	0.083		
Cr-T0 (mm)	-0.10 (-0.40 to 0.20)	0.497							-0.02 (-0.07 to 0.03)	0.444
Tx time, T1 - T0	-0.01 (0.00 to 0.03)	0.054	-0.02 (0.01 to 0.04)	0.005 *	-0.02 (0.00 to 0.03)	0.017 *	-0.02 (0.00 to 0.03)	0.018 *	-0.02 (0.00 to 0.03)	0.024 *
Age	0.00 (-0.01 to 0.02)	0.443	0.01 (0.00 to 0.02)	0.162	0.01 (0.00 to 0.01)	0.240	0.01 (0.00 to 0.02)	0.239	0.01 (0.00 to 0.02)	0.168
Sex										
F	—		—		—		—		—	
M	-0.08 (-0.24 to 0.08)	0.307	-0.07 (-0.21 to 0.07)	0.344	-0.09 (-0.24 to 0.06)	0.248	-0.09 (-0.25 to 0.07)	0.256	-0.07 (-0.23 to 0.08)	0.349
R2			0.307		0.250		0.227		0.200	

[1]CI = Confidence Interval

L/ incisors, ΔBW-6	Univariate		Multivariate (Mul.)							
N=40			Mul. w/ group		Mul. w/ IPD		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value
Group										
Control	—		—							
Expansion	-0.09 (-0.22 to 0.04)	0.182	-0.14 (-0.28 to -0.01)	0.033 *						
IPD	-0.01 (-0.08 to 0.07)	0.864			-0.01 (-0.08 to 0.07)	0.803				
ΔINCL	0.00 (-0.01 to 0.02)	0.723					0.00 (-0.01 to 0.02)	0.771		
Cr-T0 (mm)	-0.01 (-0.06 to 0.03)	0.639							-0.02 (-0.06 to 0.02)	0.277
Tx time, T1 - T0	-0.01 (-0.01 to 0.02)	0.336	-0.01 (0.00 to 0.03)	0.096	-0.01 (-0.01 to 0.02)	0.306	-0.01 (-0.01 to 0.02)	0.319	-0.01 (-0.01 to 0.03)	0.185
Age	0.00 (-0.01 to 0.01)	0.782	0.00 (-0.01 to 0.01)	0.597	0.00 (-0.01 to 0.01)	0.609	0.00 (-0.01 to 0.01)	0.519	0.00 (-0.01 to 0.01)	0.574
Sex										
F	—		—		—		—		—	
M	-0.02 (-0.16 to 0.11)	0.725	-0.02 (-0.15 to 0.12)	0.814	-0.02 (-0.16 to 0.12)	0.759	-0.01 (-0.15 to 0.12)	0.849	-0.02 (-0.16 to 0.12)	0.763
R2			0.161		0.055		0.056		0.079	

[1]CI = Confidence Interval

2) Lower premolars:

L/ premolars, ΔBH	Univariate		Multivariate (Mul.)							
N=40			Mul. w/ group		Mul. w/ ΔW		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value	Beta (95% CI)[1]	p-value
Group										
Control	—		—							
Expansion	-0.89 (-1.7 to -0.11)	0.026 *	-0.76 (-1.44 to -0.08)	0.029 *						
ΔW	-0.30 (-0.53 to -0.08)	0.009 *			-0.29 (-0.48 to -0.09)	0.006 *				
ΔINCL	-0.17 (-0.28 to -0.06)	0.004 *					-0.15 (-0.26 to -0.05)	0.005 *		
Cr-T0 (mm)	-0.17 (-0.47 to 0.13)	0.260							-0.11 (-0.42 to 0.19)	0.458
Tx time, T1 - T0	-0.06 (-0.14 to 0.03)	0.193	-0.03 (-0.11 to 0.06)	0.532	-0.03 (-0.11 to 0.05)	0.453	-0.03 (-0.11 to 0.05)	0.462	-0.04 (-0.13 to 0.05)	0.343
Age	0.02 (-0.03 to 0.07)	0.434	0.01 (-0.05 to 0.06)	0.746	0.02 (-0.04 to 0.07)	0.555	0.01 (-0.04 to 0.06)	0.717	0.01 (-0.05 to 0.07)	0.741
Sex										
F	—		—		—		—		—	
M	0.09 (-0.77 to 0.95)	0.836	0.08 (-0.79 to 0.95)	0.852	0.16 (-0.64 to 0.96)	0.684	0.05 (-0.77 to 0.88)	0.895	0.05 (-0.86 to 0.97)	0.907
R2			0.146		0.226		0.245		0.083	

[1]CI = Confidence Interval

L/ premolars, ΔBW-3 N=40	Univariate		Multivariate (Mul.)							
			Mul. w/ group		Mul. w/ ΔW		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**
Group										
Control	—		—							
Expansion	-0.07 (-0.26 to 0.12)	0.442	-0.03 (-0.22 to 0.15)	0.718						
ΔW	-0.05 (-0.13 to 0.02)	0.170			-0.05 (-0.12 to 0.02)	0.181				
ΔINCL	-0.03 (-0.07 to 0.01)	0.117					-0.03 (-0.06 to 0.01)	0.139		
Cr-T0 (mm)	-0.02 (-0.10 to 0.06)	0.671							-0.01 (-0.09 to 0.08)	0.873
Tx time, T1 - T0	-0.01 (-0.03 to 0.01)	0.288	-0.01 (-0.02 to 0.01)	0.415	0.00 (-0.02 to 0.01)	0.560	0.00 (-0.02 to 0.01)	0.608	-0.01 (-0.02 to 0.01)	0.378
Age	0.01 (0.00 to 0.02)	0.171	0.01 (-0.01 to 0.02)	0.351	0.01 (-0.01 to 0.02)	0.258	0.01 (-0.01 to 0.02)	0.311	0.01 (-0.01 to 0.02)	0.356
Sex										
F	—		—		—		—		—	
M	-0.08 (-0.28 to 0.12)	0.416	-0.08 (-0.28 to 0.12)	0.419	-0.07 (-0.25 to 0.12)	0.476	-0.08 (-0.28 to 0.11)	0.390	-0.08 (-0.30 to 0.13)	0.434
R2			0.076		0.157		0.184		0.074	

[1]CI = Confidence Interval

L/ premolars, ΔBW-6 N=40	Univariate		Multivariate (Mul.)							
			Mul. w/ group		Mul. w/ ΔW		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**
Group										
Control	—		—							
Expansion	-0.06 (-0.22 to 0.09)	0.419	-0.07 (-0.20 to 0.07)	0.321						
ΔW	-0.05 (-0.11 to 0.01)	0.100			-0.05 (-0.11 to 0.00)	0.060				
ΔINCL	-0.02 (-0.05 to 0.01)	0.180					-0.02 (-0.05 to 0.01)	0.119		
Cr-T0 (mm)	-0.03 (-0.09 to 0.03)	0.347							-0.03 (-0.09 to 0.02)	0.252
Tx time, T1 - T0	0.00 (-0.02 to 0.01)	0.915	0.00 (-0.01 to 0.02)	0.617	0.00 (-0.01 to 0.02)	0.421	0.00 (-0.01 to 0.02)	0.501	0.00 (-0.01 to 0.02)	0.539
Age	0.01 (0.00 to 0.02)	0.166	0.01 (0.00 to 0.02)	0.150	0.01 (0.00 to 0.02)	0.111	0.01 (0.00 to 0.02)	0.138	0.01 (0.00 to 0.02)	0.159
Sex										
F	—		—		—		—		—	
M	-0.13 (-0.30 to 0.03)	0.113	-0.13 (-0.30 to 0.04)	0.133	-0.11 (-0.26 to 0.04)	0.133	-0.13 (-0.29 to 0.03)	0.116	-0.13 (-0.31 to 0.04)	0.132
R2			0.144		0.271		0.231		0.164	

[1]CI = Confidence Interval

3) Lower molars

L/ molars, ΔBH N=40	Univariate		Multivariate (Mul.)							
			Mul. w/ group		Mul. w/ ΔW		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**
Group										
Control	—		—							
Expansion	-0.17 (-0.62 to 0.28)	0.444	-0.31 (-0.81 to 0.20)	0.229						
ΔW	-0.04 (-0.14 to 0.07)	0.492			-0.07 (-0.23 to 0.08)	0.334				
ΔINCL	-0.02 (-0.09 to 0.04)	0.497					-0.05 (-0.15 to 0.06)	0.371		
Cr-T0 (mm)	-0.01 (-0.14 to 0.11)	0.814							-0.04 (-0.18 to 0.10)	0.562
Tx time, T1 - T0	0.02 (-0.02 to 0.05)	0.334	0.03 (-0.02 to 0.08)	0.221	0.03 (-0.02 to 0.07)	0.232	0.03 (-0.02 to 0.07)	0.235	0.02 (-0.02 to 0.07)	0.329
Age	-0.01 (-0.04 to 0.03)	0.726	0.00 (-0.05 to 0.04)	0.918	-0.01 (-0.05 to 0.04)	0.812	-0.01 (-0.06 to 0.04)	0.784	0.00 (-0.05 to 0.04)	0.924
Sex										
F	—		—		—		—		—	
M	0.17 (-0.26 to 0.61)	0.429	0.19 (-0.28 to 0.66)	0.427	0.14 (-0.38 to 0.66)	0.588	0.14 (-0.39 to 0.67)	0.593	0.18 (-0.31 to 0.66)	0.465
R2			0.084		0.061		0.062		0.048	

[1]CI = Confidence Interval

L/ molars, ΔBW-3 N=40	Univariate		Multivariate (Mul.)							
			Mul. w/ group		Mul. w/ ΔW		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**
Group										
Control	—		—							
Expansion	-0.10 (-0.32 to 0.13)	0.398	-0.11 (-0.33 to 0.11)	0.335						
ΔW	-0.05 (-0.11 to 0.01)	0.124			-0.06 (-0.14 to 0.02)	0.134				
ΔINCL	-0.03 (-0.08 to 0.01)	0.097					-0.05 (-0.11 to 0.01)	0.126		
Cr-T0 (mm)	-0.06 (-0.14 to 0.02)	0.111							-0.07 (-0.16 to 0.02)	0.115
Tx time, T1 - T0	0.00 (-0.02 to 0.02)	0.862	0.00 (-0.01 to 0.02)	0.803	0.00 (-0.01 to 0.02)	0.610	0.01 (-0.01 to 0.03)	0.604	0.00 (-0.01 to 0.02)	0.584
Age	0.00 (-0.01 to 0.01)	0.930	0.00 (-0.02 to 0.01)	0.897	0.00 (-0.02 to 0.01)	0.605	-0.01 (-0.02 to 0.01)	0.512	0.00 (-0.02 to 0.02)	0.878
Sex										
F	—		—		—		—		—	
M	0.02 (-0.23 to 0.26)	0.894	0.02 (-0.24 to 0.27)	0.897	-0.02 (-0.30 to 0.26)	0.888	-0.03 (-0.30 to 0.25)	0.846	0.01 (-0.26 to 0.27)	0.959
R2			0.022		0.059		0.084		0.087	

[1]CI = Confidence Interval

L/ molars, ΔBW-6	Univariate		Multivariate (Mul.)							
N=40			Mul. w/ group		Mul. w/ ΔW		Mul. w/ΔINCL		Mul. w/ Cr-T0	
Characteristics	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**	**Beta (95% CI)[1]**	**p-value**
Group										
Control	—		—							
Expansion	-0.13 (-0.44 to 0.18)	0.385	-0.10 (-0.41 to 0.21)	0.524						
ΔW	0.00 (-0.10 to 0.09)	0.977			0.01 (-0.09 to 0.11)	0.855				
ΔINCL	-0.01 (-0.07 to 0.05)	0.787					-0.01 (-0.07 to 0.06)	0.863		
Cr-T0 (mm)	-0.07 (-0.20 to 0.06)	0.261							-0.07 (-0.20 to 0.06)	0.295
Tx time, T1 - T0	-0.01 (-0.03 to 0.01)	0.322	-0.01 (-0.03 to 0.01)	0.400	-0.01 (-0.04 to 0.01)	0.236	-0.01 (-0.07 to 0.06)	0.863	-0.01 (-0.03 to 0.02)	0.553
Age	0.00 (-0.02 to 0.01)	0.978	0.00 (-0.02 to 0.02)	0.730	0.00 (-0.02 to 0.02)	0.775	-0.01 (-0.07 to 0.06)	0.863	0.00 (-0.02 to 0.02)	0.718
Sex							-0.01 (-0.07 to 0.06)	0.863		
F	—		—		—		-0.01 (-0.07 to 0.06)	0.863	—	
M	-0.12 (-0.45 to 0.21)	0.477	-0.12 (-0.47 to 0.22)	0.475	-0.12 (-0.49 to 0.25)	0.515	-0.01 (-0.07 to 0.06)	0.863	-0.13 (-0.49 to 0.22)	0.455
R2			0.047		0.038		0.038		0.082	

[1]CI = Confidence Interval