ORIGINAL ARTICLE

Craniofacial changes in Class III malocclusion as related to skeletal and dental maturation

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Introduction: In this large cross-sectional study, we aimed to analyze growth trends in white subjects with Class III malocclusion using both skeletal and dental maturation staging. **Methods:** The sample consisted of 1091 pretreatment lateral cephalometric records of Class III patients (560 female, 531 male). Cephalometric dentoskeletal measurements were compared at subsequent stages in cervical vertebral maturation and Hellman's categorization of dental development by means of ANOVA with Bonferroni post-hoc tests in both sexes separately. **Results:** The findings indicated that, in Class III malocclusion, the pubertal peak in mandibular growth occurs between stages 3 and 4 of cervical vertebral maturation, with average increases in total mandibular length of about 8 and 5.5 mm in Class III boys and girls, respectively. **Conclusions:** Significant changes in total mandibular length occur until young adulthood (18 years on average), with increases between late maturation stages (4 through 6) that were twice as large as in subjects with normal occlusion for the Class III females, and 3 times as large as in subjects with normal occlusion for the Class III males. Growth trends toward accentuated Class III profile and increased vertical dimension of the face also become apparent at late developmental stages (corresponding with complete eruption of the second and third molars). (Am J Orthod Dentofacial Orthop 2007;132:171-8)

In spite of its relatively low prevalence, Class III malocclusion is a challenging orthodontic problem. Information on growth trends in Class III patients is needed for both effective treatment planning and reasonable expectations in terms of stability of treatment outcomes. A better understanding of the amount and direction of growth in Class III patients also comes into play when deciding between orthodontic and surgical approaches to the malocclusion.

Several investigators have attempted to contribute to the knowledge of Class III facial growth trends by assembling groups of orthodontically untreated Class III subjects as control groups when evaluating treatment effects. Investigators evaluating predominantly Asian populations have led the way.[1-5] Longitudinal data on Class III subjects of European ancestry have become available only within the last decade.[6-10] The annualized changes as reported in these studies indicate that the rate of maxillary growth in Class III malocclusion during developmental ages is lower than expected for normal subjects (less than 1 mm per year), and that mandibular growth is 3 to 4.5 mm per year. These longitudinal studies were limited in either sample size or observation interval, or both; this unfortunately restricts their applicability to Class III subjects meeting the same inclusion criteria.

Other investigations focused on data collected from many Class III subjects at a single time and used these to make inferences on average craniofacial growth. An example of this type of study is that of Guyer et al,[11] who attempted to characterize Class III patients at various developmental stages by studying lateral cephalograms of 144 Class III children between 5 and 15 years of age. The sample was divided into 4 groups according to chronological age; the authors compared this sample with children with normal occlusions and well-balanced faces (the so-called Bolton standards).[12] The investigators reported that the differences in craniofacial form between Class I and Class III subjects were present in all 4 age groups. Similar results were described by Tollaro et al,[13] who investigated early Class III craniofacial development in untreated European Class III children between the ages of 4 and 6 years with full deciduous dentitions.

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The craniofacial characteristics of a sample of 285 white Class III subjects were contrasted with 210 normal controls by Battagel.[14] Boys and girls were examined separately in 4 age groups: 7 to 10 years, 11 to 12 years, 13 to 14 years, and 15 years and older. Class III boys in all age groups had retrusive maxillary positions and protrusive mandibular positions relative to the controls. The girls had a different growth pattern. Relative to the controls, they had more prominent mandibles and more proclined maxillary incisors. The sex differences in Class III malocclusion were highlighted recently by Baccetti et al.[15]

The largest cross-sectional Class III study to date was conducted by Miyajima et al[16] with a sample of 1376 Japanese female subjects, 2.7 to 47.9 years of age. The sample was organized into groups based on the stage of dental development described by Hellman.[17,18] The maxilla exhibited a retrusive position at an early developmental stage and retained a fairly constant anteroposterior relationship to the cranial base structures with continued development. Likewise, the mandible was protrusive early in development and became increasingly prognathic with age. Recently, Deguchi et al[19] used a large cross-sectional sample (562 subjects) as a control group in a long-term study on the effects of chincup therapy in Asian patients with Class III malocclusion. Three age periods were investigated (8, 13, and 17 years), with no differentiation between boys and girls. Both ANB angle and the Wits appraisal worsened with growth, mainly due to continuous mandibular advancement relative to the maxilla.

The cross-sectional study by Battagel[14] gives additional information about the growth characteristics of Class III patients. The author emphasized that the largest increments for mandibular length in the male subjects were at the oldest age interval (15 years and older), indicating peak growth at this late age period. The female samples showed that the maximum changes in facial characteristics occurred between the average ages of 11 and 12 years but continued after age 15. In the control female group at age 14 to 17 years, facial growth had ceased, but development remained active in the Class III group.

Both classical and more recent studies on mandibular growth in normal subjects have shown that mandibular growth decreases significantly after the pubertal peak,[20-27] and atlases on craniofacial growth show clearly that increases in facial measurements are limited after 15 years of age, particularly in girls.[28] These data suggest that growth trends in Class III malocclusion might differ from those of subjects with normal facial and occlusal developmental patterns, because peak growth occurs rather late, and relatively high rates of growth persist until young adulthood. The significant increase in mandibular length described by Deguchi et al[19] in Class III subjects from 13 through 17 years of age provides additional evidence in this regard.

No previous investigation, however, analyzed a large enough cross-sectional set of white Class III subjects to derive an estimate of growth during the developmental ages in boys and girls separately by using a reliable indicator of skeletal maturity. Recently, the cervical vertebral maturation (CVM) method has gained popularity because of its validity in assessing skeletal maturation during the circumpubertal period and in detecting the growth spurt[26,27] (interval between cervical stage 3 (CS3) and cervical stage 4 (CS4), according to the most recent version of the method[27]). Another method for categorization of development during the circumpubertal ages is the appraisal of dental stages according to Hellman,[17,18] as used in the study by Miyajima et al.[16]

Our aim in this study was to evaluate craniofacial dimensions in Class III subjects at various stages of skeletal maturity as assessed with the CVM method and Hellman's dental stages. The goal was to estimate the amount of growth at prepubertal, pubertal, and postpubertal ages in a large sample of subjects with Class III disharmony, information that would be valuable for diagnosis and treatment planning for this type of malocclusion.

MATERIAL AND METHODS

The parent sample consisted of 1549 pretreatment lateral cephalometric records of white Class III patients collected from 12 private orthodontic practices in Michigan and Ohio, the University of Michigan Graduate Orthodontic Clinic, and the Department of Orthodontics of the University of Florence in Italy.

To be included in the final group, patients had to satisfy all of the following inclusionary criteria: (1) white ancestry; (2) no orthopedic or orthodontic treatment before the cephalogram was taken; (3) diagnosis of Class III malocclusion (anterior crossbite with every attempt to exclude pseudo crossbites, edge-to-edge incisal relationship, accentuated mesial step relationship of the deciduous second molars, and permanent first molar relationship of at least one half cusp Class III); and (4) no congenitally missing or extracted teeth.

The final sample of 1091 subjects with Class III malocclusion met the inclusionary criteria. The sample consisted of 560 females and 531 males. The female age range was 3 years 6 months to 57 years 7 months. The male group ranged from 3 years 3 months to 48 years 5 months.

Table I. Dental developmental stages

Stage 2A/C	Eruption of deciduous molars/permanent incisors and beginning of first molars
Stage 3A	Eruption of permanent first molars complete
Stage 3B	Eruption of permanent canines and premolars
Stage 3C	Beginning of eruption of permanent second molars
Stage 4/5A	Eruption of permanent second molars complete/ eruption of third molars

The lateral cephalograms of the Class III subjects were staged according to the CVM method.[27] It comprises 6 stages (CS) from CS1 through CS6. In white subjects with normal occlusion, the growth spurt occurs between CS3 and CS4. One investigator (B.C.R.) assessed the stages on all patient films. That evaluation was verified by another investigator (T.B.).

Hellman[17,18] defined 5 main stages of dental development and, within each stage, 3 possible subcategories denoting the eruption status of the tooth in question. Subdivision A describes a completely erupted tooth, clinically present in the mouth. Subdivision B is when the deciduous teeth are shed and the permanent successors begin to erupt. Subdivision C is the beginning of eruption of a molar. In our study, we adapted Hellman's original method and combined a few of the main categories, because of small sample sizes. The untreated Class III subjects therefore were classified into 5 developmental groups (Table I).

The eruption status was not clear in some films in the radiographic sample. A definitive dental developmental stage could be established for 520 of the 560 females and 495 of the 531 males in this study.

Lateral cephalograms were hand traced by using 0.003-in matte acetate and a sharpened 2H lead drafting pencil. All cephalograms were traced by 1 of 2 investigators (B.C.R. and A.L.), and landmark identification was verified by a third (J.A.M.). Any disparities were addressed by retracing the structure. The descriptive cephalometric analysis required the digitization of 71 landmarks on each tracing. A cephalometric analysis including measures adopted from the analyses of Steiner,[29] Jacobson,[30] Ricketts,[31] and McNamara[32] was performed on each tracing.

Statistical analysis

With the sample categorized according to indexes of skeletal maturity (6 stages of CVM) and dental stages (5 stages from Hellman's original method), descriptive statistics for the cephalometric measurements were calculated for each stage group by sex. The data were analyzed with a commercial social science statistical package (SPSS for Windows, version 12.0, SPSS, Chicago, Ill).

Initially, sex differences were tested by using the Hotelling T^2 test to see whether the differences between the sexes were significant with respect to the cephalometric measurements. The results indicated significant differences and dictated that male and female groups should be analyzed separately, thus confirming previous data.[15] Consequently, 1-way analysis of variance (ANOVA) was used to identify significant differences ($P < .05$ and $P < .01$) between the means for each cephalometric variable in consecutive developmental groups. The Bonferroni correction assisted in the identification of significant differences. In spite of the cross-sectional nature of this study, the terms "increase" and "decrease" will be used in the Results and Discussion sections to depict positive and negative differences, respectively, because these terms are more reader-friendly.

The error of the method for the cephalometric measurements was evaluated by repeating the measures in 100 randomly selected cephalograms. Errors were on average 0.6° for angular measurements and 0.9 mm for linear measurements.

RESULTS

Analysis of CVM stages

In the female subjects, no statistically significant difference for any cephalometric variable was assessed in the transitions from CS1 to CS2 and CS2 to CS3. The comparison between CS3 and CS4 showed significant increases for total mandibular length (Co-Gn), maxillomandibular differential, lower anterior facial height (ANS-Me), and dentoalveolar height at the maxillary molar (U6-PP). The same comparisons were significant for the transition from CS4 to CS5. In addition to the same significant comparisons, during the transition from CS5 to CS6, the increases in upper anterior facial height (N-ANS), extrusion of the maxillary (U1-ANS) and mandibular (L1-Me) incisors, as well as the protrusion of the lower lip in relation to the E-plane (LL-E plane) became significant (Table II [online, go to www.mosby/AJODO/com], Figs 1-3).

As with the female groups, no statistically significant difference for any cephalometric variable was assessed in the males in the transitions from CS1 to CS2 and CS2 to CS3. The comparison between CS3 and CS4 showed significant increases for total mandibular length (Co-Gn), maxillomandibular differential, upper and lower anterior facial heights (N-ANS and ANS-Me), and dentoalveolar height at the maxillary molar (U6-PP) and mandibular incisor (L1-Me). A significant decrease was recorded for the molar relationship. During the transition from CS4 to CS5, significant increases were found for total mandibular

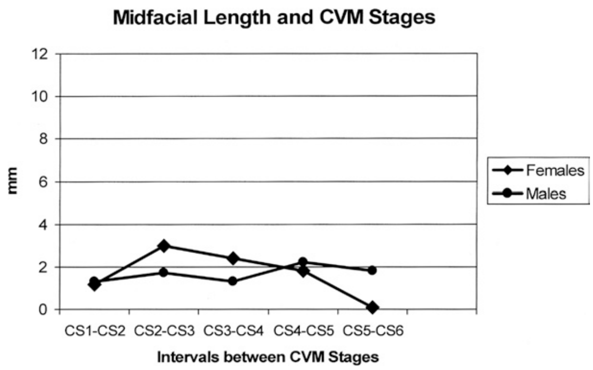

Fig 1. Average differences between CVM stages for midfacial length in Class III subjects.

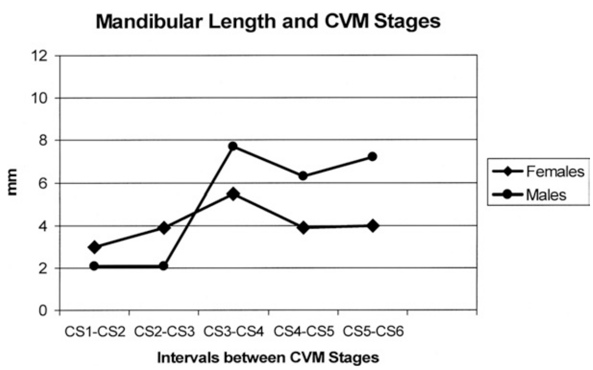

Fig 2. Average differences between CVM stages for mandibular length in Class III subjects.

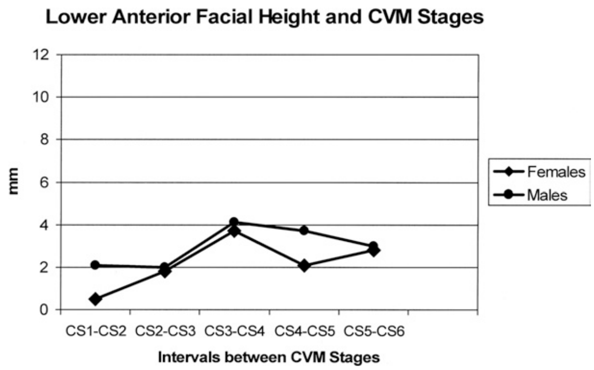

Fig 3. Average differences between CVM stages for lower anterior facial height in Class III subjects.

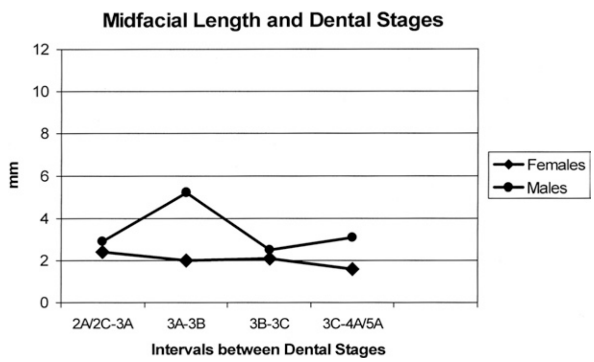

Fig 4. Average differences between dental stages for midfacial length in Class III subjects.

length (Co-Gn), upper and lower anterior facial heights (N-ANS and ANS-Me), and dentoalveolar height at the maxillary molar (U6-PP) and mandibular incisor (L1-Me). The transition from CS5 to CS6 showed significant increases in the position of the chin in relation to nasion perpendicular (Pog-Na perp), Co-Gn, maxillomandibular differential, and protrusion of the lower lip relative to the E-plane. The decreases in ANB angle and Wits appraisal were significant as well when CS5 was compared with CS6 (Table II, Figs 1-3).

Analysis of dental stages

In the female subjects, the comparison between stages 2A/2C and 3A showed significant increases for length of the anterior cranial base (S-N), total mandibular length (Co-Gn), upper anterior facial height (N-ANS), and dentoalveolar height at the maxillary molar (U6-PP) and mandibular incisor (L1-Me). A significant sagittal advancement of the maxillary incisors (U1- Pt A) along with their proclination (U1-SN), and a significant reduction of the interincisal angle were found in this initial interval. The same comparisons were significant for the transition from stage 3A to stage 3B, with the addition of significant increases in the sagittal position of the chin in relation to nasion perpendicular, maxillomandibular differential, lower anterior facial height (ANS-Me), and dentoalveolar height of the maxillary incisor (U1-ANS). The differences in the inclination of the maxillary incisors to S-N and in the interincisal angle were not significant during this interval. During the transition from stage 3B to stage 3C, the increases in total mandibular length (Co-Gn), maxillomandibular differential, molar relationship, and upper anterior facial height (N-ANS) were all significant. In the transition from 3C through 4A/5A, significant increases were recorded for Co-Gn, maxillomandibular differential, and lower anterior facial height (ANS-Me). Significant differences were found also for dentoalveolar height at the maxillary incisor (U1-ANS), maxillary molar (U6-PP), and mandibular incisor (L1-Me) (Table III [online, go to www.mosby/AJODO/com], Figs 4-6).

In the males, there were a few statistically significant differences in the transition from stage 2A/2C to stage 3A: significant increases in Co-Gn, upper anterior

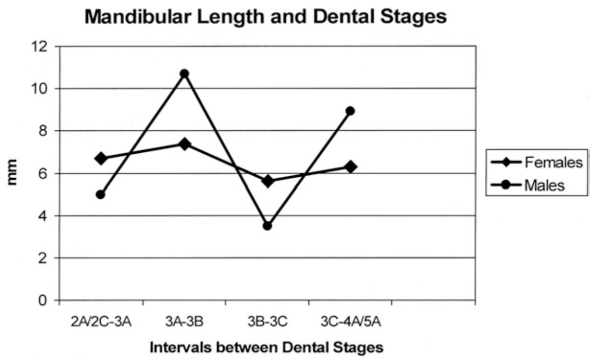

Fig 5. Average differences between dental stages for mandibular length in Class III subjects.

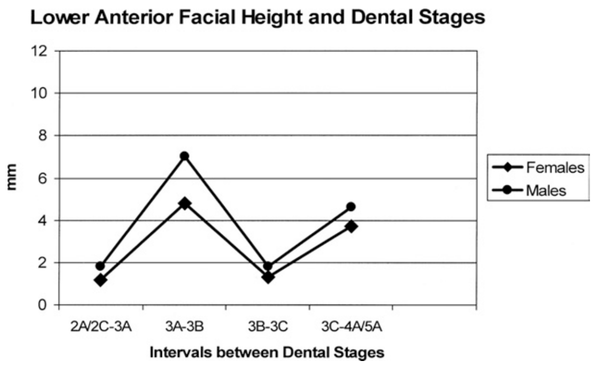

Fig 6. Average differences between dental stages for lower anterior facial height in Class III subjects.

facial height (N-ANS), sagittal advancement of the maxillary incisors (U1- Pt A) with their proclination (U1-SN), and a significant reduction of the interincisal angle. Many significant differences were found between stages 3A and 3B: increases in the length of anterior cranial base (S-N), Co-Gn, maxillomandibular differential, and molar relationship. The comparison between stage 2A/2C with stage 3A also showed significant increases for upper and lower anterior facial heights (N-ANS and ANS-Me), in distance of the maxillary molar from the palatal plane (U6-PP), and in dentoalveolar height at the mandibular incisor (L1-Me), and a significant proclination of the maxillary incisors (U1-ANS and U1-Pt A). During the transition from stage 3B to stage 3C, only the increases in total mandibular length (Co-Gn) and lower anterior facial height (ANS-Me) were significant. In the transition from 3C through 4A/5A, significant increases were recorded for Co-Gn, maxillomandibular differential, and upper and lower anterior facial height (N-ANS and ANS-Me). Significant differences were found also for dentoalveolar height at the maxillary molar (U6-PP) and mandibular incisor (L1-Me). The sagittal position of the lower lip relative to the E-plane also showed significant increases (Table III, Figs 4-6).

DISCUSSION

In this investigation, we attempted for the first time to describe trends of growth in Class III malocclusion by analyzing a large cross-sectional white sample at various stages of skeletal and dental maturation. The CVM method[26,27] and the dental stages according to Hellman[17,18] were used to create consecutive stages across the circumpubertal period of Class III subjects. Findings of notable interest addressed topics of both physiological and clinical relevance in the Class III patient, such as the pubertal peak in mandibular growth, changes in the maxilla and the vertical dimensions of the face and profile, and duration of active growth.

As staged through the CVM method, the male groups had the most evident trends of growth in the Class III sample. No significant changes in subsequent CVM stages were found for cranial base and maxillary measurements. Cranial flexure was reduced when compared with values for normal subjects at all developmental stages. The atlas by Riolo et al[28] reported that the cranial flexure angle was about 130° at all ages, whereas the mean value in our male Class III samples was consistently between 121° and 122° with no significant changes in subsequent stages. A reduced cranial flexure and, consequently, an advanced position of the glenoid fossa are confirmed as anatomical characteristics of Class III malocclusion throughout the developmental ages.[13,33]

Particularly interesting were the findings related to changes in the mandibular region. The between-stage differences in total mandibular length became significant at the CS3-CS4 interval; mandibular length in the male Class III subjects had the greatest difference between CVM stages: approximately 8 mm. Therefore, Class III patients have the peak in mandibular growth at the same maturation stage as those with normal occlusion,[26,27] from CS3 through CS4 in CVM. The pubertal peaks in mandibular growth occurred between the ages of 11 years 4 months and 12 years 10 months in the girls, and 12 years 8 months and 14 years 2 months in the boys. These data also show that the duration of the peak interval is approximately 6 months longer in Class III patients of both sexes than in those with normal occlusion with an average CS3-CS4 interval of 1 year. The longer interval in part can account for the large increases in mandibular dimensions in the Class III subjects during the growth spurt, as assessed here.

The increases in mandibular length continued to be significant also at later maturational intervals in our Class III samples. Total mandibular length showed between-stage differences of about 6 mm from CS4 to CS5 and about 7 mm from CS5 to CS6 in the males. A similar trend was found in the Class III female samples. In spite of differences between the 2 sexes in the amount of between-stage changes (agreeing with previous evidence of sexual dimorphism in Class III malocclusion[15]), from CS3 to CS4 (peak interval), total mandibular length had a significant difference of 5.5 mm in the girls, and the CS4-CS5 and CS5-CS6 differences were both about 4 mm. These data suggest that the amount of increase in mandibular length at postpeak intervals is much greater in Class III patients (both male and female) than in Class I patients, whose CS4-CS5 and CS5-CS6 increases in Co-Gn are expected to be 2 to 3 mm.[26,27] Active, clinically significant growth in the mandible, especially with respect to normal trends of growth in subjects with Class I occlusion, appears to continue for a long period after the adolescent growth spurt in those with Class III malocclusion (up to about 18 years in our samples).

The finding of prolonged significant increases in mandibular length was confirmed by the analysis of the differences between the dental stages in subjects with Class III malocclusion of both sexes. Total mandibular length increased significantly at every interval between dental stages up to the eruption of the second and third molars. The amount of increase in mandibular length during the permanent dentition period (interval between dental stages 3C and 4A/5A) was approximately 9 mm in male subjects and more than 6 mm in females. A similar amount of increase (about 7 mm) was found by Miyajima et al[16] in Japanese Class III female subjects during the same developmental interval. No significant between-stage differences were recorded for the growth of the maxilla.

When the lack of significant between-stage differences for maxillary growth and advancement are considered, it is easily understood that excessive amounts of mandibular lengthening from the pubertal intervals onward were responsible for significant concurrent worsening of the maxillomandibular differential in Class III subjects of both sexes when analyzed with both the CVM method and the stages of dental development. At the final stages, significant protrusion of the lower lip relative to the E plane became apparent as well, thus indicating late worsening of the Class III profile.

The outcomes of this investigation agree with the observations by Deguchi et al,[19] who described worsening of Class III skeletal characteristics along with growth, mainly due to continuous mandibular advancement relative to the maxilla. The Class III sample studied by Battagel[14] showed also that the maximum change for facial characteristics in the female groups occurred between the average ages of 11 and 12 years but continued after age 15. In Class I girls aged 14 to 17 years, facial growth essentially had ceased, but development remained active in the Class III group. The Japanese female sample with Class III malocclusion studied by Miyajima et al[16] using dentitional stage categorization showed similar trends: the maxilla showed a retrusive position at an early developmental stage and retained a fairly constant anteroposterior relationship to the cranial base structures with continued development, whereas mandibular position worsened with growth. None of these previous studies, however, analyzed growth trends in Class III malocclusion with a reliable indicator of skeletal maturity.

As for the vertical measurements, between-stage differences became significant during the peak interval (CS3-CS4) in both sexes with Class III malocclusion. These increases were found in skeletal and dentoalveolar measurements for vertical development. The analysis of dental stages showed that these pubertal changes in vertical characteristics occurred during the late mixed dentition, corresponding with the eruption of the canines and the premolars. However, late stage intervals (CS5 and CS6) and dental stages 3C to 4A/5A showed significant increases in vertical dimensions, corresponding with the completion of the permanent dentition, thus confirming previous findings by Miyajima et al[16] in Japanese female Class III subjects.

The persistence of typical Class III growth characteristics well beyond the adolescent growth spurt into early adulthood as found in this large cross-sectional study of growth trends in Class III malocclusion has important clinical consequences. A much longer period of active mandibular growth, the absence of any catch-up growth by the maxilla, and the significantly more vertical direction of facial growth during late adolescence appear to be unfavorable aspects of Class III malocclusion in both sexes during the postpubertal stages. Treatment planning with orthodontic or orthopedic appliances should take into account this pattern of prolonged mandibular growth, in terms of duration of retention and timing for the evaluation of stability of treatment protocols. The timing for orthognathic surgery in Class III patients, as well as "surgical age" for other procedures in dentistry (eg, implants in the mandibular arch), should also be considered carefully in light of our findings indicating that mandibular growth continues into young adulthood in all patients with Class III malocclusion.

CONCLUSIONS

In this large cross-sectional study, we aimed to derive growth trends in white male and female subjects with Class III malocclusion by using both skeletal and dental maturation staging. The findings can be summarized as follows.

1. The pubertal peak in mandibular growth occurs between CS3 and CS4 in CVM, with average increases in total mandibular length of about 8 and 5.5 mm in Class III boys and girls, respectively; the average duration of the peak interval CS3 to CS4 is approximately 18 months in Class III subjects of both sexes.
2. Increases in maxillary dimensions between subsequent maturation stages are not significant in Class III subjects when evaluated with either skeletal or dentitional stages.
3. Significant changes in total mandibular length continued until young adulthood (18 years on average), with increases between late maturation stages (CS4-CS6) that were twice greater than in subjects with normal occlusion for the Class III females, and 3 times greater than in subjects with normal occlusion for the Class III males.
4. Increases in vertical facial dimensions in Class III subjects occurred at both the pubertal growth spurt (corresponding with the eruption of canines and premolars) and late developmental stages (corresponding with tge complete eruption of second and third molars).

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Table II. Descriptive statistics and comparison of craniofacial measurements at subsequent stages in CVM (CS)

	CS1 (n = 167)		*CS2 (n = 51)*		*CS3 (n = 60)*		*CS4 (n = 85)*		*CS5 (n = 90)*		*CS6 (n = 107)*						
	mean age: 8 y 2 mo		*mean age: 10 y 8 mo*		*mean age: 11 y 8 mo*		*mean age: 12 y 10 mo*		*mean age: 14 y 1 mo*		*mean age: 17 y 2 mo*						
Females	*X*	*SD*	*X*	*SD*	*X*	*SD*	*X*	*SD*	*X*	*SD*	*X*	*SD*	*1 vs 2*	*2 vs 3*	*3 vs 4*	*4 vs 5*	*5 vs 6*
Cranial base																	
SNFH (°)	8.9	2.9	9.5	2.7	8.6	3.1	9.8	2.8	9.2	3	9.1	2.9	NS	NS	NS	NS	NS
S-N (mm)	67.9	3.5	68.5	3.5	70.2	4.3	71.1	3.4	71.5	3.6	72.4	3.6	NS	NS	NS	NS	NS
Cranial flexure (°)	121.8	5.4	122	4.9	123.1	5.2	122.9	5.4	123.2	5.5	123	5.6	NS	NS	NS	NS	NS
Maxillary skeletal																	
SNA angle (°)	80.3	3.3	80.2	3.9	80	4.6	79.8	3.1	81	3.9	80.7	3.6	NS	NS	NS	NS	NS
PtA to NaPerp (mm)	−0.7	2.6	−0.3	3.6	−1.4	3.5	−0.5	3.2	0.2	3.7	−0.4	3.7	NS	NS	NS	NS	NS
PP-FH (°)	−0.5	3.2	−1.1	3.2	−0.1	4.1	−1	3.3	−0.4	2.9	0.5	3.9	NS	NS	NS	NS	NS
Co-Pt A (mm)	82.1	4.5	83.3	4.6	86.3	5.9	88.7	5.2	90.5	5.1	90.4	4.7	NS	NS	NS	NS	NS
Mandibular skeletal																	
SNB angle (°)	79.4	3.2	79.9	3.5	79.8	3.7	79.7	3.1	80.9	3.7	81.2	3.6	NS	NS	NS	NS	NS
Pog-Na Perp (mm)	0.4	1.2	0.9	1.4	1.4	2.5	1.5	1.6	1.5	1.8	2.4	1.8	NS	NS	NS	NS	NS
Facial angle (°)	88.5	2.9	90	3.5	89.1	3	90.3	3	90.9	3	91.4	3.4	NS	NS	NS	NS	NS
Co-Gn (mm)	106.4	6.3	109.4	6.5	113.3	7.7	118.8	7.8	122.7	6.7	126.7	6.2	NS	NS	*	*	*
Maxillary/mandibular																	
MPA (°)	25.9	4.3	24.7	5	25.7	4.9	26.9	5.6	25.8	5.4	25.7	5.6	NS	NS	NS	NS	NS
ANB angle (°)	0.9	2.2	0.3	2	0.2	2.7	0.1	2	0.1	2.2	−0.5	3	NS	NS	NS	NS	NS
Wits (mm)	−4.2	2.5	−4.6	2.4	−4.9	2.8	−5	2.8	−5.1	2.9	−5.7	4.1	NS	NS	NS	NS	NS
Mx-Md diff (mm)	24.4	3.9	26.1	3.5	27.1	3.9	30.1	4.3	32.3	4.6	36.3	4.6	NS	NS	*	*	†
Molar relation (mm)	−3.9	1.7	−4.1	1.8	−4.2	2	−5.1	1.5	−5.5	1.9	−6.1	2.5	NS	NS	NS	NS	NS
Vertical																	
Nasion to ANS (mm)	47.2	3.8	48.4	3.2	50.4	3.6	52.2	3.1	53.2	3.4	55.1	3.7	NS	NS	NS	NS	*
ANS to Me (mm)	60.3	4.6	60.8	5	62.6	4.7	66.3	5.6	68.4	5.7	71.2	5.9	NS	NS	*	*	†
UFH/LAFH ratio	82.4	7.2	83.2	7.9	83.9	6.4	82.5	7.2	80.9	7.3	80.4	7.9	NS	NS	NS	NS	NS
U1-ANS (mm)	24.5	2.7	25	2.8	25.6	3	27.8	3.6	25.5	2.9	29.6	3.1	NS	NS	NS	NS	*
U6-PP (mm)	18.3	2	19.4	2.2	19.8	2.2	22	2	23.6	2.2	25.5	2.4	NS	NS	*	†	†
L1-Me (mm)	36.2	2.4	36.3	2.3	37.5	2.8	38.9	2.6	40	3	41.3	3.2	NS	NS	NS	NS	*
Dentoalveolar																	
U1-Pt A (mm)	1.1	2.7	2.2	2.4	2.9	1.9	3.3	2.3	4.3	2.4	4	2.9	NS	NS	NS	NS	NS
U1-SN (°)	100.3	9	103.3	8.5	105	5.6	103.3	5.4	106.3	6.5	105	7.2	NS	NS	NS	NS	NS
IMPA (°)	88.2	7	87.6	6.7	88	8.4	84	6.3	85.8	7.6	83.9	8.3	NS	NS	NS	NS	NS
FMIA (°)	65.9	6.9	67.7	6.9	66.3	8.8	68.9	6.9	68.4	8.1	70.4	8.4	NS	NS	NS	NS	NS
L1-A Pog (mm)	3	1.9	2.8	2	3.3	2.7	2.8	2.4	3.5	2.6	3.2	2.6	NS	NS	NS	NS	NS
Interincisal angle (°)	136.6	11.7	134.9	11.2	132.6	8.8	135.9	9.2	132.9	11.7	136.3	10.8	NS	NS	NS	NS	NS
Soft tissue																	
UL-E plane (mm)	−4	2.3	−4.3	1.8	−5.1	2.3	−5.5	2.6	−6.4	2.7	−8.0	2.9	NS	NS	NS	NS	NS
LL-E plane (mm)	−0.7	2.4	−1	2.2	−1.6	2.7	−2.1	2.5	−2.4	3	−4	2.9	NS	NS	NS	NS	*
Nasolabial angle (°)	112.4	12.8	112.8	11.8	112.2	14.9	111	12.2	109.7	12.3	109.8	12	NS	NS	NS	NS	NS

Table II. Continued

	CS1 (n = 163)		CS2 (n = 62)		CS3 (n = 61)		CS4 (n = 82)		CS5 (n = 65)		CS6 (n = 98)						
	mean age: 8 y 10 mo		mean age: 11 y 3 mo		mean age: 12 y 9 mo		mean age: 14 y 2 mo		mean age: 15 y 4 mo		mean age: 18 y 3 mo						
Males	*X*	*SD*	*X*	*SD*	*X*	*SD*	*X*	*SD*	*X*	*SD*	*X*	*SD*	*1 vs 2*	*2 vs 3*	*3 vs 4*	*4 vs 5*	*5 vs 6*
Cranial base																	
SNFH (°)	8.3	2.7	8.2	3.6	8.5	3.1	9.2	2.5	8.6	2.7	7.7	3.5	NS	NS	NS	NS	NS
S-N (mm)	71.2	3.6	71.8	3.5	71.8	3.6	73.7	3.6	76	3.9	77.3	4.2	NS	NS	NS	NS	NS
Cranial flexure (°)	121	4.7	121.1	5.4	122.1	4.8	122.3	4.6	122.9	5.2	121.8	6	NS	NS	NS	NS	NS
Maxillary skeletal																	
SNA angle (°)	80.2	3.7	80.5	3.6	79.3	4.5	81	3.5	81.8	4.6	81.1	4.4	NS	NS	NS	NS	NS
PtA to NaPerp (mm)	−1.4	2.8	−1.3	2.8	−2.3	4.2	−0.8	3.2	−0.3	4.4	−1.5	4.6	NS	NS	NS	NS	NS
PP-FH (°)	−0.5	3.2	−0.2	2.8	0.3	3.4	0.0	3.2	0.8	3.5	0.9	4.4	NS	NS	NS	NS	NS
Co-Pt A (mm)	84.8	4.6	86.1	5	87.8	4.8	89.1	4.1	92.3	6.3	94.1	5.6	NS	NS	NS	NS	NS
Mandibular skeletal																	
SNB angle (°)	79.5	3.5	80	3.2	79.4	3.2	80	3.1	80.5	3.8	82.4	4.5	NS	NS	NS	NS	NS
Pog-Na perp (mm)	0.3	1.2	0.7	0.9	0.8	1.3	1.2	1.6	1.3	1.3	2.9	2.1	NS	NS	NS	NS	*
Facial angle (°)	88	2.9	88.5	2.6	88.4	2.7	89.9	2.8	89.7	3.7	91.4	4	NS	NS	NS	NS	NS
Co-Gn (mm)	111.3	6.2	114.4	6.6	116.5	7.3	124.2	5.9	130.5	6.5	137.7	8.4	NS	NS	†	†	†
Maxillary/mandibular																	
MPA (°)	26.5	4.5	26.5	5	27.5	4.5	27.2	4.5	27.2	5.4	25.4	6.1	NS	NS	NS	NS	NS
ANB angle (°)	0.7	2.2	0.5	2.3	−0.1	2.7	0.9	2.5	1.2	2.5	−1.3	2.8	NS	NS	NS	NS	*
Wits (mm)	−4.4	2.4	−4.6	2.6	−5.3	2.7	−4.4	3	−3.7	3.7	−5.9	4.5	NS	NS	NS	NS	*
Mx-Md diff (mm)	25.3	3.8	27.3	3.8	29.3	4.1	32	4.1	32.2	4	41	6	NS	NS	*	NS	*
Molar relation (mm)	−3.8	1.7	−4.1	1.9	−4.4	2.2	−6.1	3	−6.4	1.9	−6.9	3.6	NS	NS	*	NS	NS
Vertical																	
Nasion to ANS (mm)	48.4	3.4	50.4	4.9	51.9	4.2	55.9	3.3	57	3.6	58.7	4.3	NS	NS	†	NS	NS
ANS to Me (mm)	62.6	4.9	64.9	5.2	66.9	5.5	71	5.5	74.7	6.8	77.6	6.6	NS	NS	†	*	NS
UFH/LAFH ratio	81.3	6.8	81.4	7.5	81.3	7.9	82.3	6.9	80.1	6.8	78.7	7.6	NS	NS	NS	NS	NS
U1-ANS (mm)	25.6	2.9	26.8	3.1	27.6	3.4	29.3	2.9	30.2	3.5	31.2	3.5	NS	NS	NS	NS	NS
U6-PP (mm)	19.1	2.3	20.7	2.8	21.9	2.8	23.9	2.5	25.8	2.9	27.9	3.2	NS	NS	†	†	NS
L1-Me (mm)	37.9	2.6	39	2.5	39.6	3	42.1	3.1	44.1	3.3	45.6	3.3	NS	NS	†	*	NS
Dentoalveolar																	
U1-Pt A (mm)	0.7	2.4	1.7	2.6	2.3	2.3	3.6	2.5	3.8	2.6	4.4	2.1	NS	NS	NS	NS	NS
U1-SN (°)	99.7	8.8	102.1	6.9	102.4	6.4	103.9	6.3	105.1	6.4	106.1	7.9	NS	NS	NS	NS	NS
IMPA (°)	87.3	6.3	86.2	7.3	85.8	6	85.9	7.3	85.3	7.1	83.6	6.9	NS	NS	NS	NS	NS
FMIA (°)	66.2	6.3	67.3	6.8	66.7	6.2	66.9	8.2	67.4	7.6	71	7.7	NS	NS	NS	NS	NS
L1-A Pog (mm)	3.1	1.7	3.3	2	3.6	2.2	3.6	2.5	3.3	2.4	3.7	2.9	NS	NS	NS	NS	NS
Interincisal angle (°)	138.2	11.6	137	10.2	135.8	8.7	133.8	9.8	133.7	9.3	137.2	10.4	NS	NS	NS	NS	NS
Soft tissue																	
UL-E plane (mm)	−3.3	2.2	−4.1	2.4	−4.3	2.7	−5	2.7	−6.3	2.7	−8.1	3.4	NS	NS	NS	NS	NS
LL-E plane (mm)	0.1	2.3	−1	2.4	−0.7	3.2	−1.3	2.9	−1.9	3.4	−4	2.9	NS	NS	NS	NS	*
Nasolabial angle (°)	112.4	12.7	114.2	15.5	114.5	12.5	116.2	9.8	111.6	9.7	106.7	12.8	NS	NS	NS	NS	NS

NS, Not significant; *X,* mean; *Mx,* maxillary; *Md,* mandibular; *diff,* difference.
*$P < .05$; †$P < .01$.

Table III. Descriptive statistics and comparison of craniofacial measurements at subsequent stages in dental development

	2A/2C (n = 35)		*3A (n = 189)*		*3B (n = 69)*		*3C (n = 64)*		*4A/5A (n = 162)*					
Females	*X*	*SD*	*X*	*SD*	*X*	*SD*	*X*	*SD*	*X*	*SD*	*2A/2C vs 3A*	*3A vs 3B*	*3B vs 3C*	*3C vs 4A/5A*
Cranial base														
SNFH (°)	8.5	2.8	9	2.9	9.7	2.6	8.5	2.9	9.4	2.9	NS	NS	NS	NS
S-N (mm)	65.6	2.9	68.5	3.6	70.1	3.4	71.4	3.6	72.4	3.4	*	*	NS	NS
Cranial flexure (°)	120.5	5	122.5	5.3	122.4	4.3	121.5	5.4	123.6	5.9	NS	NS	NS	NS
Maxillary skeletal														
SNA angle (°)	80.7	3.3	80.2	3.7	79.8	3.1	80.9	3.8	80.7	3.8	NS	NS	NS	NS
PtA to NaPerp (mm)	−0.7	2.5	−0.8	2.9	−0.5	3.2	−0.7	3.4	0.1	3.7	NS	NS	NS	NS
PP-FH (°)	−0.9	3.5	−0.4	3.4	−0.9	3.3	0.6	3.7	−0.1	3.4	NS	NS	NS	NS
Co-Pt A (mm)	80	4	82.4	4.6	84.4	4.9	86.5	4.8	88.1	4.6	NS	NS	NS	NS
Mandibular skeletal														
SNB angle (°)	79.2	3	79.5	3.5	79.7	3.1	80.9	3.6	80.9	3.7	NS	NS	NS	NS
Pog-Na Perp (mm)	−0.2	1.2	0.6	1.2	1.4	1.4	1.8	2.2	2	1.8	NS	†	NS	NS
Facial angle (°)	87.6	2.8	88.9	3.1	90.2	2.9	90.4	3.5	91.3	3.3	NS	NS	NS	NS
Co-Gn (mm)	101.6	5	108.3	6.2	115.7	7.6	120.3	6.1	126.6	7.1	†	†	†	†
Maxillary/mandibular														
MPA (°)	27.9	4.1	25.4	4.7	26.8	5.1	26.3	5.7	25.6	5.3	NS	NS	NS	NS
ANB angle (°)	1.5	2	0.7	2.2	0.2	1.8	0	2.7	−0.1	2.8	NS	NS	NS	NS
Wits (mm)	−4.2	2.1	−4.3	2.7	−5.2	3.3	−5.3	3.3	−5.4	3.7	NS	NS	NS	NS
Mx-Md diff (mm)	22.6	3.2	25.1	3.8	29.8	4.6	31.9	4.8	34.5	5.3	NS	†	*	†
Molar relation (mm)	−4.1	1.7	−3.9	1.7	−4.7	2	−5.8	1.8	−5.7	2.4	NS	NS	*	NS
Vertical														
Nasion to ANS (mm)	44.8	3	48.1	3.5	51.3	3.5	53.5	3.7	54.5	3.7	†	†	†	NS
ANS to Me (mm)	59.5	4.7	60.7	4.9	65.5	5.4	66.8	5.7	70.5	5.9	NS	†	NS	†
UFH/LAFH ratio	79.6	6.5	83.2	7.6	81.7	6.8	83.4	7.1	80.4	7.5	NS	NS	NS	NS
U1-ANS (mm)	23.6	2.7	24.8	2.9	27.4	3.1	27.6	3.2	29.3	3.1	NS	†	NS	†
U6-PP (mm)	17.2	1.5	18.8	2.1	21.4	3.6	22.6	2.4	24.8	2.5	*	†	NS	†
L1-Me (mm)	34.9	2.1	36.7	2.5	38	2.8	39.4	3.1	41.1	3	*	†	NS	†
Dentoalveolar														
U1-Pt A (mm)	−0.8	2.2	1.7	2.6	3.1	1.9	3.8	2.8	4.2	2.6	†	†	NS	NS
U1-SN (°)	94.5	9.6	102.5	8.1	103.6	5.5	105.6	6.7	105.2	6.9	†	NS	NS	NS
IMPA (°)	86.6	5.7	88.8	6.8	84.6	7.6	84.9	8.2	84.7	7.8	NS	NS	NS	NS
FMIA (°)	65.5	6.3	6.8	6.7	68.6	7.2	68.8	9.7	69.6	8	NS	NS	NS	NS
L1-A Pog (mm)	2.2	1.8	3.2	1.9	2.9	2.3	3	2.9	3.3	2.6	NS	NS	NS	NS
Interincisal angle (°)	142.5	10.5	134.3	10.7	135.2	8.8	134.6	12.7	135	10.7	†	NS	NS	NS
Soft tissue														
UL-E plane (mm)	−4.1	2.6	−4.1	2.1	−5.1	2.3	−6.6	3.1	−7.6	2.8	NS	NS	NS	NS
LL-E plane (mm)	−1	2.3	−0.7	2.4	−1.8	2.3	−1.8	3.1	−3.5	3.1	NS	NS	NS	*
Nasolabial angle (°)	114.1	12.9	112.8	12.6	112.5	10.8	110.5	11.2	109	12.7	NS	NS	NS	NS

Table III. Continued

Males	2A/2C (n = 29)		3A (n = 197)		3B (n = 59)		3C (n = 45)		4A/5A (n = 165)		2A/2C vs 3A	3A vs 3B	3B vs 3C	3C vs 4A/5A
	X	SD	X	SD	X	SD	X	SD	X	SD				
Cranial base														
SNFH (°)	7.2	4.6	8.3	2.7	9.2	2.6	9	3.2	8.2	3.2	NS	NS	NS	NS
S-N (mm)	68.7	3	70.7	3.5	73.1	3.6	74.6	3	76.6	4.3	NS	*	NS	*
Cranial flexure (°)	120.5	4.7	121	4.9	121.7	4.4	121.7	5.4	122.3	5.5	NS	NS	NS	NS
Maxillary skeletal														
SNA angle (°)	79.6	3.4	80.2	3.8	80.5	4	80.8	3.6	81	4.4	NS	NS	NS	NS
PtA to NaPerp (mm)	−2.7	2.5	−1.4	2.9	−0.4	3.4	−0.3	3.7	−1	4.5	NS	NS	NS	NS
PP-FH (°)	0.4	3.1	−0.4	3.3	−0.2	2.8	−0.2	3.3	0.6	4.1	NS	NS	NS	NS
Co-Pt A (mm)	82	3.9	84.9	4.6	90.1	4.7	92.6	4.2	95.7	5.8	NS	†	*	†
Mandibular skeletal														
SNB angle (°)	79.3	3.9	79.6	3.4	79.6	3.2	79.9	3.5	81.4	4.2	NS	NS	NS	NS
Pog-Na Perp (mm)	−0.1	1.3	0.5	1.1	1.2	1.6	1.2	1.9	2.3	2	NS	NS	NS	NS
Facial angle (°)	86.3	3.2	88.2	2.6	89.4	3	89.5	3	90.6	3.7	NS	NS	NS	NS
Co-Gn (mm)	105.6	5.2	110.6	5.7	121.3	6.3	124.8	5.8	133.7	9.2	*	†	*	†
Maxillary/mandibular														
MPA (°)	28	3.5	26.3	4.6	27.8	5.5	27.2	4.6	26.2	5.7	NS	NS	NS	NS
ANB angle (°)	0.3	2.3	0.7	2.3	0.9	2.5	0.8	2.2	−0.4	2.8	NS	NS	NS	NS
Wits (mm)	−3.9	2.6	−4.4	2.3	−4.7	2.8	−4.2	2.8	−5.1	4.2	NS	NS	NS	NS
Mx-Md Diff (mm)	23.7	4.2	25.7	3.4	31.3	3.8	32.2	3.8	38	6.4	NS	†	NS	†
Molar relation (mm)	−4.2	1.5	−3.7	1.9	−5.2	1.8	−5.4	2.2	−6.4	3.2	NS	†	NS	NS
Vertical														
Nasion to ANS (mm)	46.5	5.1	49.2	3.7	53.7	3.5	55.4	3.9	57.8	4	*	†	NS	†
ANS to Me (mm)	61.1	4.5	62.9	4.3	69.9	5.7	71.7	5.1	76.3	6.9	NS	†	*	†
UFH/LAFH ratio	80.5	9.1	82.1	7	80.2	6.8	80.6	8.1	79	7.5	NS	NS	NS	NS
U1-ANS (mm)	24	2.6	25.7	2.6	29.3	3	29.7	2.5	30.9	3.5	NS	†	NS	NS
U6-PP (mm)	18.1	2.3	19.4	2.1	23.2	2.4	24.5	2.4	26.9	3.2	NS	†	NS	†
L1-Me (mm)	36.7	2.1	38.2	2.4	41.2	3.2	42.1	2.7	44.8	3.5	NS	†	NS	†
Dentoalveolar														
U1-Pt A (mm)	−0.8	2.3	1	2.3	3	2.3	4	2.2	4.3	2.8	*	†	NS	NS
U1-SN (°)	94.8	11.2	101.1	7.6	103	5.8	104.7	5.7	105.8	7.1	†	NS	NS	NS
IMPA (°)	82.4	6.6	85.7	6.5	84.6	6.4	85.2	6.9	84.6	7.1	NS	NS	NS	NS
FMIA (°)	69.5	6.5	66.1	6.4	67.6	7.5	65.6	8	67.2	7.7	NS	NS	NS	*
L1-A Pog (mm)	1.9	1.6	3.2	1.8	3.4	2.5	3.8	2.7	3.7	2.6	NS	NS	NS	NS
Interincisal angle (°)	147.6	13.8	136.8	10.3	135.4	8.7	131.9	8.8	135.2	9.9	†	NS	NS	NS
Soft tissue														
UL-E plane (mm)	−3.8	2.6	−3.6	2.3	−4.4	3	−5.7	2.4	−7.4	3.6	NS	NS	NS	NS
LL-E plane (mm)	−0.8	2.8	−0.2	2.3	−1	3.2	−1.8	2.8	−3.5	3.4	NS	NS	NS	*
Nasolabial angle (°)	109.5	18.6	114.1	13.2	115.2	11.4	113	9.1	110.8	11.7	NS	NS	NS	NS

NS, Not significant; *X,* mean; *Mx,* maxillary; *Md,* mandibular; *diff,* difference.
*$P < .05$; †$P < .01$.