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Original article

# Influence of BMI percentile on craniofacial morphology and development in children and adolescents

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## Summary

**Background:** The prevalence of childhood and adolescent obesity is increasing worldwide. Reports suggest that elevated body mass index (BMI) is associated with larger craniofacial dimensions and advanced dental and skeletal development. Such an association is important for timing orthodontic treatment relative to pubertal growth and dental eruption.
**Materials and Methods:** To evaluate associations between BMI, craniofacial morphology, dental age, and cervical vertebrae maturation staging (CVMS), 400 participants were consecutively selected (8–15 years, $n$ = 200 overweight and obese BMI >85%, 200 normal weight) from the University of North Carolina database. Records were analysed for cephalometric measures, Demirjian index values, and CVMS. Bivariate statistics and linear regression analysis evaluated whether CVMS, dental age, and cephalometric dimensions varied with BMI.
**Results:** Overweight/obese children and adolescents had a proportionally larger bimaxillary prognathic skeletal pattern compared to those of normal weight. These cephalometric measurements [articulare–gnathion (Ar–Gn), condylion–anterior nasal spine (Co–ANS), sella–gonion (S–Go), nasion–menton (N–Me), anterior nasal spine–menton (ANS–Me), sella-nasion-A point (SNA), sella-nasion-B point (SNB), and sella-nasion-pogonion (SNPg)] were significantly different [statistically ($P$ < 0.05) and clinically (>2 mm or >2 degrees)] between the two study groups, with a linear relationship between BMI percentile and craniofacial dimension. The overweight/obese BMI group had a mean dental age 1.4 years advanced relative to the normal weight group ($P$ < 0.05), with an advancement of nearly one CVM stage between the ages of 12 and 14 ($P$ < 0.05).
**Limitations:** The study is retrospective.
**Conclusions:** Obese/overweight children and adolescents have proportionally larger antero-posterior and vertical dimensions and are more likely to experience advanced dental and skeletal maturation. Obese/overweight subjects may enter their growth spurt at a younger age and have earlier eruption of teeth, affecting treatment timing. BMI percentile should be a consideration for orthodontic treatment in growing patients.

## Introduction

Obesity rates are increasing dramatically around the world, causing significant health issues in every segment of the population, including children and adolescents (1–2). Health sequelae include cardiovascular disease, hypertension, type 2 diabetes mellitus, obstructive sleep apnoea (OSA), increased risk of death from COVID-19, and reduced quality of life with psychosocial problems (1–9). The onset of type 2 diabetes, a disease once thought to only affect adults, is now seen in children due to obesity (10). Minimal to no improvement has been seen in the US obesity epidemic, as children's lifestyles are progressively more sedentary; children spend less time exercising and playing outside, while instead focusing on stationary activities like playing video games and browsing the internet (11–13). For children aged 6–11, the National Health and Nutrition Examination Survey revealed a striking increase in the prevalence of childhood obesity, from 4.2 per cent in 1965 to 15.8 per cent in 2002 and 18.5 per cent in 2016 (14–15). Adolescents aged 12–19 had a similar trajectory, with 4.6 per cent of children being obese in 1965, growing to 20.6 per cent in 2016. The prevalence of obesity among non-Hispanic black (22.0 per cent) and Hispanic (25.8 per cent) youth was higher than among both non-Hispanic white (14.1 per cent) and non-Hispanic Asian (11.0 per cent) youth (15). Childhood obesity is occurring at progressively younger ages in a growing fraction of the population.

Weight is typically classified by body mass index (BMI), a numerical score used to classify a person's weight status. In adults, BMI is calculated as weight (kilograms) divided by height (metres squared) (1–2). For children aged 2–20 years old (yo), BMI is interpreted as a percentile, calculated from growth charts published by the Centers for Disease Control (CDC) (16).

In addition to overall growth, obesity has a profound impact on dental development and craniofacial growth. Excess weight in children is associated with early onset of puberty due to increased Leptin secretion from adipocytes (7, 17). Elevated BMI also correlates with accelerated dental development and cervical vertebrae maturation (CVM) in children and adolescents (18–21). Not surprisingly, craniofacial growth is also impacted by obesity as obese children and adolescents have exhibited bimaxillary prognathism with greater craniofacial dimensions, despite lower levels of growth hormone (22, 23). They also demonstrated reduced mandibular plane angles and soft-tissue profile convexity (23). Though interesting, most studies had relatively small, homogenous samples (22, 23), Mack *et al.* found advancement of CVM and dental development in a large cohort but did not assess craniofacial dimensions (19). The initial evidence linking BMI to developmental metrics demonstrates the promise of these inquiries while highlighting the need for further investigation with a larger group. Advanced dental and skeletal maturation in overweight children may have significant effects on orthodontic treatment planning, such as the timing of serial extractions and growth modification (7, 24). Serial extractions must be appropriately timed for optimal outcome, and growth modification must occur at peak growth for maximal effect.

Despite the importance of these data for orthodontic care, robust studies linking juvenile BMI percentile with dental, skeletal, and craniofacial developmental metrics are lacking. The purpose of this retrospective cohort study was to investigate the relationships between BMI percentile, craniofacial dimensions, dental maturation age, and CVM stage in growing patients. We hypothesized that craniofacial morphology would be significantly larger for overweight and obese subjects, and their average dental age and CVM stage would be advanced relative to normal weight patients. To this end, 400 subjects were consecutively selected from the University of North Carolina (UNC) Orthodontic database and evaluated for associations between BMI percentile, CVM stage, dental development, and cephalometric dimensions. This is the first large-scale investigation into these factors in a well-distributed population, derived from a region plagued by obesity.

## Methods

### Sample preparation

This retrospective study used data obtained from patients treated in the post-graduate orthodontic clinic in the UNC Adams School of Dentistry from September 2014 to September 2018. Potential subjects' records were reviewed for inclusion and exclusion criteria (Table 1). Records included height, weight, date of birth, gender, race, ethnicity, date of pretreatment records, medical history, and panoramic and lateral cephalometric radiographs. At the pretreatment records appointment, patients were asked to remove their overgarments and shoes before standing on a standard mechanical scale with a mounted standiometer to measure weight and height, respectively. Using data from Sadeghianrizi *et al.*, power calculations of seven measurements [sella-nasion-A point (SNA), sella-nasion-B point (SNB), sella-nasion-pogonion (SNPg), sella–nasion–gonion–gnathion (S–N–Go–Gn), Go–pogonion (Go–Pg), N–anterior nasal spine (N–ANS), and sella–gonion (S–Go)] were conducted comparing the obese and control groups; a study sample size of $n$ = 400 total ($n$ = 200 per group, experimental and control) was sufficiently powered (power = 0.9, alpha of 0.05) to detect significant differences in these measurements (22). A total of 1381 potential subjects' records (collected between September 2013 and September 2018) were screened with 981 being excluded due to a disqualifying age, a history of significant medical

**Table 1.** Inclusion and exclusion criteria.

| Inclusion criteria | Exclusion criteria |
|---|---|
| Age ≥8 years but <15 years at the time of pretreatment records | Second, third, and fourth cervical vertebrae not clearly visible on the lateral cephalometric radiograph |
| Pretreatment panoramic and lateral cephalometric radiographs of adequate diagnostic quality taken within 1 month of each other | Presence of congenital anomalies of the second, third, or fourth vertebrae |
| Height and weight recorded within 1 month of the panoramic and lateral cephalometric radiographs | Congenital tooth or craniofacial anomalies visible in the panoramic radiograph |
| Body mass index (BMI) percentile between 5 and 100 (normal weight, overweight, and obese) | Significant medical conditions that would affect physical growth and development |
| A full complement of permanent mandibular teeth excluding third molars. | Craniofacial defects |
| | BMI percentile <5 (underweight) |

condition(s) impacting growth, BMI percentile under 5 per cent, lateral cephalograms with unclear cervical vertebra, or congenital anomalies or defects of the teeth, face, or cervical vertebrae visible on radiograph (Table 1). Consecutive subjects that met inclusion criteria were selected until the sample size of 400 was reached. Experimental subjects were overweight to obese with a BMI percentile greater than or equal to 85 (BMI 85–94.9 per cent is overweight; BMI 95–100 per cent is obese). The control group included patients with a BMI percentile of less than 85, a normal weight. Underweight subjects with a BMI percentile of 4.9 or less were excluded. The protocol for this project was approved by the Institutional Review Boards of Nova Southeastern University (IRB # 2018–658) and the University of North Carolina at Chapel Hill (IRB # 13–2184).

## Cephalometric, dental, and skeletal maturity analyses

Cephalometric radiographs were traced by a single examiner using Dolphin® Imaging software (Dolphin Imaging and Management Solutions, Chatsworth, California, USA). The examiner was blinded to the subjects' identity, weight, height, BMI, and BMI percentile; subjects' radiographs were analysed in random order. Linear and angular measurements in the sagittal and vertical dimensions were taken (Figure 1). A clinically significant difference in mean linear measurement was defined *a priori* as a difference of 2 mm or greater between groups (25). For angular measurements, clinical significance was defined as a difference of 2 degrees or more between mean values (25).

A single examiner assessed pretreatment panoramic radiographs to determine the dental maturity score and developmental age using the Demirjian *et al.* method (20). Briefly, the mesial seven teeth in the lower left quadrant (LL1–LL7) were scored and summed to give an overall Dermirjian score. A dental score of '0' equals no tooth calcification, and a score of '100' denotes complete tooth development. The overall score was then equated to a dental age using a linear regression model (20). The chronological age was based on age in years and months. Dental age advancement was calculated by subtracting chronological age from the calculated dental age. A positive difference reflects an acceleration in dental age and a negative value indicates a delay in dental development (5). Development of the second, third, and fourth cervical vertebrae on the lateral cephalometric radiograph was assessed by the single examiner to determine the CVM stage using the Baccetti *et al.* method (CVMS I–V) (20). BMI percentile was calculated from growth charts published by the CDC (16).

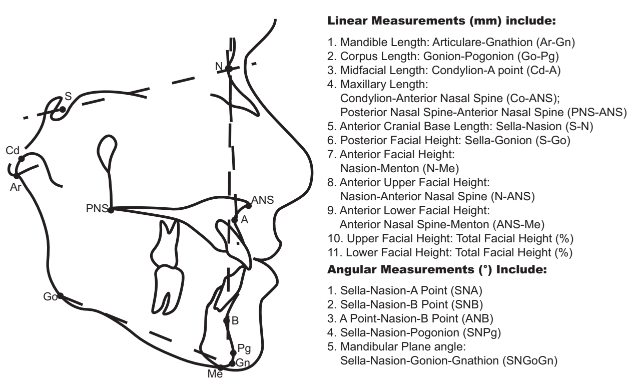


**Figure 1.** Lateral cephalogram tracing points used for linear and angular measurements. Tracing of a lateral cephalogram with landmarks labeled for linear and angular measurements. A: A point, ANS: anterior nasal spine, Ar: articulare, B: B point, Cd: condylion, Gn: gnathion, Go: anatomical gonion, Me: menton, N: nasion, Pg: pogonion, PNS: posterior nasal spine, and S: sella. Dots were used for linear measurements. Dotted lines were used for angular measurements.

Two weeks after initial analyses, 40 subjects from each group ($n$ = 80 total) were selected by a random number generator. The same examiner reanalysed these patients' records for a concordance correlation reliability test, including cephalometric tracing, Demirjian dental scoring, and CVM staging.

## Statistical analysis

Descriptive statistics were calculated for all study variables, including means, standard deviations of continuous variables, and counts and percentages for categorical data. A bivariate analysis was conducted for each BMI group and all age groups within each BMI group with Bonferonni correction for multiple testing. To test the difference between the continuous non-age grouped data and the 8–10 yo groups, a Mann–Whitney $U$ non-parametric test was used. For age groups 11–14 yo, Welch's $t$-test was used. For categorical responses, Fisher's Exact Test was used. Outcome variables included cephalometric craniofacial measurements, CVM stage, Demirjian dental score, dental age, and dental advancement. The difference between normal weight and overweight/obese subjects in these outcome variables was statistically evaluated. Effect size estimates included relevant 95 per cent confidence intervals. A general linear regression model was used, adjusted for race, ethnicity, and gender, with Tukey tests (for three-level models) and Bonferonni correction (for all models) for multiple testing (Figure 3; Supplementary Figure 1; Supplementary Tables 10 and 11). For the reliability test, the concordance correlation coefficient was used. RStudio and R 3.5.4 were used for all statistical analyses (R Studio, Boston, Massachusetts, USA). Statistical significance was accepted at $P < 0.05$. The concordance correlation coefficient test was used to measure intra-examiner reliability (Supplementary Table 12); a single examiner conducted all measurements, so no inter-examiner reliability could be calculated. Rho C concordance values are measured from 0.00 to 1.00, with the closer to 1.00, the better the reliability.

# Results

## Sample demographics

There were equal numbers of subjects in each BMI group ($n$ = 200 per group, 400 total), with equivalent mean chronological ages (12.6 years; Table 2). BMI and gender were considered independent of one another in our sample, while BMI percentile and race were not, consistent with published reports (15).

## Craniofacial measurements

Craniofacial dimensions were significantly different between the normal and overweight/obese groups. Mean mandibular length (Ar–Gn, ages 9, 11, and 13), maxillary length [Co–ANS, ages 12 and 13; posterior nasal spine–anterior nasal spine (PNS–ANS), age 12], posterior face height (S–Go, ages 11, 12, and 13), and anterior face heights (N–Me, age 12; anterior lower third ANS–Me, ages 12 and 13) were significantly larger in the overweight/obese group than in the normal BMI group (Figure 2; Table 3; Supplementary Tables 1–7). Maxillary, mandibular, and pogonial angular measures (SNA, ages 12 and 13; SNB, age 12; and SNPg, age 12) were also significantly larger in the elevated BMI group. These differences were seen when grouped by specific age, as indicated in parentheses, and when amalgamated into cohorts of all

**Table 2.** Sample demographics.

| | | Normal weight 5% < BMI < 85% (*n* = 200) | | Overweight to obese BMI > 85% (*n* = 200) | | |
|---|---|---|---|---|---|---|
| | | Frequency | Percentage (%) | Frequency | Percentage (%) | *P*-value* |
| Race and ethnicity | | | | | | *P* < 0.05 |
| | African American | 13 | 6.5 | 30 | 15.0 | 0.004 (*P* < 0.05)*** |
| | Caucasian | 135 | 67.5 | 108 | 54.0 | |
| | Hispanic | 36 | 18.0 | 53 | 26.5 | |
| | Asian | 11 | 5.5 | 5 | 2.5 | |
| | Other** | 5 | 2.5 | 4 | 2 | |
| Gender | | | | | | |
| | Female | 107 | 53.5 | 116 | 58.0 | 0.36 (*P* > 0.05)*** |
| | Male | 93 | 46.5 | 84 | 42.0 | |
| Age | | | | | | |
| | 8 years | 4 | 2.0 | 5 | 2.5 | |
| | 9 years | 11 | 5.5 | 5 | 2.5 | |
| | 10 years | 19 | 9.5 | 16 | 8.0 | |
| | 11 years | 23 | 11.5 | 34 | 17.0 | |
| | 12 years | 53 | 26.5 | 51 | 25.5 | |
| | 13 years | 54 | 27.0 | 49 | 24.5 | |
| | 14 years | 36 | 18.0 | 40 | 20.0 | |

**P*-values calculated by chi-squared test. *P* < 0.05 is considered significant. Chi-square tests were performed to compare the frequencies of race and gender in each body mass index (BMI) group.

**Racial and ethnic groups included African American, Caucasian, Hispanic, Asian, and other. The 'other' category could include Native American, Alaska Native, Native Hawaiian, and Other Pacific Islanders. Our 'other' sample included only Native Americans.

****P* < 0.05 indicates that race and ethnicity and BMI% are not independent of one another. *P* > 0.05 indicates gender and BMI% are independent of one another.

ages. There were no significant differences between the overweight and obese subgroups (Supplementary Table 8). When stratified by gender, most craniofacial metrics were significantly different between the normal weight and overweight/obese boys and girls; however, there were no significant differences between the male weight groups for maxillary length (Co–ANS and PNS–ANS) and anterior face heights (N–Me and ANS–Me; Supplementary Table 9). Differences in mean maxillary (SNA) and mandibular (SNB) angular measures were statistically distinct for girls, but the boys failed to meet the Bonferroni criteria for significance, (while having a *P*-value less than 0.05).

Among the statistically significant differences, clinical import was evaluated; a difference of 2 mm, 2 degrees, or larger was considered clinically significant (25). With this more stringent criteria, there were significant differences found in mean mandibular length (Ar–Gn, ages 9 and 13), maxillary length (Co–ANS, ages 12 and 13), posterior face height (S–Go, ages 11, 12, and 13), and anterior face heights (N–Me, age 12; anterior lower third ANS–Me, ages 12 and 13) with all ages grouped into one cohort and at the specific ages specified (Figure 2; Table 3; Supplementary Tables 1–7). SNA, SNB, and SNPg had clinically significant increases in the overweight/obese group at age 12 (Supplementary Table 5).

To evaluate how craniofacial measurements varied with BMI percentile, linear regression analysis was performed with data adjusted for gender, race, and ethnicity. All of the craniofacial measurements that were clinically and statistically different between groups varied linearly with BMI percentile, including Ar–Gn, Co–ANS, S–Go, N–Me, ANS–Me, SNA, SNB, and SNPg (Figure 3; Supplementary Figure 1; Supplementary Tables 10 and 11). Increased BMI percentile is linearly associated with elevated craniofacial dimensions.

While overweight/obese children had larger craniofacial skeletal dimensions of clinical significance, there were no differences in face height proportions and mandibular plane (S–N–Go–Gn) angles, suggesting that there is no increased likelihood of anterior–posterior or vertical discrepancies in the higher BMI group (Table 3).

## Dental age versus chronological age

The mean chronological age was equivalent for both cohorts, but there was a significant difference in mean dental age with a clinically impactful acceleration of 1.4 years in overweight/obese children (Figure 2; Table 3; Supplementary Tables 1–7). The difference between dental age and chronological age was calculated as a proxy for the degree of dental advancement (19). The overweight/obese group showed 1.4 years of advancement relative to the normal weight cohort, with all ages grouped (Figure 2; Table 3). There were no significant differences between the overweight and obese subgroups (Supplementary Table 8). For each age group, there were significant differences in mean dental advancement of 0.8–1.6 years (range: −0.81 at age 11 to −1.6 years at ages 9 and 14; Figure 2; Table 4; Supplementary Tables 1–7). Demirjian score, dental age, and dental advancement also varied linearly with BMI percentile when adjusted for race, ethnicity, and gender (Figure 3; Supplementary Figure 1; Supplementary Tables 10 and 11). Increased BMI is linearly associated with a statistically and clinically significant advancement in dental development at all ages from 8 to 14 yo.

## CVM stage

Similarly, high BMI percentile subjects had a significantly advanced CVM stage relative to the normal BMI subjects (Figure 2; Table 3). On average, overweight/obese children were nearly a half stage advanced relative to normal weight children, with all ages grouped,

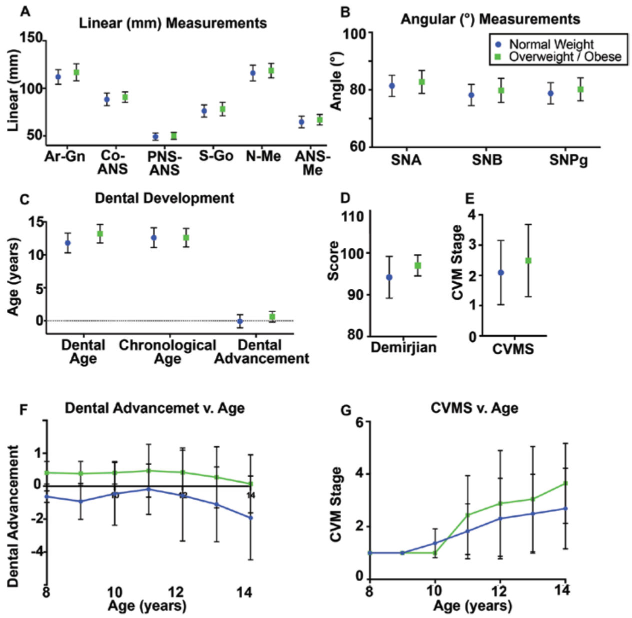


**Figure 2.** Craniofacial dimensions, dental development, and cervical vertebrae maturation (CVM) stage of normal weight and overweight/obese children. **(A)** Mean values and standard deviations (SDs) of linear cephalometric measurements (mm), including articulare–gnathion (Ar–Gn), condylion–anterior nasal spine (Co–ANS), posterior nasal spine–anterior nasal spine (PNS–ANS), sella–gonion (S–Go), nasion–menton (N–Me), and ANS–Me. **(B)** Mean values and SDs of angular cephalometric measurements, including SNA, SNB, and SNPg. **(C)** Mean values and SDs of dental developmental metrics (years), including dental age, chronological age, and dental advancement (=dental age – chronological age). **(D)** Mean values and SDs of Demirjian scores. **(E)** Mean values and SDs of CVM staging (CVMS). **(F)** Mean dental advancement as a function of age. **(G)** Mean CVMS as a function of age. Normal weight mean values are blue circles and overweight/obese mean values are green squares.The mean differences between normal weight and overweight/obese groups are statistically significant ($P < 0.05$) for all measurements, except for chronological age (Tables 3 and 4).

though there were no significant differences between the overweight and obese subgroups (Table 3; Supplementary Table 8). Alteration in cervical vertebrae maturation staging (CVMS) is most relevant to adolescents nearing peak pubertal growth. As a result, variation in CVMS by age was examined (Table 4). For ages 8–10, most subjects had a CVM stage of 1, rendering statistical tests and significance non-applicable (Table 4; Supplementary Tables 1–3). For ages 11–14, the prime years for peak pubertal growth, bivariate statistics showed significant differences in mean CVMS between normal and overweight/obese groups (Figure 2; Table 4; Supplementary Tables 4–7). For adolescents 12–14 yo, the average CVM stage fell between 2 and 4, indicating that subjects were nearing or undergoing peak growth (Table 4) (21). During these critical years, overweight/obese children were advanced nearly an entire CVM stage relative to normal weight subjects, a clinically impactful difference for growth modification.

## Reliability

The concordance coefficient reliability value for craniofacial measurements, Demirgian dental advancement, and CVM stage were all 0.90 or above, indicating high reliability (Supplementary Table 12). The cephalometric exception was Co–ANS at rho C = 0.71, likely due to difficulty in visualizing the condyle. For dental staging, LL2 and LL3 (rho C = 0.78 and 0.83) had lower reliability, possibly related to focal trough distortion. For accurate dental staging, the examiner must discern root tips, which could be obscured on LL2 and LL3 from focal trough distortion (20). Overall, intra-examiner reliability was high.

# Discussion

This is the first American study to evaluate craniofacial measurements, dental age, and CVM stage relative to BMI in a well-distributed sample of growing patients. The patient cohort of 200 normal weight and 200 overweight/obese children is the largest in the literature (by 4–5×) to evaluate craniofacial dimensions as a function of BMI and is derived from a diverse population of the Southeastern USA plagued by obesity (Table 2). Dental and CVMS skeletal development were markedly advanced in overweight/obese children, with linear relationships between BMI percentile, craniofacial dimensions, and dental advancement (Figures 2 and 3; Tables 3 and 4). These clinically and statistically significant associations suggest that BMI percentile in children and adolescents should be an important consideration for orthodontic treatment timing.

Prior reports suggested that obesity significantly impacts skeletal CVM stage and dental age, with acceleration of development and eruption (16, 18–20). Hilgers *et al.* measured Demirjian dental age in 104 children and found a mean acceleration of 1.31 years in overweight subjects and 1.53 years in obese patients (18). In our patient pool, overweight and obese subjects were grouped into a 200 person cohort that had a mean acceleration of 1.4 years relative to normal weight children, similar to Hilgers *et al.* (Figure 2; Tables 3 and 4). A prior study at UNC identified a significant relationship between BMI percentile, dental age, and CVMS in a large cohort (19). Mack *et al.* found that, for every 1 percentile of increase in BMI percentile for chronological age, there was a 0.005-year increase in Demirjian dental age, while, in our sample, we saw a 0.042-year increase in Demirjian dental age per BMI percentile (Supplementary Table 11). This 8.4-fold difference in Demirjian dental age advancement per BMI percentile is possibly due to the fact that Mack *et al.* used a modified version of the Demrijian index based on gender. Mack *et al.* and our study found that CVMS was advanced nearly a half stage for overweight/obese subjects when not grouped for age (19). When stratified by age, an advancement of nearly an entire CVMS was found in 12–14 yo patients as they progressed through peak pubertal growth (Figure 2; Table 4). The current data are consistent with published findings and indicate that an increase in BMI percentile is associated with advanced dental and skeletal maturation of statistical and clinical significance (19–21).

Craniofacial dimensions are also affected by elevated BMI. Two European studies with modest samples ($n$ < 100) found that obese subjects had bimaxillary prognathism, less soft-tissue convexity, and greater craniofacial measurements despite lower levels of growth hormone (23). Our results are consistent, with overweight/obese patients displaying significantly elevated mean mandibular length (Ar–Gn), maxillary length (Co–ANS), posterior face height (S–Go), anterior face height (N–Me and ANS–Me), SNA, SNB, and SNPg (Figure 2; Table 3; Supplementary Tables 1–7). However, in our sample, there were no differences in face height proportions, A point-Nasion-B point (ANB), or mandibular plane (S–N–Go–Gn) angles, suggesting that there is no increased likelihood of anterior–posterior or vertical discrepancies in the higher BMI group (Table 3). Our findings indicate that overweight adolescents' facial dimensions may be significantly larger than normal weight subjects, but proportionally so. In other words, obese children and adolescents were not

**Table 3.** Continuous data for craniofacial dimensions, dental age, and cervical vertebrae maturation stage for all ages.

| Variable | Normal weight BMI group (*n* = 200) | | | | Overweight/obese BMI group (*n* = 200) | | | | *P*-value* | Mean Diff.** |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | SD | Min | Max | Mean | SD | Min | Max | | |
| Height (m) | 1.57 | 0.12 | 1.22 | 1.85 | 1.55 | 0.14 | 1.02 | 1.85 | 0.403 | 0.02 |
| Weight (kg) | 46.5 | 9.7 | 24.0 | 72.6 | 63.5 | 15.1 | 31.8 | 116.6 | <0.001*** | −17.0 |
| Ar–Gn (mm) | 112.0 | 7.7 | 86.0 | 132.6 | 116.9 | 8.9 | 11.6 | 144.8 | <0.001*** | −4.9 |
| Go–Pg (mm) | 74.2 | 6.1 | 58.3 | 89.7 | 75.2 | 6.5 | 61.3 | 91.3 | 0.094 | −1.0 |
| Co–ANS (mm) | 88.4 | 6.6 | 68.6 | 112.7 | 90.8 | 5.6 | 75.2 | 123.6 | <0.001*** | −2.4 |
| PNS–ANS (mm) | 49.3 | 3.8 | 38.0 | 59.9 | 50.1 | 3.6 | 40.5 | 60.7 | 0.025**** | −0.8 |
| S–N (mm) | 71.2 | 4.5 | 55.9 | 84.6 | 71.5 | 3.8 | 61.8 | 81.5 | 0.457 | −0.3 |
| S–Go (mm) | 76.2 | 6.4 | 56.4 | 94.1 | 78.2 | 7.0 | 58.8 | 96.5 | 0.032**** | −2.0 |
| N–Me (mm) | 116.1 | 8.3 | 91.0 | 139.3 | 118.6 | 7.6 | 97.3 | 140.4 | 0.001*** | −2.5 |
| N–ANS (mm) | 53.0 | 4.0 | 39.2 | 62.2 | 53.5 | 4.1 | 41.5 | 65.2 | 0.275 | −0.5 |
| ANS–Me (mm) | 64.7 | 6.1 | 53.2 | 81.6 | 67.0 | 5.5 | 51.0 | 82.3 | <0.001*** | −2.3 |
| UFH:total FH | 0.46 | 0.02 | 0.39 | 0.53 | 0.45 | 0.03 | 0.4 | 0.58 | 0.010**** | 0.01 |
| LFH:total FH | 0.56 | 0.03 | 0.48 | 0.63 | 0.56 | 0.02 | 0.52 | 0.62 | 0.004**** | 0.00 |
| SNA (deg) | 81.4 | 3.7 | 69.9 | 91 | 82.8 | 4.0 | 68.9 | 94.0 | <0.001*** | −1.4 |
| SNB (deg) | 78.2 | 3.7 | 68.6 | 90.2 | 79.8 | 4.2 | 70.1 | 93.2 | <0.001*** | −1.6 |
| ANB (deg) | 3.2 | 2.3 | −5.5 | 9.9 | 3.1 | 2.8 | −6.9 | 10.4 | 0.510 | 0.1 |
| SNPg (deg) | 78.8 | 3.7 | 69.8 | 91.5 | 80.2 | 4.0 | 70.3 | 93.7 | <0.001*** | −1.4 |
| S–N–Go–Gn (deg) | 30.9 | 5.7 | 16.2 | 49.9 | 31.2 | 6.5 | 14.7 | 79.1 | 0.651 | −0.3 |
| Demirjian score | 94.2 | 5.0 | 63.0 | 98.9 | 97.0 | 2.5 | 81.5 | 100.0 | <0.001*** | −2.8 |
| Dental age | 11.8 | 1.5 | 7.2 | 14.6 | 13.2 | 1.4 | 8.7 | 15.9 | <0.001*** | −1.4 |
| Chronological age | 12.6 | 1.5 | 8.2 | 14.9 | 12.6 | 1.4 | 8.3 | 15.0 | 0.762 | 0.0 |
| Dental adv***** | −0.8 | 1.0 | −4.7 | 2.2 | 0.6 | 0.8 | −1.6 | 3.0 | <0.001*** | −1.4 |
| CVMS | 2.09 | 1.06 | 1.00 | 4.00 | 2.49 | 1.19 | 1.00 | 5.00 | <0.001*** | −0.40 |

ANB, A point-Nasion-B point; ANS, anterior nasal spine; Ar, articulare; BMI, body mass index; CVMS, cervical vertebrae maturation staging; FH, face height; Gn, gnathion; Go, gonion; LFH, lower face height; Me, menton; N, nasion; Pg, pogonion; PNS, posterior nasal spine; S, sella; SD, standard deviation; UFH, upper face height.

*Continuous bivariate statistics not grouped by age; $P < 0.05$ is considered significant.

**A negative mean difference represents the overweight/obese BMI group had a larger mean value than the normal weight group for that variable.

***Indicates significance after Bonferroni adjustment ($P < 0.00217 = 0.05/23$ tests).

****For *P*-values less than 0.05 that are significant but do not pass the multiple testing Bonferroni correction. Please interpret at your discretion.

*****Dental adv = dental advancement = dental age − chronological age.

more likely to be skeletally Class II or Class III or to demonstrate disproportions in the vertical dimension.

Posterior face height (S–Go), anterior face height (N–Me), and SNA had statistically significant *P*-values and met Bonferonni multiple testing criteria in either the linear regression model or by descriptive statistics, but not by both (Figure 3; Table 3; Supplementary Table 10). This indicates that these factors are influenced by gender, ethnicity, and/or race, which were included as covariates during linear analysis (Figure 3; Supplementary Table 10). Therefore, conclusions must be interpreted with the reader's discretion. Because the mean differences between BMI groups were clinically significant for these craniofacial metrics, findings could still be relevant to practitioners.

Because the study is retrospective and cross-sectional rather than prospective and longitudinal, we cannot evaluate whether the overweight/obese subjects will ultimately be larger than normal weight children at the end of growth or if they are simply advanced. Obtaining longitudinal cephalometric records through the conclusion of growth would be interesting but challenging both due to the loss of follow-up and ethical considerations for radiation exposure. However, assessing these patients' final records for craniofacial dimensions as an imperfect proxy for growth conclusion could be a valuable future direction.

Though our sample included diverse racial populations, the percentage representation was not equal among the BMI groups (Table 2). Race was not an inclusion or exclusion criteria, nor was it used for selective sampling of participants. As a result, the normal weight group included more Caucasians and Asians than the overweight/obese cohort, which had a greater representation of African Americans and Hispanics, reflective of our patient population at UNC and nationally (15). To adjust for potential confounding from racial and gender differences in facial dimensions, the linear model had gender, ethnicity, and race as covariates (Figure 3; Supplementary Tables 10 and 11). Collecting data from additional patients to increase minority representation would allow us to compare facial dimensions between minority cohorts at different BMI percentiles and is a worthwhile future direction.

An additional limitation is our use of BMI percentile as a surrogate measure of body fatness. BMI is a measure of excess weight rather than excess fat (26). It cannot distinguish between excess muscle, fat, or bone mass and can be influenced by muscle mass, height, and level of sexual maturation in children and adolescents. For obese children (BMI greater than and equal to 95 per cent), BMI percentile is a good indicator of excess body fat but, among overweight children (BMI greater than 85 per cent but less than 95 per cent), elevated BMI percentile can be due to increased levels of either fat or fat-free mass. Therefore, BMI percentile is not a perfect metric of body fatness, yet it is validated, easily calculated, and widely used (26).

In dentofacial orthopaedics, prediction and control of craniofacial growth is essential for determining optimal treatment timing,

**Table 4.** Continuous data for dental advancement and cervical vertebrae maturation (CVM) stage by age.

| | Variable | Normal weight BMI group | | | | Overweight/obese BMI group | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | SD | Min | Max | Mean | SD | Min | Max | *P*-value* | Mean Diff. |
| Dental advancement | Age 8 ($n$ = 4, 5)** | −0.6 | 0.3 | −1.0 | −0.3 | 0.84 | 0.49 | 0.12 | 1.50 | 0.001 | −1.40 |
| = dental age − chronological age | Age 9 ($n$ = 11, 5) | −0.85 | 0.69 | −2.05 | 0.14 | 0.77 | 0.54 | 0.04 | 1.52 | <0.001 | −1.61 |
| | Age 10 ($n$ = 19, 16) | −0.40 | 0.96 | −2.40 | 1.42 | 0.84 | 0.49 | 0.12 | 1.50 | 0.001 | −1.40 |
| | Age 11 ($n$ = 23, 34) | −0.05 | 0.83 | −1.78 | 1.28 | 0.76 | 0.67 | −0.56 | 2.64 | <0.001 | −0.81 |
| | Age 12 ($n$ = 53, 51) | −0.62 | 1.00 | −3.30 | 2.22 | 0.60 | 0.69 | −0.50 | 2.44 | <0.001 | −1.22 |
| | Age 13 ($n$ = 54, 49) | −1.00 | 0.89 | −3.43 | 1.12 | 0.51 | 0.93 | −1.30 | 2.42 | <0.001 | −1.52 |
| | Age 14 ($n$ = 36, 40) | −1.45 | 1.06 | −4.68 | 0.35 | 0.17 | 0.88 | −1.63 | 1.90 | <0.001 | −1.62 |
| CVM stage | Age 8 ($n$ = 4, 5) | 1.0 | 0.0 | 1.0 | 1.0 | 1.00 | 0.00 | 1.00 | 1.00 | N/A | 0.00 |
| | Age 9 ($n$ = 11, 5) | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | N/A | 0.00 |
| | Age 10 ($n$ = 19, 16) | 1.11 | 0.32 | 1.00 | 2.00 | 1.00 | 0.00 | 1.00 | 1.00 | N/A | 0.00 |
| | Age 11 ($n$ = 23, 34) | 1.48 | 0.73 | 1.00 | 3.00 | 2.32 | 0.98 | 1.00 | 4.00 | <0.001 | −0.85 |
| | Age 12 ($n$ = 53, 51) | 1.94 | 0.86 | 1.00 | 4.00 | 2.65 | 0.93 | 1.00 | 5.00 | <0.001 | −0.70 |
| | Age 13 ($n$ = 54, 49) | 2.48 | 1.02 | 1.00 | 4.00 | 3.41 | 1.04 | 1.00 | 5.00 | <0.001 | −0.93 |
| | Age 14 ($n$ = 36, 40) | 3.06 | 0.95 | 1.00 | 4.00 | 3.95 | 0.68 | 2.00 | 5.00 | <0.001 | −0.89 |

BMI, body mass index; SD, standard deviation.

*Continuous bivariate statistics not grouped by age; $P < 0.05$ is considered significant. For ages 8–10, most subjects had a CVM stage of 1, rendering statistical tests and significance non-applicable.

**The first number after $n$ is the number of subjects in the normal weight BMI group. The second number is the number of subjects in the overweight/obese BMI group.

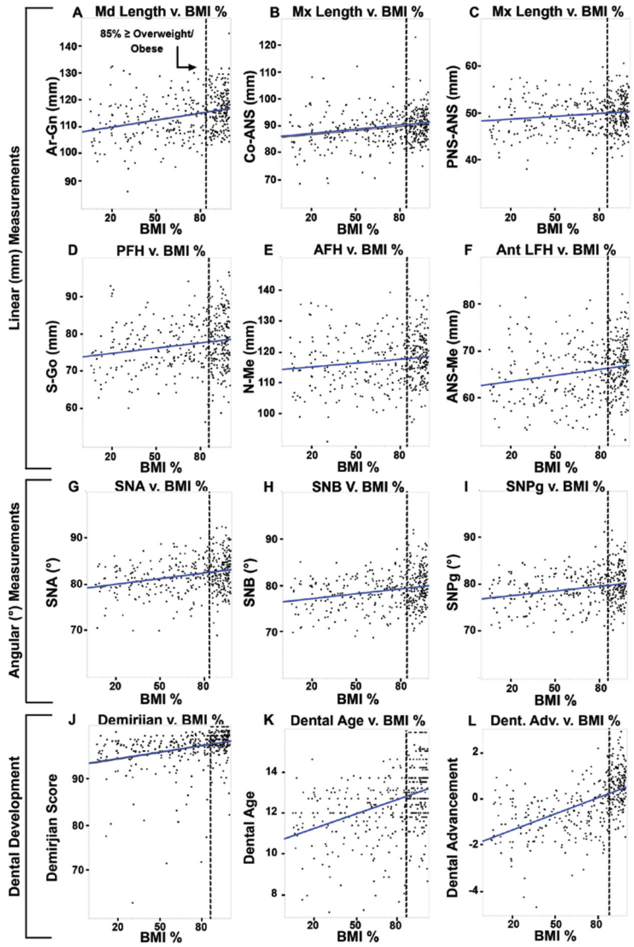


**Figure 3.** Significant linear regression plots of craniofacial dimensions and dental development as a function of body mass index (BMI) percentile. **(A–F)** Linear (millimetres) measurements. (A) Mandibular (Md) length articulare–gnathion (Ar–Gn) versus BMI%. (B) Maxillary (Mx) length Co–anterior nasal spine (Co–ANS) versus BMI%. (C) Mx length posterior nasal spine–ANS (PNS–ANS) versus BMI %. (D) Posterior face height (PFH) sella–gonion (S–Go) versus BMI%. (E) Anterior face height (AFH) nasion–menton (N–Me) versus BMI%. (F) Anterior lower face height (Ant LFH) ANS–Me versus BMI%. **(G–I)** Angular measurements. (G) Maxillary angulation SNA versus BMI%. (H) Md angulation SNB versus BMI%. (I) SNPg versus BMI%. **(J–L)** Dental development. (J) Demirjian score versus BMI%. (K) Dental age versus BMI%. (L) Dental advancement versus BMI%. Dental advancement = dental age − chronological age. Dotted line: 85% BMI percentile that is the dividing line between normal weight (BMI% <85%) and overweight/obese (BMI% ≥85%). Data adjusted for gender, race, and ethnicity. All data are statistically significant ($P$ < 0.05) with Bonferonni adjustment (Supplementary Table 10).

method, and the likelihood of stable retention (7, 23). Currently, orthodontists consider occlusion, smile aesthetics, soft-tissue envelope, gender, and race when making treatment decisions as girls develop earlier than boys and aesthetic facial norms vary by race and culture (27). However, weight is rarely a factor. A recent survey found that 73 per cent of orthodontists did not assess weight in any way and 55 per cent never collected any weight information; only 4 per cent of providers weighed patients and measured height using a stadiometer (28). With the current surge in child and adolescent obesity and its impacts on development, weight should be a consideration for treatment timing as obese children go through puberty and undergo dental development earlier than normal weight individuals (7). This consideration is critical for the planning of time-sensitive interventions like serial extractions, skeletal expansion, Class II headgear, Class III reverse pull headgear, bone-anchored mini plates, use of functional appliances, and any other type of growth modification (23). As the prevalence of early-onset obesity continues to grow, it becomes imperative that orthodontists and general dentists understand how to adjust treatment timing in overweight populations (7). Orthodontists also have the opportunity to expand their scope as health care providers by being actively involved in weight assessment and counselling to positively impact the current and future health of patients.

## Conclusions

Growing children and adolescents with an overweight or obese BMI percentile have a proportionally larger bimaxillary prognathic growth pattern in comparison to patients of normal weight. This finding was confirmed by several cephalometric measurements, including Ar–Gn, Co–ANS, S–Go, N–Me, ANS–Me, SNA, SNB, and SNPg, which were significantly different (both statistically and clinically) between the two study groups, with a linear relationship between BMI percentile and increasing craniofacial dimensions. Although overweight and obese children were more likely to have larger craniofacial growth in the sagittal dimension, they were proportional, with no increased expression of a skeletal Class II, Class III, or vertical disharmonies.

Overweight and obese children and adolescents had advanced dental maturation in comparison to normal weight patients. Despite the two study groups having equivalent mean chronological ages, the overweight/obese BMI group had a mean dental age that was 1.4 years advanced relative to the normal weight group, indicating that permanent teeth are likely to erupt at a younger age in overweight children.

Overweight/obese subjects demonstrated an advancement of nearly one CVM stage between the ages of 12 and 14. BMI percentile should be a consideration in the treatment planning and timing for overweight and obese children and adolescents.

## Supplementary material

Supplementary material is available at *European Journal of Orthodontics* online.

**Supplemental Figure 1:** Significant linear regression plots of dental development as a function of BMI percentile expressed by CVM Group. Linear regression plots for both CVMS 1 & 2 (black) and CVMS 3 & 4 (red). [A.-B.] Linear (mm) Measurements. [A.] Mandibular (Md) Length Ar-Gn v. BMI %. [B.] Maxillary (Mx) Length Co-ANS v. BMI %. [C.-D.] Angular measurements. [C.] Mandibular angulation SNB v. BMI%. [D.] SNPg v. BMI%. [E.-G.] Dental Development. [E.] Demirjian Score v. BMI%. [F.] Dental Age v. BMI%. [G.] Dental Advancement v. BMI%. Dental Advancement = Dental age – Chronological Age. Dotted Line: 85% BMI percentile that is the dividing line between normal weight (BMI% < 85%) and overweight / obese (BMI% > or = 85%). Data adjusted for gender, race and ethnicity. All dental development metrics were significant ($p<0.05$) with Bonferroni adjustment. Linear and angular measurement plots were statistically significant ($p<0.05$) for one or both lines. (Details in Supplementary Table 10.)

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## Author contributions

AD proposed the research project and associated aims in combination with mentors TJ and CG, collected and analysed data for his master’s thesis, which served as the basis for the manuscript, and participated in manuscript preparation and revision. CRediT: project administration, conceptualization, investigation, formal analysis, writing—original draft, writing—review and editing. LJ restructured the master’s thesis project prepared by AD and wrote the manuscript presented here with input from all senior authors and worked with KM for linear regression and descriptive statistical analysis. LJ and CB assembled figures, tables, and oversaw manuscript revision and submission. CRediT: project administration, investigation, formal analysis, writing—original draft, writing—review and editing. LJ recruited grant money that paid for CB’s salary, KM’s analysis, and supported LJ’s efforts as well. CB assembled figures and tables and helped with manuscript preparation and submission in concert with LJ and JW. CRediT: writing—review and editing. JW restructured and revised the manuscript with LJ. JW, LJ, and CB assembled tables and assisted with manuscript revision and submission. CRediT: writing—review and editing. KM provided statistical input on reporting of data and carried out linear regression statistical analysis. He participated in manuscript preparations. CRediT: formal analysis, writing—review and editing. PH provided statistical input on reporting of data and carried out initial statistical analyses. CRediT: formal analysis. CG oversaw the project as AD’s faculty co-mentor and participated in the development of the research aims and approach with AD and TJ. CG and AD met in person to review data and results. CG assisted with thesis preparation. CRediT: supervision, conceptualization, funding acquisition, writing—review and editing. TJ oversaw the project as AD’s faculty co-mentor, facilitated access to the University of North Carolina orthodontics research databases for data collection, and participated in the development of the research aims and approach with AD and CG. AD and TJ met remotely to review data and results and discuss thesis preparation. TJ assisted with manuscript revisions. CRediT: project administration, supervision, funding acquisition, conceptualization, writing—review and editing.

## Data availability

The data that support the findings are included in the Supplemental Materials. Any further information is available from the corresponding author upon reasonable request.

## Conflict of interest

The authors have no conflicts of interest to declare.

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