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Clinical implications of age-related change of the mandibular plane angle

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Abstract

Objective—To identify trajectories of ontogenetic change in the mandibular plane angle (MPA) and to describe the influence of sex and other factors on MPA during growth.

Setting/Sample—The data consisted of 7,026 MPA measurements from lateral cephalographs representing longitudinal series from ages 6 to 21 for 728 individuals from the Craniofacial Growth Consortium Study (CGCS).

Materials and Methods—Facial type was determined from MPA for each assessment, with the assessment closest to age 18 representing the adult facial type. The sample includes 366 males and 362 females, each with between 2 and 15 cephalographs. The mean number of cephalographs per individual is 10. Variation in childhood MPA (earliest assessment between 6 and 9 years of age), adult MPA (closest assessment to age 18 between 15 and 21 years of age), and change in MPA from childhood to adulthood were compared by sex and adult facial type using ANOVA and post-hoc t-tests.

Results—MPA decreased from childhood to adulthood in 92% of males and 81% of females, yet increased in 36% of males and 50% of females with the hyper-divergent adult facial type. Childhood MPA and overall change in MPA were significantly different by adult facial type.

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Conclusions—Adult facial type is associated with differences in childhood MPA and change in MPA during growth. There are multiple ontogenetic pathways by which an individual can achieve a normo-divergent adult facial type, and an individual's childhood MPA does not necessarily correspond to his or her adult facial type.

Introduction

Mandibular plane angle (MPA) is used in the clinical diagnosis and treatment of malocclusions and dysmorphologies, particularly in cases of open- and closed-bite skeletal patterns. Cephalometric analyses have long incorporated MPA in the assessment of normal and abnormal occlusion,^{1–3} and have shown that the use of MPA in the determination of facial type is both practical and clinically relevant.⁴ The facial types associated with high, average, and low MPA have been observed to exhibit different patterns of facial growth.^{5–9} Accurate models of change in MPA will help to maximize the efficacy of orthodontic treatment by elucidating normal variation in MPA at different time points as well as variation in MPA during growth. Change in MPA captures several aspects of mandibular and craniofacial development, including mandibular growth rotation, remodeling of the mandibular corpus, and changing anterior and posterior facial heights, resulting in considerable variation in the rate and magnitude of growth-related change in the MPA.¹⁰ Previous studies have demonstrated a tendency for MPA to decrease during childhood and adolescence, although the observed timing and rate of change have varied by study.^{6,7,10–13} To better illustrate patterns of growth-related change in MPA, we examined change in MPA from childhood to adulthood in different facial types in a large sample of individuals with longitudinal cephalometric data.

Materials and Methods

Study sample

Data for this study were obtained from the Craniofacial Growth Consortium Study (CGCS). The CGCS consists of landmark data for 13,856 cephalographs collected from 1,753 individuals, derived from six of the largest growth studies in the United States. The six studies, carried out from 1929 to 1984, sampled populations of primarily European ancestry in Colorado, Iowa, Michigan, Ohio, and Oregon. Despite variation in mean cranial size between studies, growth trajectories are similar among the six studies.¹⁴ Inclusion for the present study was restricted to individuals with at least one *childhood* cephalograph (between 6 and 9 years of age) and at least one *adult* cephalograph (between 15 and 21 years of age). All cephalographs taken between the ages of 6 and 22 were included, resulting in a sample of 7,026 cephalographs from 728 individuals (366 males, 362 females). The number of cephalographs per individual ranged from 2 to 15, with a median of 10.

Cartesian coordinates for 119 standard cephalometric landmarks were collected using the eDigit software suite developed by the Craniofacial Research Instrumentation Laboratory (CRIL) at the University of the Pacific, Arthur A. Dugoni School of Dentistry.^{15–19} Each cephalograph was assessed by three individuals; these assessments were compared and points falling outside an *a priori* error envelope for each landmark were excluded.¹⁷ Coordinate positions from retained landmarks were then averaged among the three

assessments. Repeated assessment of each landmark followed by error detection and averaging reduces random and systematic error in landmark identification.^{15,17,20} Since the present study analyzes only angular measures, no correction for radiographic enlargement was required.

As is common in human longitudinal studies, the interval between assessments varies across individuals in the CGCS. In cases where multiple cephalographs were collected from an individual within a one-year span, the earliest assessment was analyzed.

Mandibular plane angle

MPA was calculated from cephalometric landmarks as the angle between the anterior cranial base, represented by the Sella-Nasion plane, and the inferior border of the mandibular corpus, represented by the Gonion-Menton plane (Figure 1). Gonion was defined as the midpoint between the left and right inferior-most points at which the inferior surface of the mandibular corpus meets the ramus. In this study, *childhood MPA* is defined as the earliest MPA assessment between 6 and 9 years of age for each individual. *Adult MPA* is similarly defined as the MPA assessment nearest to age 18 and between 15 and 21 years of age for each individual. *Change in MPA* for each individual was calculated as the difference between the childhood MPA and the adult MPA divided by the age difference between those assessments.

Facial type

Assessments were grouped by chronological age into nine groups (6-, 7-, 8-, 9-, 10-, 11-, 12-, 13-, and 14-year-olds) to quantify changes in facial type classification over the course of growth. Facial types were defined for those with $MPA > 39^\circ$ as *hyper-divergent*, those with $39^\circ \geq MPA \geq 28^\circ$ were classified as *normo-divergent*, and those with $MPA < 28^\circ$ were classified as *hypo-divergent*.^{1,6-7,21} Each individual was assigned an *adult facial type* describing the facial type of the individual's adult MPA assessment. Individuals were also assigned one of three possible facial types, based on the measured MPA within each age group. As a result, facial type for an individual need not be consistent over the course of growth. For each age group, the percentage of individuals whose facial type matched, or correctly classified, their adult facial type was calculated.

Statistical analyses

ANOVA with post-hoc pairwise two-sided t-tests with Bonferroni correction were used to test for significant differences, by sex, in mean childhood MPA and change in MPA using adult facial type as the grouping variable. Mean differences for childhood MPA, change in MPA, and adult MPA were also considered, with facial types pooled, using sex as the grouping variable. All analyses were performed in R Version 3.5.1.

Longitudinal modeling

Change in MPA was modeled separately in males and females by facial type and with all facial types pooled. Seven model types were fit to the full sample and subsamples representing each facial type for males and females. The following natural cubic spline was fit with one, two, or three knots:²²

$$Y_{ij} = \sum_{n=1}^3 (\theta_n + \theta_{in}) t_{ij}^n + \sum_{k=1}^3 \theta_k (t_{ij} - \kappa_k)^3 + \varepsilon_{ij},$$

where Y_{ij} is the change in MPA, t_{ij} is the chronological age for the i^{th} individual at measurement occasion j , θ_{in} is the random subject effect term, and θ_n and θ_k are the fixed effect terms. κ_k are the knots used for the spline with k representing the specific knot. Knots were evenly placed at centiles of age based on the data distribution.²³

The following multilevel polynomial model was fit:

$$Y_{ij} = \Theta_{i0} + \Theta_{i1}(t_{ij}) + \Theta_{i2}(t_{ij})^2 + \dots + \Theta_{in}(t_{ij})^n + \varepsilon_{ij},$$

where Y_{ij} is the trait value and t_{ij} is the chronological age of individual i at measurement occasion j . Θ_{in} is the n^{th} order polynomial coefficient ($n = 1, 3, 4$, or 5). Θ_{in} consists of both fixed and random effect terms as $\Theta_{in} = \theta_n + [\theta_{in}]I_n$ where θ_n is the population-average value and θ_{in} is the individual deviation from that value. A simple random subject effect and up to n -order random subject effects were considered, such that I_n is equal to 1 or 0. Random subject effects were nested in an adult facial type random effect for models in which all facial types were combined.

Each model was fit using the NLME package²⁴ and lme() function with first-order continuous autoregressive error.^{25–27} Only data from individuals with at least eight MPA assessments between 6 and 22 years of age were used to model longitudinal change in MPA. Final model selection was performed using AICc.²⁸ Models of the samples with facial types pooled and with hyper-, normo-, and hypo-divergent facial types separated were compared using the root mean square error (RMSE) for each model. To validate these final models, five-fold cross-validation was used.

Results

Variation in MPA

Means and standard deviations for childhood MPA, change in MPA, and adult MPA by sex and facial type are provided in Table 1. The median ages of childhood and adult MPA assessments were 6.5 years and 17.8 years, respectively. The age difference between childhood and adult assessments ranged from 6.4 years to 14.2 years, with a median of 10.9 years. Childhood MPA in individuals with a normo-divergent adult facial type ranged from 29.5° to 46.4° in males and from 26.9° to 44.3° in females. Change in MPA in individuals with a normo-divergent adult facial type ranged from −1.44 to 0.33° per year in males and −1.12 to 0.44° per year in females. Differences in childhood MPA by adult facial type were statistically significant in both males and females ($p < 0.01$; Figure 2), as were differences in change in MPA by adult facial type ($p < 0.01$; Figure 3). Across all facial types, MPA decreased with age in 92% of males (335 out of 366) and 81% of females (294 out of 362). Of the 33 males and 42 females with hyper-divergent adult facial type, MPA increased in 12 males (36%) and 21 females (50%).

Adult MPA was slightly higher in females than males ($p < 0.01$), and, although mean change in MPA was negative in both males and females, the magnitude of MPA reduction was greater in males than in females ($p < 0.01$). Childhood MPA did not differ significantly by sex ($p = 0.89$).

Facial type

Most individuals (63.4% of males and 51.9% of females) were classified in more than one facial type categories between six and fourteen years of age. The rate at which adult facial type matched the facial type assigned at each age from six to fourteen years of age ranged from 57% to 99% in males and from 69% to 100% of females (Supplementary Table 1), with the percentage of individuals matching their adult facial type increasing with age.

Longitudinal modeling

AICc for all model types across all eight groups are provided (Supplementary Table 2). In some pooled and normo-divergent male models, and most pooled, normo- and hypo-divergent female models, n -order random subject effects were included based on AICc. All other models included a simple random subject effect. Natural cubic splines with one knot were the best-fit models for normo- and hypo-divergent males and males with all facial types combined. Third-order polynomials were the best-fit models for normo- and hypo-divergent females and females with all facial types combined. Best-fit models for hyper-divergent males and females were linear. None of the model types demonstrated a tendency towards overfitting based on consistent RMSE values from five-fold cross-validation (Supplementary Table 3).

Differences among the best-fit population average models were apparent (Table 2, Figure 4). Male and female models with all facial types combined had higher RMSE values than models separated by facial type. For both males and females, models for all facial types combined were similar in shape to models for the normo-divergent facial type. In males, the normo- and hypo-divergent models demonstrated two periods of MPA reduction. The normo- and hypo-divergent models for females demonstrated a single period of MPA reduction.

Discussion

MPA is an angular measure of the vertical dimensions of the face that is useful in the orthodontic diagnosis and treatment of skeletal malocclusion.^{10,30–32} Although MPA ultimately quantifies relative anterior and posterior facial heights, multiple growth processes, including rotational growth at the mandibular condyle and remodeling of the inferior border of the mandibular corpus, contribute to differential vertical growth of the anterior and posterior face. Together, these growth processes may increase or decrease MPA. Unfortunately, the terminology used to describe mandibular growth rotation varies and is often confusing;³⁰ The rotation of the mandibular corpus relative to the anterior cranial base quantified by MPA is referred to as total rotation³⁰ or apparent³¹ rotation. This is different from internal³⁰ or true³¹ mandibular rotation, which specifically describes the relative growth of the condyle and posterior border of the mandibular ramus, and can be masked by

remodeling of the inferior border of the mandibular corpus. The continued use of MPA to identify vertical skeletal relationships and facial types in clinical- and research-settings demonstrates the value of this measure in quantifying and modelling growth-related change and understanding subsequent impacts on orthodontic treatment outcomes.

Using univariate statistics and longitudinal modeling, the present study demonstrated multiple growth trajectories by which individuals achieved hyper-, normo-, and hypo-divergent adult facial types. Based on longitudinal assessments from the CGCS, MPA decreased with age in most individuals, supporting previous longitudinal studies of mandibular rotation.^{2–8,13,32,33} Substantial variation in both the degree and direction of growth-related change was also observed. Significant differences in childhood MPA and in change in MPA by adult facial type showed that variation in adult MPA, and consequently in adult facial type, resulted from morphological variation present at age 6 as well as variation in craniofacial growth from ages 6 to 15. Longitudinal models of growth-related change in MPA further elucidated morphological differences observed by facial type and demonstrated changes occurring in MPA throughout growth.

Modeling change in MPA

The size and variability of a sample has considerable influence over any model that could be fit to those data. The CGCS is a large longitudinal dataset that presents a unique opportunity to model change in complex craniofacial traits like MPA in a sample composed of individuals occupying multiple geographic regions within North America. Differences in growth are demonstrated among facial types through observation of the raw data and longitudinal models.

Due to our choice of information criteria for model selection, we expect small samples to be described by models with fewer parameters than larger samples.²⁹ The hyper-divergent samples contain the fewest number of individuals in both males and females, and are also fit with the least complex models. Linear models fit the hyper-divergent data as well or better than the more complex models based on RMSE values (Supplementary Table 2), which provide a measure of model fit that is not adjusted for model complexity. This indicates that the best-fit linear models reflect a linear pattern of change in MPA among hyper-divergent individuals.

When change in MPA is modeled with facial types combined, RMSE values are higher than when facial types are modeled separately. The models produced here support previous findings that MPA-based facial types are associated with consistent differences in the pattern of craniofacial growth that may be useful in the prediction of craniofacial growth and morphology.⁹

MPA facial types, typical trends observed and variation

A decrease in MPA of 2–3° between 8 and 18 years of age is considered normal based on current growth standards, and is applied in clinical facial type determination.³⁴ We find considerable variation in annual change in MPA among normo-divergent individuals, with two standard deviations of the mean ranging from –0.91° per year to 0.21 per year. The tendency to describe growth-related change in MPA linearly is not, however, supported by

our longitudinal models of MPA in normo- and hypo-divergent individuals. These samples are better described by natural cubic splines or cubic polynomial models, demonstrating that MPA does not have a constant rate of change over the course of craniofacial growth.

Our results showed significantly greater negative growth-related change in MPA in hypo-divergent individuals than in normo- or hyper-divergent individuals, supporting Karlsen's findings based on the Oslo Growth Material that more negative change in MPA was observed from ages 6 to 12 in individuals with low MPA (less than 26°) than in those with high MPA (greater than 35°).^{6,7} Differences between our findings and those of Karlsen could result from differences in the timing of facial type determination: facial type was determined at 18 ± 3 years of age in our study to capture MPA close to maturity; high or low MPA groups were determined in Karlsen's study at 12 years of age because this was the oldest age for which data were collected.^{6,7} A study of craniofacial growth patterns in Korean adolescents also found a significant differences in annual change in MPA between deep and open bite subjects from ages 6 to 14.⁸

Individuals who were normo-divergent in adulthood had a wide range of childhood MPA values and change in MPA values. Excluding individuals from the normo-divergent sample on the basis of anteroposterior malocclusions could have reduced the range of normo-divergent childhood MPA values, but anteroposterior malocclusions are inherently affected by vertical patterns and were not assessed in this study.²

Limitations

The analyses described here provided useful information about patterns of change in MPA from the largest longitudinal sample of cephalometric data ever compiled. However, methods to determine facial type differ by clinician and researcher, and MPA-based facial typing criteria are often adjusted by age and ethnicity. We chose to use consistent values for MPA-based facial typing across ages to focus our analyses on change in MPA. Inconsistencies in MPA within and among individuals could result from measurement error. The large sample and triple determination of landmarks in this study greatly reduces error in landmark coordinates and, thus, measurement of MPA. Three-dimensional assessment of MPA using CBCT images could account for the stochastic error introduced to two-dimensional angular measurements by differences in skull orientation during imaging.^{35,36} When combining records from multiple historical archives it is possible that small differences in protocol between studies may introduce error, and we have controlled for these variables at every opportunity.

Clinical implications

The majority of individuals with MPA greater than 39° at ages six (males: 62%, females: 55%) and seven (males: 63%, females: 53%) reached a normo-divergent adult facial type (Supplementary Table 1). On the other hand, MPA increased during growth in 99 individuals (19% of females, 8% of males). There is therefore considerable risk of conflating those individuals who are hyper-divergent with decreasing MPA and those individuals who are hyper-divergent with increasing MPA. Further study of the morphological and developmental characteristics that differentiate these two groups of hyper-divergent

individuals will help to develop new screening techniques to identify patients in need of early treatment. Currently known differential diagnoses for hyper-divergent facial patterns, such as a prolonged finger sucking habit and mouth breathing, common in the pediatric group due to increase proliferation of lymphoid tissue, and other possible environmental factors may also contribute to these different patterns of vertical growth.^{37,38} Early treatment to reduce MPA should be evaluated in light of these results to avoid the use of techniques that could disrupt craniofacial growth in individuals who could reach a normo-divergent facial type without orthodontic intervention.^{39,40}

Orthodontic treatments that are extrusive in nature, resulting in an increase in MPA, could exacerbate hyper-divergence in those individuals whose MPA increases as part of normal growth. Additional research into the morphology and ontogeny of those individuals is required to identify risk factors that can be used to predict increases in MPA. At early ages, facial and mandibular morphology may predict facial type more reliably than MPA alone.⁹

Many individuals exhibited sudden changes in the direction and rate of vertical facial growth. We conclude that rigid boundaries between facial types may fail to adequately describe those individuals near the boundary between hyper- and normo-divergence (39°) or normo- and hypo-divergence (28°), and recommend that diagnosis include additional cephalometric measurements and a thorough craniofacial evaluation for the basis of the patient's phenotype. Our ongoing research will use the longitudinal data presented here to identify developmental and morphological differences among facial types to improve predictive assessment of craniofacial growth.

Conclusions

We found that differences in adult MPA are associated with variation in childhood MPA and variation in growth-related change in MPA. The observed differences in childhood MPA and growth-related change in MPA by adult facial type indicated that multiple patterns of craniofacial growth can produce a normal adult MPA, and that hyper- and hypo-divergent adults do not necessarily follow a shared developmental pathway. Current craniofacial growth standards are based on a subset of the data used in this study, and do not accurately represent the variation observed in the larger CGCS sample. These findings demonstrate the need to update current craniofacial growth standards using a large and diverse sample.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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sample. These individuals have rightfully earned a place of honor in the history of human growth, development, and aging.

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Figure 1. Mandibular plane angle (blue) defined by the Sella-Nasion plane (red) and the Gonion-Menton plane (red).

Figure 2. Childhood MPA by adult facial type in males (left) and females (right). ****p<0.0001.

Figure 3.
Change in MPA by adult facial type in males (left) and females (right). ** $p < 0.01$;
*** $p < 0.0001$.

Figure 4. Spaghetti plots of growth-related change in mandibular plane angle by adult facial type in males (left) and females (right) with best-fit population average models superimposed in bold. Best-fit population average models of all facial types combined are shown in black.

Table 1.

Sample size and mean values for childhood MPA, change in MPA, and adult MPA by sex and adult facial type. Standard deviations are provided in parentheses.

Adult facial type	Males				Females			
	Hyper	Normo	Hypo	Total	Hyper	Normo	Hypo	Total
Number of individuals	33	203	130	366	42	236	84	362
Percentage of sample by sex	9.02%	55.46%	35.52%	100%	11.60%	65.19%	23.20%	100%
Mean childhood MPA (°)	43.03 (3.70)	36.84 (3.42)	31.09 (3.23)	35.36 (4.94)	41.47 (2.58)	36.05 (3.39)	30.16 (3.04)	35.31 (4.62)
Mean adult MPA (°)	41.68 (2.38)	33.07 (3.01)	24.26 (3.02)	30.72 (6.13)	41.92 (2.80)	33.40 (3.18)	25.25 (2.32)	32.5 (5.64)
Mean change in MPA (°/yr)	-0.14 (0.42)	-0.35 (0.28)	-0.64 (0.28)	-0.44 (0.34)	0.04 (0.26)	-0.25 (0.29)	-0.47 (0.24)	-0.27 (0.31)

Table 2.

Coefficient estimates and root mean square error (RMSE) for best-fit models. Statistically significant coefficients ($p < 0.05$) are bolded.

	Males				Females			
	Hyper	Normo	Hypo	All	Hyper	Normo	Hypo	All
Number of assessments	362	1852	1144	3322	368	2255	787	3410
Number of individuals	32	179	108	319	35	217	74	326
Best-fit Model	Linear	NCS with 1 knot	NCS with 1 knot	NCS with 1 knot	Linear	Third order polynomial	Third order polynomial	Third order polynomial
RMSE	2.179	2.366	2.240	3.817	2.199	2.442	1.934	3.533
θ_1	-0.089 (0.070)	-3.332 (0.704)	-6.038 (0.985)	-4.200 (0.548)	0.077 (0.048)	-0.060 (0.212)	-0.263 (0.348)	-0.191 (0.176)
θ_2		0.312 (0.069)	0.570 (0.095)	0.398 (0.054)		-0.026 (0.017)	-0.039 (0.028)	-0.014 (0.023)
θ_3		-0.010 (0.002)	-0.018 (0.003)	-0.013 (0.002)		0.001 (0.0004)	0.002 (0.001)	0.0007 (0.0007)