Original Article

Proportional Analysis of Longitudinal Craniofacial Growth Using Modified Mesh Diagrams

Jiuhui Jiang[a]; Tianmin Xu[b]; Jiuxiang Lin[b]; Edward F. Harris[c]

ABSTRACT

Objective: To study the craniofacial changes of adolescents followed longitudinally with their heads oriented in natural head position.

Materials and Methods: Longitudinal cephalograms of adolescents (n = 28) with normal occlusion, selected from among 900 candidates, were taken at 13 and again at 18 years of age. Modified elaborate mesh diagrams were developed defined by 90 anatomic landmarks and an additional 172 interpolated points for each cephalogram using a preset computer program. Detailed proportional and disproportional craniofacial changes were showed by both statistical and graphical methods.

Results: In females, most craniofacial regions exhibited growth that was proportionate to the mesh core rectangle reference on extracranial true vertical. In males, there was an upward, disproportional enhanced shift of the anterior cranial base and a downward enhanced shift of the mandibular symphysis and inferior border of the corpus.

Conclusions: This elaborate mesh analysis, based on mesh core rectangle and referenced on estimated natural head position, provides a novel graphical as well as quantitative method of assessing craniofacial growth. From 13 to 18 years of age, two sexes with normal occlusion displayed different growth patterns referenced on estimated natural head position. In females, most craniofacial regions exhibited growth proportional to the mesh core rectangle. In males, there was an upward, enhanced shift of the anterior cranial base and a downward enhanced shift of the mandibular symphysis and inferior border of the corpus.

KEY WORDS: Craniofacial growth; Proportional analysis; Mesh diagram; Natural head position

INTRODUCTION

For centuries, research workers in such diverse fields as art, architecture, and industry have used various grids to assess man's facial proportions. A grid method also has been used cephalometrically, namely, the mesh diagram analysis that was introduced by Moorrees in 1948.[1] The conventional mesh diagram is composed of 24 rectangles overlain onto a cephalometric tracing. The vertical lines are parallel to the extracranial true vertical, which represents the natural head position,[1] and the horizontal line is perpendicular to this. All the rectangles are exactly the same, arranged in six rows and four columns. The four rectangles in the middle of the face were termed the *core rectangles.* The vertical dimension of the core rectangle is defined by the subject's upper facial height (nasion to ANS) and the horizontal dimension by facial depth (sella to nasion), so the mesh rectangle dimensions are specific to a person at a specific age. Few proportional methods have been used to study craniofacial growth longitudinally, and even fewer incorporate "real-life" natural head position.

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MATERIALS AND METHODS

Subjects (n = 75) were selected from among some 900 high school students based on possession of normal occlusions (ie, Class I molar relationship with less than 3 mm of crowding, less than 3 mm overjet, and an overbite less than one-third coverage of lower in-

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Table 1. Description of Landmarks in a Modified Elaborate Mesh Diagram

Point	Description
Po	Porion
POi	Interior point of porion
Ba	Basion
PCp	Posterior point of posterior clinoid
PCs	Superior point of posterior clinoid
PCa	Anterior point of posterior clinoid
S	Sella turcica
ACi	Interior point of anterior clinoid
ACp	Posterior point of anterior clinoid
ACs	Superior point of anterior clinoid
Se	Sphenoethmoidal
SOr	Supraorbitale
GBp	Posterior point of glabella
GB	Glabella
N	Nasion
FMN	Frontomaxillary nasal suture
Epin	Epinasale
Or(p)	Posterior orbitale
Or	Orbitale
KR	Key ridge
PTMS	Pterygomaxillary fissure superior
PTM	Pterygomaxillary fissure inferior
PNS	Posterior nasal spine
ICp	Posterior point of incisive canal
ICa	Anterior point of incisive canal
ANS	Anterior nasal spine
A	Subspinale
Pr	Prosthion
UIE	Upper incisor incisal edge
Pr(p)	Prosthion lingual corresponding point
UIA	Upper incisor apex
UMA	Upper molar mesial apex
Ms	Upper molar mesial corona-root contact point
UM	Upper molar mesial cusp tip
UMd	Upper molar distal cusp tip
UMD	Upper molar most distal cusp tip
Msd	Upper molar distal corona-root contact point
UMAd	Upper molar distal apex
UMR	Upper molar root branch point
LMD	Lower molar most distal cusp tip
LMd	Lower molar distal cusp tip
LM	Lower molar mesial cusp tip
OA	First lower bicuspid cusp tip
Mi	Lower molar distal corona-root contact point
LMA	Lower molar mesial apex
LMR	Lower molar root branch point
LMAd	Lower molar distal apex
Mid	Lower molar distal corona-root contact point
J	Intersection point of mandible body superior border and a anterior border of ramus
RMA	Most concave point in anterior border of mandible ramus
ACCo	ACCoronoid
CPp	Posterior point of coronoid process
AA	Articulare, anterior
Co	Condylar process
Ar	Articulare, posterior
RMP	Most concave point in posterior border of mandible ramus
Go	Gonion
Me	Menton
Gn	Gnathion
Pg	Pogonion
B	Supramentale
Id	Infradentale
LIE	Lower incisor incisal edge
Id(l)	Lower incisor lingual bony contact point
LIA	Lower incisor apex
RGn	Lingual symphyseal point
D	Central point of symphysis
MRP	Posterior point in internal cortical plate of symphysis
MRI	Inferior point in internal cortical plate of symphysis
MRA	Anterior point in internal cortical plate of symphysis
MP	Posterior point in inferior border of third molar germ
MI	Medial point in inferior border of third molar germ
MA	Anterior point in inferior border of third molar germ
CNL	Posterior point of mandibular foramen
CNR	Anterior point of mandibular foramen
G	Soft tissue glabella
Ns	Soft tissue nasion
Pn	Pronasale
Cm	Columella point
Sn	Subnasale
As	Soft tissue A point
UL	Labrale superior
Sts	Stomion superius
Sti	Stomion inferius
LL	Labrale inferior
Bs	Soft tissue B point
Pos	Soft tissue pogonion
Gns	Soft tissue gnathion
Mes	Soft tissue nenton
C	Cervical point
RMA	Most concave point in anterior border of mandible ramus
ACCo	ACCoronoid
CPp	Posterior point of coronoid process
AA	Articulare, anterior
Co	Condylar process
Ar	Articulare, posterior
RMP	Most concave point in posterior border of mandible ramus
Go	Gonion

cisor). No previous orthodontic treatment and no respiratory problem have been reported. These 75 adolescents agreed to participate in the present research project, with cephalograms taken annually from 13 to 18 years of age inclusively. These data are part of a collection from the Craniofacial Growth and Development Centre at Peking University. The study protocol was reviewed and approved by the Institutional Review Board of the Stomatological School of Peking University. Just 28 subjects (15 females, 13 males) completed the study. One of the authors rotated the cephalograms to their estimated natural head positions.[2,3] These oriented radiographs were then scanned and saved as digital computer files.

Modified Mesh Diagram

A modified mesh diagram was generated by a computer using preset software. The mesh diagram[1,4,5]

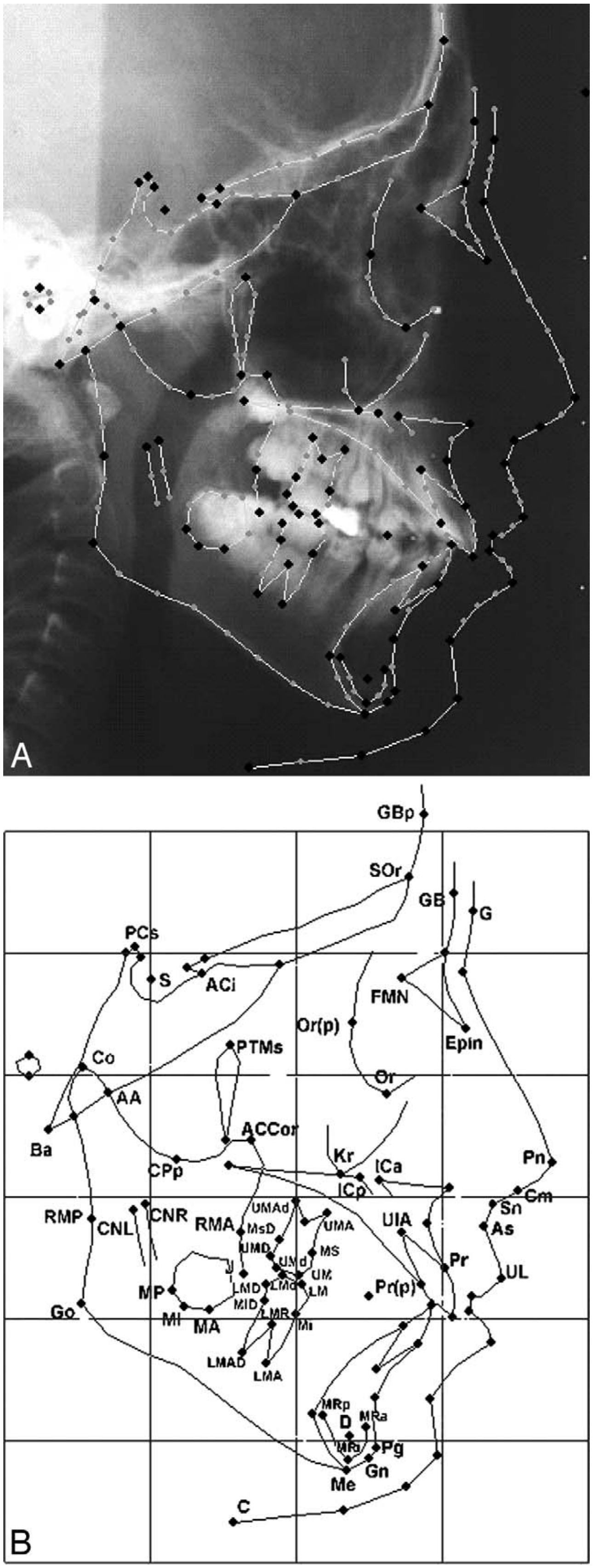

Table 2A. Significant Landmark's Proportional Coordinate Differences in the Female

	Age	n	Mean	Standard Deviation	Significance (Two-Tailed)
UMd Y	13	15	2.66	0.09	.050*
	18	15	2.73	0.09	
UMD y	13	15	2.56	0.08	.029*
	18	15	2.64	0.10	
MSD Y	13	15	2.42	0.08	.025*
	18	15	2.49	0.10	
LMR Y	13	15	3.08	0.10	.043*
	18	15	3.15	0.11	
Prn y	13	15	1.74	0.05	.030*
	18	15	1.79	0.08	

* Significance is at the .05 level (two tailed).

was generated using half of the nasion-ANS distance as the vertical scale and half of the sella-nasion distance as the horizontal scale. Registration was at nasion, with the vertical lines parallel to the extracranial true vertical.

The computer program then constructed 24 same-size rectangles as with the conventional technique[4,5] in which only 25 landmarks had been developed. In the present study, 90 anatomic landmarks (Table 1, Figure 1A) and the other 172 interpolated points were digitized from each cephalogram (Figure 1A). Then, the total 262 points were connected with straight-line segments that produce a relatively accurate lateral cephalometric outline. This oriented cephalometric rendering, along with the mesh's 24 rectangles, is termed the *elaborate mesh diagram* (Figure 1B). This computer-assisted method develops a much more comprehensive and accurate picture of the person's craniofacial structures.

Statistical Analysis

The computer-assisted method also lends itself to quantification. Cartesian coordinates of the 90 landmarks for each cephalogram were obtained. It should be pointed out that the coordinates here are not the absolute numbers but proportionate coordinates (ratios) scaling the absolute dimensions of each core rectangle.[1] The elaborate mesh diagrams for 28 subjects were regenerated again 2 to 4 weeks later. The coordinates were also collected again. No significant mean differences between the two series of proportionate coordinates were found by using paired *t*-tests.

The size of measurement error was no more than

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Figure 1. (A) Illustration of landmarks in a modified elaborate mesh diagram. Dark points indicate anatomic landmarks; light points, interpolated points. (B) Illustration of a modified elaborate mesh diagram.

Table 2B. Significant Landmark's Proportional Coordinate Differences in the Male

	Age	n	Mean	Standard Deviation	Significance (Two-Tailed)
FMN X	13	13	0.26	0.02	.023*
	18	13	0.29	0.04	
Epin y	13	13	0.77	0.07	.038*
	18	13	0.84	0.09	
OR X	13	13	0.42	0.04	.043*
	18	13	0.45	0.04	
ICP Y	13	13	1.95	0.04	.044*
	18	13	1.99	0.04	
ICA Y	13	13	1.94	0.04	.033*
	18	13	1.98	0.04	
Pry	13	13	2.67	0.07	.027*
	18	13	2.75	0.09	
Pr(p) y	13	13	2.76	0.08	.045*
	18	13	2.84	0.11	
UIA Y	13	13	2.29	0.08	.024*
	18	13	2.38	0.11	
UMA Y	13	13	2.14	0.06	.011*
	18	13	2.24	0.11	
MS Y	13	13	2.50	0.07	.005**
	18	13	2.60	0.09	
UM y	13	13	2.70	0.08	.008**
	18	13	2.79	0.09	
UMD Y	13	13	2.63	0.07	.001***
	18	13	2.75	0.10	
UMD y	13	13	2.52	0.08	.002**
	18	13	2.64	0.09	
MSD Y	13	13	2.38	0.07	.001***
	18	13	2.49	0.09	
UMAD Y	13	13	2.06	0.06	.018*
	18	13	2.15	0.11	
LMD Y	13	13	2.77	0.08	.014*
	18	13	2.87	0.11	
LMd y	13	13	2.71	0.08	.013*
	18	13	2.80	0.09	
LM y	13	13	2.76	0.08	.022*
	18	13	2.85	0.09	
MI Y	13	13	3.00	0.09	.043*
	18	13	3.08	0.10	
LMR Y	13	13	3.07	0.10	.013*
	18	13	3.18	0.11	
LMAD Y	13	13	3.25	0.13	.049*
	18	13	3.35	0.12	
MID Y	13	13	2.91	0.08	.025*
	18	13	3.00	0.12	
J X	13	13	1.39	0.10	.027*
	18	13	1.47	0.07	
RMA X	13	13	1.41	0.10	.043*
	18	13	1.48	0.07	
ACCor x	13	13	1.27	0.09	.005*
	18	13	1.37	0.07	
GO Y	13	13	3.03	0.15	.034*
	18	13	3.20	0.22	
ME Y	13	13	4.30	0.14	.031*
	18	13	4.44	0.18	
GN Y	13	13	4.21	0.14	.013*
	18	13	4.38	0.18	
PG Y	13	13	4.06	0.14	.017*
	18	13	4.23	0.19	
D Y	13	13	4.04	0.12	.034*
	18	13	4.17	0.18	

Table 2B. Continued

	Age	n	Mean	Standard Deviation	Significance (Two-Tailed)
MRP Y	13	13	3.88	0.13	.027*
	18	13	4.01	0.15	
MRI Y	13	13	4.18	0.14	.038*
	18	13	4.32	0.19	
MRA Y	13	13	3.91	0.14	.026*
	18	13	4.04	0.14	
Prn y	13	13	1.72	0.07	.002**
	18	13	1.81	0.07	
CM Y	13	13	2.04	0.04	.000***
	18	13	2.13	0.05	
SN Y	13	13	2.15	0.05	.004**
	18	13	2.23	0.07	
As y	13	13	2.30	0.06	.021*
	18	13	2.37	0.08	
UL y	13	13	2.71	0.06	.010**
	18	13	2.82	0.13	

* Significance is at the .05 level (two tailed).
** Significance is at the .01 level (two tailed).
*** Significance is at the .01 level (two-tailed).

0.04, according to Dahlberg's formula ($S2 = \Sigma D^2/2N$), with D being the difference between repeated measurements and N the number of double measurements. Then, the average proportionate coordinates for two ages (age 13 and age 18) were calculated. The two-tailed *t*-tests were used to compare them within each sex (Table 2A,B). Differences with probabilities of less than 5% ($P < .05$) were considered statistically significant.

Average Mesh Diagram and Superimposition

The average elaborate mesh diagrams, by sex, were developed for the subjects at 13 and 18 years of age (Figure 2A–D). Then for each sex, a scaled average 18 year's diagram using the landmarks' average coordinates but scaling on the 13 year's core rectangle was constructed and was superimposed on the 13 year's average mesh diagram with registration on nasion (Figure 3A,B). This allows us to focus on only the proportionate changes of craniofacial structure by ignoring the absolute amount of growth of the mesh core rectangles.

RESULTS

The average elaborate mesh diagrams, by sex, at 13 and at 18 years of age are shown in Figure 2.

Statistical Analysis

In girls, almost all of the coordinate changes from 13 to 18 years of age are proportional; females' faces at 18 years can be viewed essentially as scaled-up versions of their faces at 13 years. The few exceptions

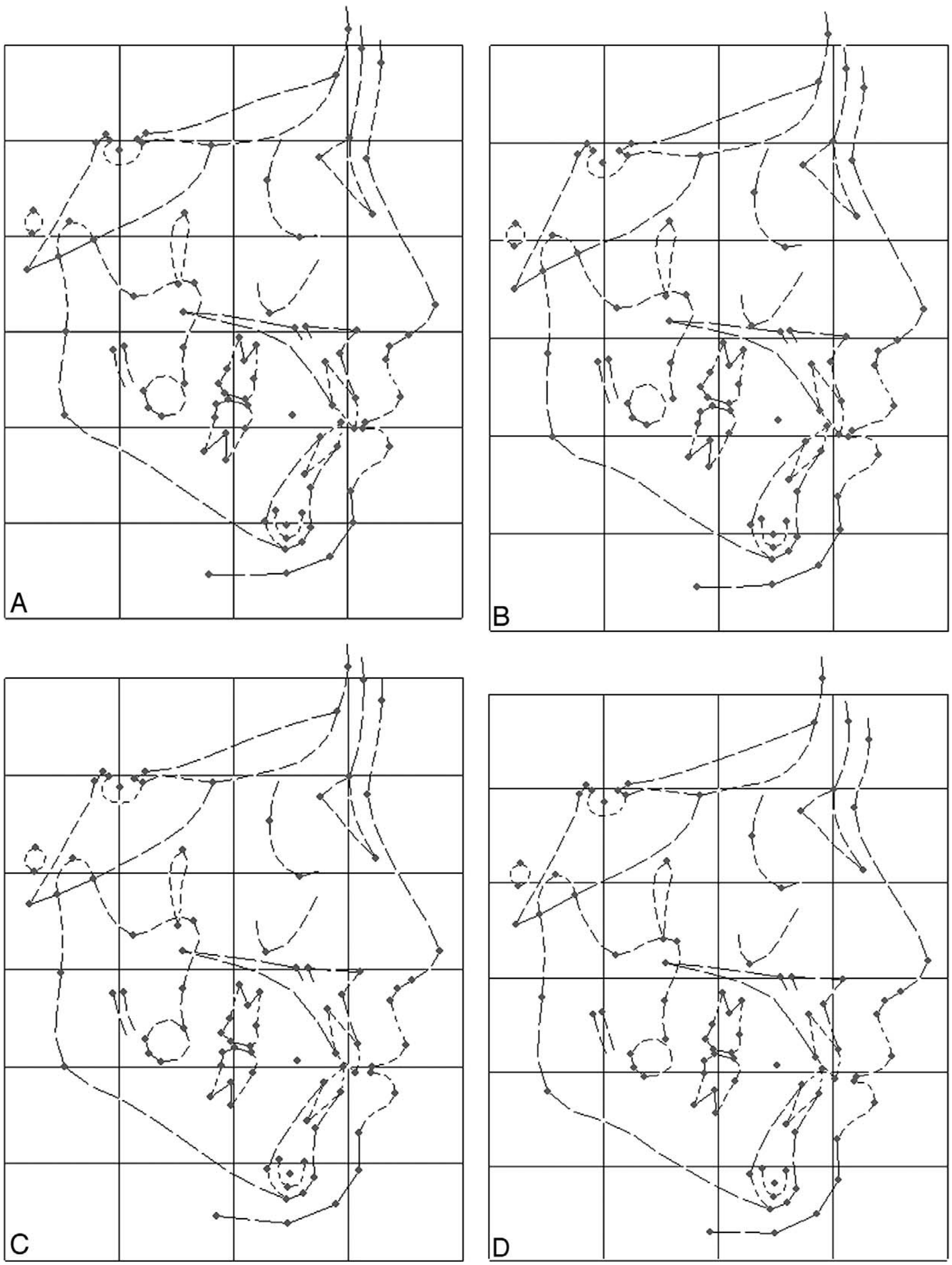
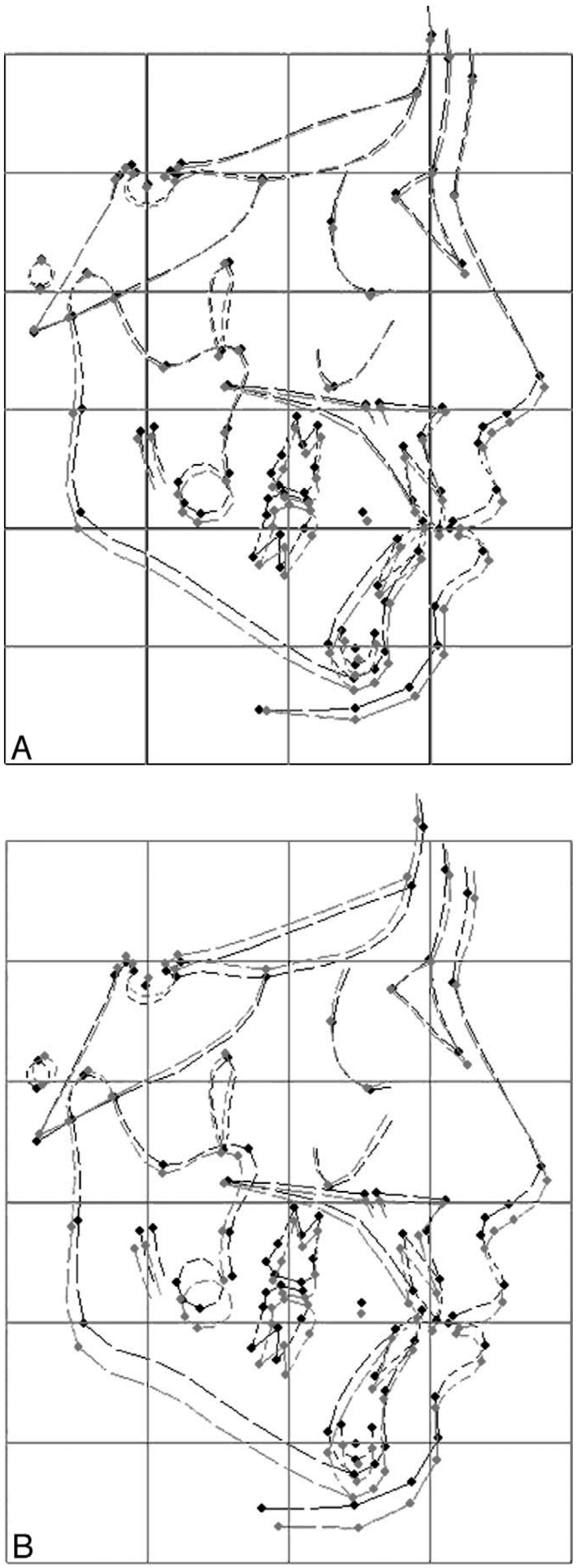


Figure 2. (A) Elaborate mesh diagram of a 13-year-old female. (B) Elaborate mesh diagram of a 13-year-old male. (C) Elaborate mesh diagram of an 18-year-old female. (D) Elaborate mesh diagram of an 18-year-old male.



are the downward increase in vertical dimension of the upper first molar distal cusp, lower first molar root furcation, and soft tissue pronasale (Table 2A). In males, more dramatic changes occurred due to the disproportional increases (Table 2B), especially in the vertical direction. Among the hard tissues, the vertical coordinates of epinasale, the upper incisors, the upper first molars, lower first molars, mandibular corpus, and symphysis exhibited disproportional increases downward. Among the soft tissues, analogous accelerated vertical vectors were seen in the tip and the base of the nose and the upper lip. A few horizontal coordinates also enlarged disproportionately in males, notably the coronoid process and the anterior border of mandible ramus.

Mesh Diagrams' Superimposition

Superimposition is a graphic way of disclosing the craniofacial growth between two ages (Figure 3) in a clear, comprehensive, and detailed fashion. In females, again, most of the structures of the craniofacial complex increased uniformly across the 6 years of growth. In contrast, there was enhanced downward extension of the inferior border of mandibular corpus, symphysis, and upper and lower lips.

Disproportional changes occurred across more craniofacial structures in the males. The anterior cranial base grew upward and the inferior border of the mandibular body, symphysis, maxillary and mandibular teeth, nasal base, and upper and lower lips extended downward disproportionately. Also, the mandible exhibited downward and backward rotation. Only the posterior cranial base, condylar process, coronoid process, maxillae, orbital bones, nasal bone, and nasal bridge grew proportionately.

DISCUSSION

Mesh Diagram and Craniofacial Growth

There are, broadly, two main methods for the study of longitudinal cephalometric data. The first consists of studying conventional angles and distances. For this, an assumedly stable reference line is relied on, which is imprecise because the locations of the bony landmarks that define the references are themselves remodeling with growth.[6,7] In addition, distances and angles reflect the relative changes between specific land-

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Figure 3. (A) Elaborate mesh superimposition diagram of a female at 18 and 13 years old. Dark line indicates 13 years old; light line, 18 years old. (B) Elaborate mesh superimposition diagram of a male at 18 and 13 years old. Dark line indicates 13 years old; light line, 18 years old.

marks. Also, numerous angles, lines, and ratios often are needed to characterize the complex changes of the facial structures.

A second method is serial superimpositions of cephalograms registered on stable landmarks. For example, the classical works of Björk and coworkers,[8–10] using metallic implants in the two jaws, yielded unbiased views of craniofacial growth. Similarly, the best fit superimposition method[11] and the structural superimpositions suggested by Björk and Skieller[12–14] are graphical approaches that provide visual views of facial development. However, the perceived relationships still depend on separate intracranial structures that remodel with growth.

A mesh diagram is based on natural head position, which is an extracranial reference line. The stability and reproducibility of an extracranial reference line has been demonstrated over both short and long intervals.[15–19] It can be seen in the present elaborate mesh diagram superimpositions that the profiles are quite consistent in each sex across 6 years of growth (Figure 3). Natural head position also depicts the true-life appearance of the subjects, as implied by the term *natural*, with the head orientated as when one is focusing on a distant point at eye level.[4,5,15,20]

Another merit of the mesh diagram is that it expresses craniofacial growth changes graphically. In the present study, the elaborate mesh diagram provides a more succinct and comprehensive picture of the changing craniofacial structures than the traditional one.

Proportional and Disproportional Growth by Sex

It is informative to analyze the subjects by sex because males and females have such different vectors of adolescent growth.[21] This graphical method shows (Figure 2) that males and females have distinctive average mesh diagrams at the same chronological ages.

The mesh diagram provides for proportional analysis. In daily life, disproportional facial changes often gain more attention. The mesh diagram scales the core rectangle that represents the size of the middle face in terms of facial depth and upper face height. It uses the growth ratio of the middle face as the basis for gauging the growth ratio of the other craniofacial structures.

The mesh core rectangles vary among individuals because the actual dimensions of the core vary. The proportional coordinates of each landmark also vary. However, there is the possibility that the average proportional coordinates of the landmarks may be the same at the two ages (age 13 and age 18 years) in each sex. And if they are the same, it means the structures are growing at essentially the same ratio as those of the average core rectangle, which is termed *proportional growth.* Otherwise, if they are not, it means the structures are growing faster or slower than the average core rectangle, which is termed as *disproportional growth.* We named the faster one an *enhanced* growth and the slower one a *decreased* growth.

More of the soft and hard tissues experienced proportional growth in females between 13 and 18 years of age. However, disproportional enhanced growth did occur in some parts, for example, the downward shift of the distal crown of the upper and lower first molars and the nose tip. Some borderline disproportional changes that have been ignored by statistical analysis are disclosed in mesh diagram superimposition, such as downward extension of the mandibular body's inferior border. It is also worth noting that purely quantitative (statistical) analysis is necessarily limited in scope—not all conceiving distances and angles among all combination of landmarks can be assessed—and whether a change is significant is modulated by sample size and amount of change. The graphical method is complementary and informative in that all of the changes are rendered in a single picture.

Males exhibited several disproportional growth changes. For example, there is a disproportionately enhanced growth of the anterior cranial base. This conflicts with the common assumption that the anterior cranial base is stable after 7 years of age.[22] The reason for this disproportionately enhanced growth is that the mesh diagram is constructed using the core rectangle that is referenced on extracranial true vertical. Actually, from this, we can induce that there has been enhanced growth in the area including the anterior cranial base and middle face compared to the growth ratio of the deeper facial structures. In the mandible, the symphysis, inferior mandibular body, and gonial angle all grew downward faster than the other structures, and the mandible experienced a downward and backward rotation. This is in contrast to the traditional mandibular superimposition that emphasizes the upward-backward translation of condylion and gonion along with the downward-forward movement of menton and pogonion.[8,10,23,24]

We see, then, that the two methods treat the same relationships in different ways. The traditional superimposition, orientated on an endocranial reference and registered on endocranial structures, is more suitable for a description of growth of facial components and absolute size changes. In contrast, the elaborate mesh diagram provides holistic information and a realistic sense of direction for growth of the entire craniofacial complex and helps identify disproportional size changes.

Several studies have dealt with craniofacial growth with the mesh diagram.[24–27] But those data are mostly cross-sectional. Longitudinal investigation seems to provide sufficient sensibility for significant findings. But there are sometimes several difficulties in data acquisition. Apart from the present study, we are aware of just one study that has used mesh diagrams to study facial growth with pure longitudinal data.[27] The subjects, not constrained to normal occlusions, were twins studies from 8 to 16 years of age. The diagrams ware based on 25 conventional landmarks, and it was found that the middle face in each sex underwent little change of the soft and hard tissue landmarks and a slight advancement of the chin and a dorsal-caudal growth of gonion.

Another possible application of results of this study is the prediction of craniofacial growth. Prediction can relate to the direction, magnitude, timing, rate of change, and/or the effects of treatment.[28] Björk[8] noted that growth prediction can be accomplished using three general methods: longitudinal, metric, and structural. This mesh diagram analysis is an example of the structural method. We can assume that a 13-year-old normal occlusion child is here. Can we predict the child's craniofacial growth to age 18? We could first construct the mesh diagram and compare it with the corresponding average to find the individual discrepancies. Then we could picture her predicted individual mesh diagram at the age of 18 by considering the initial discrepancy, the average diagram at 18 years of age, and growth. Precision is difficult because of each person's unique growth pattern influenced by poorly understood genetic and environmental factors. However, proportional analysis of a mesh diagram does show us a possibility.

CONCLUSIONS

- A proportional cephalometric method—modified elaborate mesh diagram analysis, based on mesh core rectangle and referenced on estimated natural head position—provides us a novel graphical as well as quantitative method of assessing craniofacial growth.
- From 13 to 18 years of age, two sexes with normal occlusion displayed different growth patterns referenced on estimated natural head position. In females, most craniofacial regions exhibited growth proportional to the mesh core rectangle. In males, there was an upward enhanced shift of the anterior cranial base and a downward enhanced shift of the mandibular symphysis and inferior border of the corpus.

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